Resilience Governance for Infrastructure Dependencies and Interdependencies

A Practical Model for Regional Critical Infrastructure Resilience

Northeastern University
Global Resilience Institute

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Executive Summary

Throughout the 20th Century, American communities became increasingly reliant on infrastructure systems that extended well beyond the reach of their direct control. With the dramatic expansion of the electrical grid, the development of the interstate highway system, the construction of a continental network of fuel pipelines, and the building of long-range water distribution networks such as the Colorado River Aqueduct, the infrastructure that major metropolitan regions rely upon for energy, transportation, water, and communications reach across multiple local, state, and even national jurisdictions. Not only have individual infrastructure systems become more expansive, they have become increasingly interconnected and interdependent. This trend has only accelerated in the current century with the pervasive integration of internet enabled devices into physical systems.

The evolution towards sprawling and connected systems have been animated by a desire to provide more services for growing urban populations while boosting efficiencies and reducing costs. However, one unintended consequence is that there is a growing risk of cascading and far-reaching failures when there are man-made or naturally-occurring disasters. Disasters that once were local in their impacts can now generate consequences that are regional, national, and even global. Managing these risks, especially as infrastructure ages and threats become more severe, requires communities to reexamine the ways in which they prepare for, respond to, and recover from inevitable shocks to the systems they own, operate, and rely on.

The Global Resilience Institute (GRI) at Northeastern University's examination of disasters to include Superstorm Sandy (2013), Hurricane Joaquin (2015), Boston's "snowmageddon" (2015), wildfires (2016), a potential Cascadia mega-earthquake (2017), and more, has shown that the governance structures for managing critical infrastructure risks have not kept pace with the scope and complexity of these systems. With funding from the Critical Infrastructure Resilience Institute (CIRI), a Department of Homeland Security Center of Excellence located at the University of Illinois Urbana-Champaign, GRI has examined these governance challenges in two regions: The Metro Boston Region and the Pacific Northwest. Through a survey of existing literature and several major workshops that brought together infrastructure owners and operators, emergency managers, and major industry stakeholders, GRI has identified three key barriers to building more resilient infrastructure governance structures:

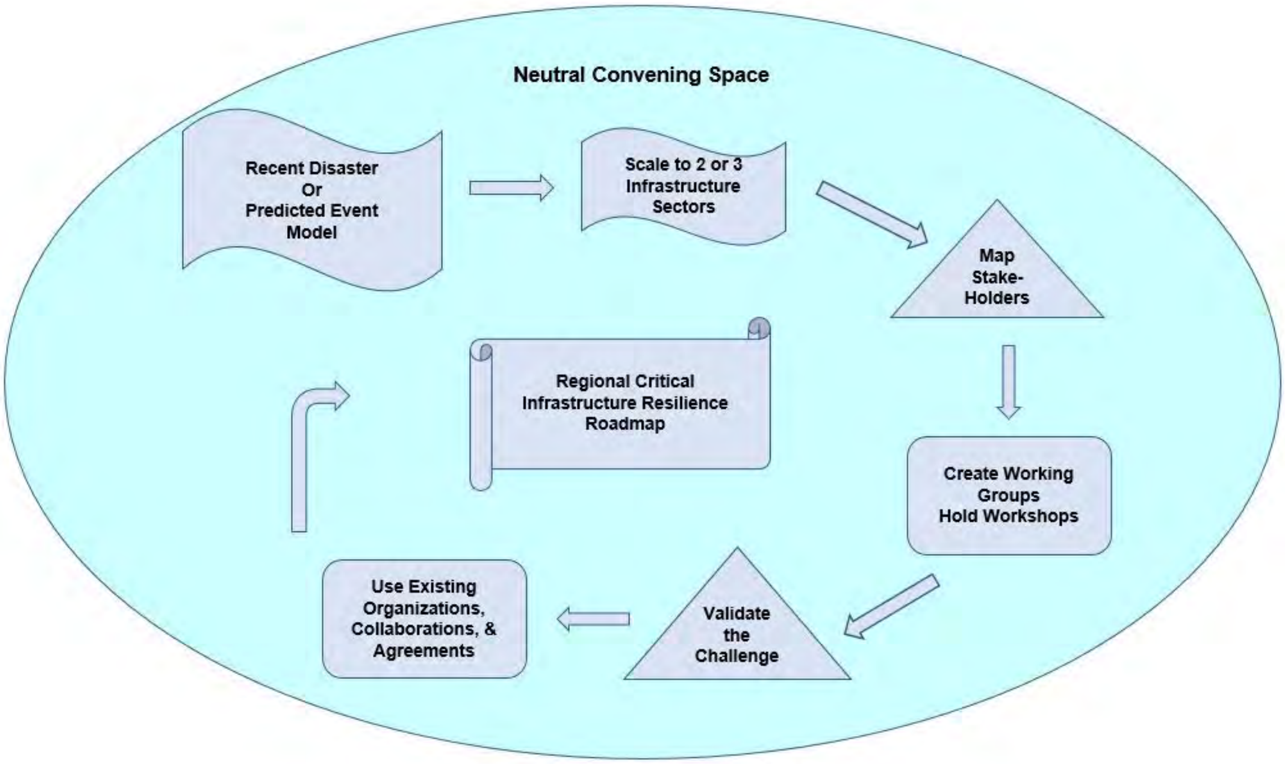
1. Regions currently have no way to evaluate in advance how prepared they are to handle foreseeable risks or to assess their capacity to respond to uncertainties associated with major disasters.
2. Regions lack an integrative approach for advancing resilience across inherently interdependent critical infrastructure systems.
3. As a nation, we lack appropriate frameworks for managing organizational and governance issues on a regional scale.

Through its work in these two regions, GRI developed a framework for other communities looking to undertake their own resilience building efforts. The process is illustrated in the graphic on the following page.

This process is built around six critical elements that make resilient governance building possible:

1. Leveraging a neutral convener to empower an open regional conversation about a critical but sensitive topic.
2. Employing a well-understood recent disaster or a well-modeled, predicted event to baseline the challenges that stakeholders will need to understand and overcome.
3. Scaling the challenge to manageable proportions by selecting two or three critical functions (systems or systems-of-systems) and evolving the development of the final governance structure over time.
4. Identifying and engaging the relevant regional stakeholders to include public officials, private corporations and relevant associations. As far as possible, leveraging existing regional organizations, associations and collaborations.
5. Using existing plans to validate and baseline the regional challenge as the basis for action.
6. Collaboratively developing practical, affordable, regionally-tailored solutions through consensus and experience.

By employing this framework, regions in search of a baseline process can adopt and develop these six elements to their communities' unique needs and circumstances. Using this model as a guide will position communities to not just survive, but thrive in the face of 21st Century turbulence.


Neutral Convening Space
Recent Disaster
Or
Predicted Event
Model
Scale to 2 or 3
Infrastructure
Sectors
Map
Stake-
Holders
Create Working
Groups
Hold Workshops
Validate
the
Challenge
Use Existing
Organizations,
Collaborations, &
Agreements
Regional Critical
Infrastructure Resilience
Roadmap

The Regional Critical Infrastructure Resilience Governance Challenge

Background: The Lessons Learned from Recent U.S. Disasters

The American tendency to treat extreme weather events and other disasters as though they are rare and unknowable is reckless and irresponsible. The deep experience of The Global Resilience Institute (GRI) at Northeastern University with U.S. disaster events beginning with Superstorm Sandy and running the gamut from northeastern snowstorms, catastrophic wildfires, massive coastal flooding, and potentially devastating earthquakes provides strong evidence that much of the destruction and damage resulting from major disasters is both predictable and largely preventable. Creating regional capacities to increase our resilience so that we can better withstand, more nimbly respond, recover and adapt to disruptions of all kinds must be a national imperative.

For the past five years, GRI has fielded teams of experts to learn lessons from significant U.S. disasters, convened representatives from other metro-regions to share those lessons, and facilitated efforts to advance critical infrastructure resilience at a regional scale. While the challenges and lessons from any given disaster may vary according to the type of disruption and its location, GRI has consistently found that there is a set of common themes and trends. Paramount among these are:

- There is a pervasive overestimation by both public officials and private infrastructure owners and operators regarding how prepared their communities and businesses are to handle foreseeable risks or to respond to uncertainties.
- There is limited regional understanding of the interdependent nature of critical infrastructure systems and the resultant cascading effects that can result when they are compromised by major disruptive events. This leads to significant vulnerabilities with potentially catastrophic consequences that are not being adequately considered in response and recovery planning.
- There are too few economic or policy incentives in place for creating resilience; in fact, in many instances, there are multiple bureaucratic and financial disincentives for investing in resilience.

Exacerbating all these challenge is the fact that every modern community is dependent on systems that extend well beyond its jurisdictional control. The nation's critical infrastructures – transport, communications, energy, water, public health (with increasingly embedded cyber vulnerabilities) – sprawl across local, state, and even national jurisdictions. Their ownership is a mix of public and private, large and small. The operation of some of these systems is highly regulated such as for electrical utilities, and loosely regulated for others such as internet. This inevitably results in incompatibilities and inefficiencies across the network of organizations and stakeholders that severely restricts the ability of any given community to manage the risks to the systems that it relies upon to provide critical functions and services.

In short, the complexity and increasing connectedness of modern systems, along with the rapid pace of technological change, necessitate regional approaches to critical infrastructure resilience. **Taken together, perhaps the most significant finding of all GRI disaster assessments is that the current governance frameworks for facilitating public-private coordination and collaboration on a regional scale are not up to the task of managing disruptive risks given the varied and extensive geographic ranges and complex interdependencies of critical infrastructure sectors.**

With this important finding underpinning its efforts, GRI undertook the task of creating a practical model for regional engagement that could lead to the establishment of a tailored regional frameworks for creating disaster resilience governance structures. Through close examinations of the potential for a Superstorm Sandy-like event in Boston and the strong potential for a mega-earthquake in the Cascadia Subduction Zone around the Puget Sound, as well as a preliminary investigation into the challenges of flooding associated with Hurricane Harvey in Houston, GRI has clearly defined the regional critical infrastructure resilience problem and developed a model for regional collaboration among public and private stakeholders that could be adapted across the United States.

Two Case Studies: Boston and the Cascadia Subduction Zone

Boston Metropolitan Area

Boston, like most coastal urban areas, has become increasingly aware of the potential impacts of inundation and flooding due to storm surge and extreme rainfall events. Between 1631 and 1890, Boston's land area tripled by leveling its hills and importing gravel to fill in marshes and mudflats. As a result, much of the city sits just a few feet above sea-level. The tidal-range in Boston Harbor is nine-feet which fortuitously helped to largely spare the city from storm surge flooding in the 20th Century. This is because the major hurricanes to strike near Boston's made landfall at or near low tide. However, should a hurricane strike Boston at high tide, the results would likely be devastating due to the combined factors of rising sea-levels, continued urban development along the waterfront, and the loss of permeable surfaces.

The Global Resilience Institute at Northeastern University partnered with the Massachusetts Emergency Management Agency (MEMA) and Boston Office of Emergency Management (OEM) to examine the threat that flooding would bring to two critical infrastructure systems that are inherently interdependent – energy and transportation. GRI staff worked with informed stakeholders to identify the most vulnerable transportation and energy assets and to formulate recommendations for actions that would strengthen the resilience of these critical systems. GRI, along with its MEMA and OEM partners, then convened a diverse group of public officials and private sector executives to assess the region-wide effects on mobility and energy that a major flooding event would generate. Altogether, approximately 80 stakeholders with direct interests in the Metro region's energy and transport functions were identified and agreed to participate in a resilience-building task force.

The participant deliberations were framed around a hypothetical, but scientifically reasonable scenario of a Superstorm Sandy-like storm striking Boston at high tide, bringing with it a 7-foot storm surge. The scenario assumed that the Boston-Metro area would have no more than 24-hour notice based on when forecasters could accurately predict a strike given the rapid speed at which hurricanes have historically moved up the East Coast once they pass Cape Hatteras, North Carolina. Using a combination of storm model visualization maps, Google-Earth displays, prior interviews with stakeholders, and workshop discussions, the GRI/MEMA/OEM team led participants through three workshops to evaluate the consequences of the flood scenario on the energy and transport sectors. They also discussed the likely impacts on other lifeline infrastructure sectors. They then identified where mitigation and storm recovery efforts should be directed in order to strengthen the regional resilience.

Four major findings resulted from these Boston workshops.

1. A Superstorm Sandy-like event in the Boston-Metro area would severely impact the liquid fuel, electrical power, and transport systems that the region depends on for mobility and energy.
2. Current public and private response plans are not up to the task of adequately addressing the most critical vulnerabilities to these impacts.
3. The overlap of public/private responsibilities and authorities for these infrastructures validate the need for a new comprehensive cross-sector approach to metropolitan area disaster recovery planning.
4. Both the private and public sector participants identified existing associations that could be leveraged to help address some vulnerabilities, but a more comprehensive and sustained effort would be required, given the magnitude of the stakes and challenges involved.

The Boston-area workshops and resulting insights reinforced many of the difficulties that GRI had previously identified when it comes to assessing the resilience of critical infrastructure at a metro-regional level. The workshops revealed that key decision makers possessed a limited understanding of the interdependencies associated with the transportation and energy infrastructures within the region until they had a chance to sit with their counterparts and share their sector-specific knowledge. The workshops also helped to expose the existence of significant dependencies on extra-regional actors that would have to be included in any resilience building efforts. It confirmed that when it comes to critical infrastructure, the most appropriate scale for productive resilience planning is at the metro-regional level as opposed to the city level.

The Boston workshops also highlighted the gaps between government planning and public-sector expectations and private-sector planning and expectations. The significant overlap of both responsibilities and authorities requires collaborative planning, but no such formal arrangement currently exist to support this kind of planning.

Cascadia Subduction Zone

The Cascadia Subduction Zone (CSZ) is an 800-mile long area where the Juan de Fuca tectonic plate is locked against the North American plate just off the Pacific Coast, running from northern California to British Columbia. The abutment of these plates makes the area prone to a subduction zone earthquake, which occurs when hundreds of years of pressure forces one plate to slide under the other, causing the ground to violently shake and in the case of the CSZ, suddenly drop about 6 feet along the fault line. For the residents of the Pacific Northwest, this would mean the destruction of lifeline infrastructure, severe shortages of vital resources, and tens of thousands of injuries and fatalities.

Though the average varies, a study published by Oregon State University places the probability that a full margin rupture – likely a 9.0 magnitude – will occur at about 10% and a rupture at the southern end – likely an 8.0 magnitude – at about a 1-in-3 chance by 2060. In any case, the potential dangers of such a significant megaquake are clear and present.

In June, 2016, FEMA held a regional functional exercise named *Cascadia Rising* to support the Pacific Northwest's preparations to respond to a CSZ megaquake. To conduct this simulation, FEMA chose to examine a 90th percentile scenario involving a megathrust earthquake along the Cascadia Subduction Zone fault line. The scenario and impacts to the region were based on a 2011 simulation developed by the Homeland Infrastructure Threat and Risk Analysis Center (HITRAC), which is part of the Department of Homeland Security's Office of Infrastructure Protection. FEMA's exercise scenario focused primarily on the region's immediate response to the earthquake, simulating how stakeholders would provide life safety and emergency management operations across six "core capabilities": communications, public health and medical, mass care services, situations assessment, critical transportation, and operational coordination.

The Global Resilience Institute (GRI) aimed to expand on the Cascadia Rising exercise by focusing on preparing the region to manage post-megaquake recovery. Specifically, it undertook an examination of the governance challenges associated with restoring the energy and transportation sectors in the weeks and months following the devastating earthquake. Building from the process developed during GRI's examination of the Boston-Metro area's resilience to a severe flooding event, the Institute developed a brief scenario of damages to the liquid fuel, electrical power, port, rail, and surface transportations sectors in the Portland-metro and Seattle-metro areas to frame the workshop discussions. The expected megaquake damage incorporated in the GRI scenario was informed largely by those used by FEMA for its Cascadia Rising exercise. Additionally, it drew from an extensive array of research studies informed by scientists, emergency managers, and infrastructure owners and operators throughout the region.

Like the Boston workshops, this event was designed to look at both public and private sector critical infrastructure owners and operators as well as their major customers across a large region. Accordingly, the lessons learned have served to augment and amplify the lessons learned in Boston. The key findings in the Puget Sound workshop were:

- Private and public stakeholders within a region are often unaware of the critical information gaps that should inform their planning, response, and recovery efforts. These "unknown unknowns" limit how effectively they are able to cope with interdependency challenges.
- Current frameworks for building resilience encourage stakeholders to examine infrastructure sectors on an individual sector-by-sector basis. However, the nature of complex interdependencies amongst sectors require that infrastructure be understood as a system of systems.
- Current competitiveness, jurisdictional, and legal hurdles hamper stakeholders' ability to share critical information or provide a disincentive for organizations to do so.
- Stakeholders from the public and private sectors acknowledge the significant adverse long-term economic consequences for the Cascadia region in the event of a slow recovery. Nonetheless, they acknowledge the difficulty of aligning and coordinating their capacities so as to improve the recovery process.

The results of the workshops in the Boston-Metro area and the Puget Sound region combined with earlier lessons observed from a series of workshops around Superstorm Sandy in New York, allowed GRI to cogently identify for key public and private stakeholders the regional critical infrastructure challenge and propose six basic principles to guide a process for tailored development of regional governance structures. These six principles are outlined in detail later in this paper.

The Regional Critical Infrastructure Resilience Problem

While virtually all of our contemporary critical infrastructure sectors operate at a regional or greater scale, our nation and our systems of governance are not organized by region. Federal funding flows through states to municipalities with the result that our systems for investing in infrastructure tend to be focused in building and maintaining assets within local or state jurisdictions. Rarely is the governance of those assets done amongst states (the Port Authority of New York and New Jersey is an important exception). Regional planning bodies, where they exist, frequently concentrate their efforts on regional economic development and do not adequately include critical infrastructure owners and operators. Although there are examples of regional collaborative agreements for specific purposes and regional mutual aid agreements, the U.S. has no apparatus that routinely considers and compels disaster resilience planning to take place at the regional level. Yet, post-disaster assessments of every major disaster event are filled with examples of local response and recovery efforts that were less effective or were made significantly more difficult as a result of inadequate regional coordination and situational awareness. At the same time, the recovery of functions critical to the region was frequently stalled because independent actions were taken based on imperfect knowledge and limited visibility. The result was to create self-defeating, sub-optimal decision making at the local level. The assessments undertaken by GRI point to three critical factors inhibiting effective regional mitigation, response and regional recovery efforts.

Regions currently have no way to evaluate in advance how prepared they are to handle foreseeable risks or to assess their capacity to respond to uncertainties associated with major disasters.

Too many Americans overestimate current capacities to respond to disasters and have a bias that discounts the risks associated with our aging infrastructure and cyber threats, and are in denial of the leading indicators of disruptive climate-related events in our future. A preoccupation with extracting greater efficiencies and reducing costs for legacy and new infrastructure, translates into systems that fail badly during extreme events. America's infrastructure is aging, oversubscribed and in many cases further strained by inadequate funding for service-life maintenance and upgrades. Old and new threats, including those arising from cyberattacks and climate change, can trigger cascading effects that compromise the essential foundations for our society and economy. Further, local and state economic development decisions rarely take into adequate account the risk posed by growing hazards. Most risk-prevention measures are in place to deal with routine risk as opposed to extreme events, and emergency management focuses almost exclusively on response to deal with the immediate life and property issues associated with disaster.

The Boston-Metro area, like most other major urban coastal regions is vulnerable to the impacts of flooding because of more frequent storm-induced surge events coupled with extreme rainfall. Boston created space for its growth by making itself bigger; the city's footprint tripled prior to 1890 and has expanded by nearly one-third since then as developers backfilled marshes, mudflats, and areas adjacent to Boston harbor to create more land for construction. Under current "normal" conditions, Boston has a nine-foot tidal range. Fortuitously for Boston, during the 20th Century, the major storms made landfall during low-tide periods, sparing the metro area from disastrous flooding. However, recent studies have found that the Boston Metro region's exposure to "100-year" flood events will rise significantly over the next 30 years causing the 100-year flood level to occur with a frequency of every eight to 30 years. Not only is the Boston-Metro region more likely to incur extreme high-water events, but the economic consequences will drastically increase, as much new development has been undertaken in areas that are vulnerable to inundation.

Planning for recovery is also too often overlooked at the local level and almost always absent at the regional level. As disasters over the past decade have demonstrated, decision makers need processes at the regional level that allow them to better understand the dependencies and interdependencies of the lifeline infrastructures that they rely on for mobility, communications, energy, water and health care. While some programs such as the Department of Homeland Security's Regional Resilience Assessment Program (RRAP) seek to identify critical infrastructure system vulnerabilities across multiple jurisdictions, because these assessments are not publicly available, their findings are often not available to be incorporated into urban planning and emergency response.

Regions lack an integrative approach for advancing resilience across inherently interdependent critical infrastructure systems.

There is no widely accepted consensus on what resilient infrastructure is, leaving decision makers to be guided only by localized success or failure stories in disparate domains for discrete hazards. Most ongoing resilience engineering efforts suffer from a lack of coordination at a systems level. Resilience-building efforts conducted by private infrastructure owners and operators are often pursued with only the limited involvement of public officials. When it comes to the public sector, most resilience engineering efforts undertaken by public agencies are pursued only at the local level. Without considering the regional root causes or resulting effects, the projects are too often not effectively integrated into regional solutions. As a result, too little understanding or insight informs the parameters necessary for system- or network-wide resilience leading to stove-piped projects that can potentially exacerbate regional problems, and in the aggregate, cost more.

There is probably no better example of this challenge than in the governance of the nation's watersheds. As demonstrated in multiple recent disasters (South Carolina, 2015; North Carolina, 2016; Texas, 2017), watersheds operate as a system of systems across multiple local jurisdictions. However, too often this reality is only recognized by the general public and their elected officials after a major flooding event. The ownership of the component parts for controlling water within watersheds are dispersed among private individuals, corporations, neighborhood associations and by local (town, city, county), state and federal entities. This fractured ownership, sprawling across multiple jurisdictions, inevitably leads to blurred lines of responsibility, as well as gaps in oversight that complicate system-wide design, maintenance and management. Additionally, years of independent and uncoordinated decisions made by those involved with civic development and planning often end up inadvertently compromising the integrity of an entire regional system. Under normal conditions, the system successfully manages the movement of water through the watershed with limited localized human interventions. However, during times of extreme precipitation, the cumulative effects of independent local decisions leads to floodwaters moving in novel and unanticipated ways, contributing to cascading failures that can impact multiple, interdependent infrastructure sectors over a wide geographic region. To meet challenges such as this, we must develop a regionally integrated approach that will inform future design and operational imperatives so as to mitigate the risk of cascading failures and speed recovery of lifeline functions when major human-made and naturally occurring disruptions occur.

As a nation, we lack appropriate frameworks for managing organizational and governance issues on a regional scale.

The nation's critical infrastructure systems sprawl across multiple political jurisdictions and thus are inherently regional. Even highly regulated infrastructures such as electric generation and distribution or communications architecture can be impacted by local decisions. Local zoning or land use ordinances can restrict siting or maintenance activities with regional implications. Less regulated systems like transportation, watersheds and health care can be severely affected during a disaster. Further, decisions that are made at the local level without an understanding of the overall regional context will inevitably slow recovery. This jurisdictional sprawl is a challenge within a state, but it is made even more complex when infrastructures cross state and even national boundaries as is increasingly the case in the United States. The Regional Plan Association's *America 2050 Project*[*] forecasts that most of the nation's population growth and the largest share of economic expansion will take place within 11 areas that represent large networks of metropolitan regions (see figure 1). Clearly regional frameworks for managing organizational and governance challenges should transcend state and boundaries with Canada and Mexico. Both the Boston-Metro and the Pacific Northwest regions emphasized these cross-border interdependency challenges. In the Northeast, energy and natural gas demands are met through partnerships with Canadian enterprises such as Hydro-Québec. Similarly, refineries in Puget Sound are essential to fulfilling British Columbia's refined fuel needs and Alaskans depend on shipping that originated in the Ports of Seattle and Tacoma in Washington State for fuel, food, and other goods. Cascading effects to regions that span national borders necessitate governance frameworks that address legal barriers to effective multi-jurisdictional coordination and collaboration.

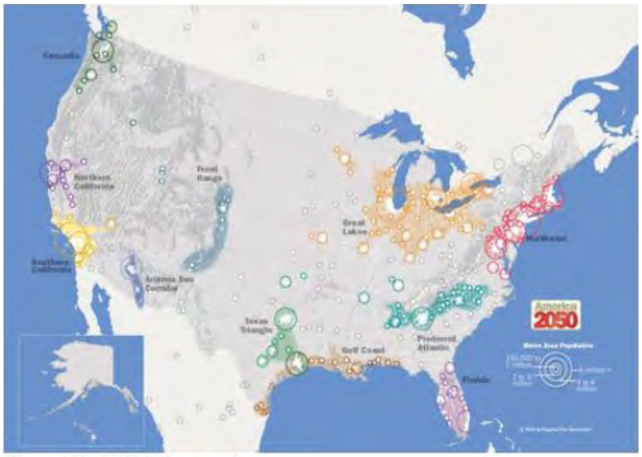


Figure 13. U.S. Mega-regions
(Source: American 2050, Regional Plan Association)

U.S. Megaregions (source: Regional Plan Associations)

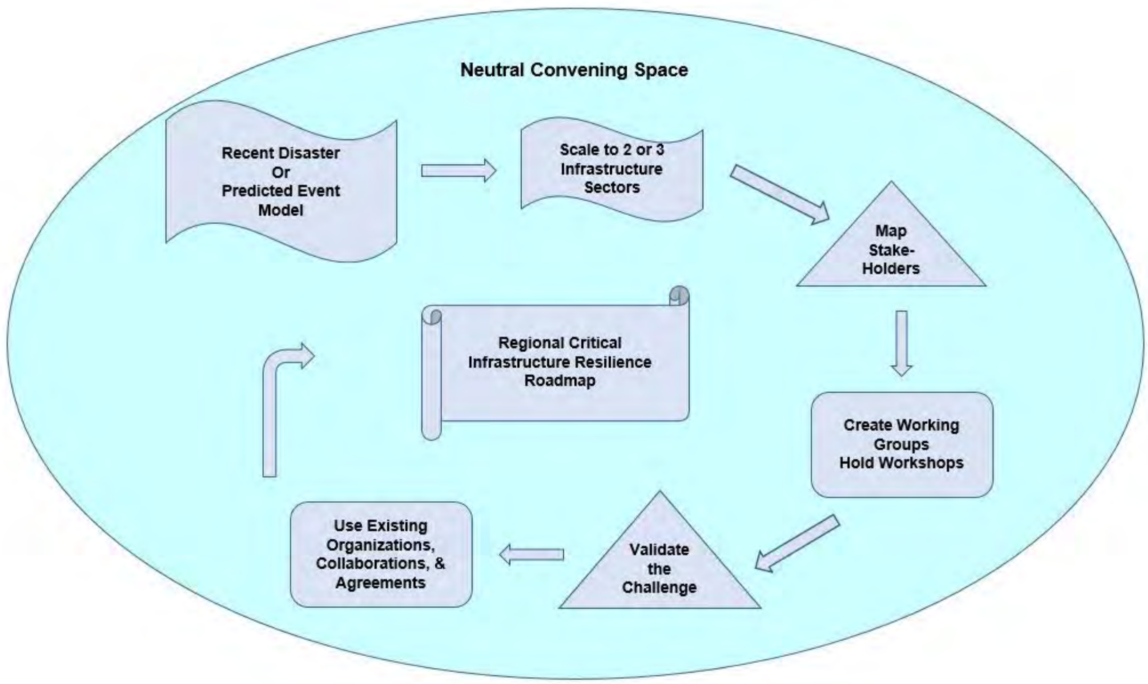
The overlap of public and private responsibilities and authorities in regards to critical infrastructure translates into significant incompatibilities in disaster planning, mitigation, response and recovery across the network of organizations and stakeholders. Assessments have repeatedly revealed that individual public and private response and recovery plans, where they exist, do not adequately address the entire set of critical vulnerabilities for any given infrastructure in the event of a large-scale disaster. The critical gaps that exist are most evident in the absence of coordination between public (largely emergency management) response and immediate recovery plans and the sector-specific plans of private infrastructure owners and operators. Communications between these critical actors is frequently conducted on an individual level or on a sector-by-sector basis. Participation by private industry in federal, state and local emergency management response exercises is often very limited and has a difficult time translating into actionable recommendations.

An excellent illustration of this problem can be found in the *Joint Multi-State After-Action Report* of the *Cascadia Rising 2016 Exercise* conducted under FEMA auspices in 2016. While there was an impressive array of multi-state public agencies that participated in the event, there was very limited private sector participation. Notably, representatives from many of the region's largest employers were not included. Not surprisingly, an examination of the findings from the exercise and subsequent recommendations reveals that almost all ended up focused on public sector actions. The potential contribution by private sector critical infrastructure owner/operators to the response and recovery were largely overlooked even though much of the critical infrastructure for the region lies primarily in private hands. Additionally, private sector needs are diverse, as each operates in a unique business and regulatory environment. Because of this, the absence of critical stakeholders, such as the fuel refineries, can result in an inadequate or false sense of understanding of private sector needs.

Compounding the public/private gap when it comes to emergency management are the inadequate public and private partnerships in the planning domain. In some ways, this can be a more serious problem since it indicates a continuing failure to recognize the interdependence of critical infrastructure and the potential for catastrophic cascading failure in disaster. Experience in all assessments indicate that these gaps result from several factors: (1) A reluctance to share proprietary information, (2) a lack of recognition of sector dependencies, (3) an unfamiliarity with planners in adjacent sectors, and (4) in some instances, anti-trust regulations that prevent major companies within a sector from sharing information and coordinating operations across a given sector. In the absence of coordinated knowledge, private sector planners find it necessary to craft assumptions (sometimes explicit; often implicit) about other public and private stakeholders' response and recovery plans that are frequently invalid. For instance, candid conversations about the capacity for truck traffic on the Interstate 5 corridor through Seattle, WA following a Puget Sound megaquake among state transportation officials and large transportation users revealed significant differences in assumptions about what was likely to be available and who would receive priority access. These types of assumptions, when revealed to be invalid during the heat of a crisis, can completely derail established plans and bring recovery to a halt.

Finally, too little attention is given to planning on how to meet the requirements of the "customers" of these regional critical infrastructures after a disaster occurs. Appropriately, emergency managers focus on efforts that translate into saving life and property. But this often is done at the expense of the vitally important imperative of planning for economic recovery. Getting people back to work and reestablishing a normal rhythm of life is critical. Failure to understand the needs and assumptions of the largest regional employers risks those businesses and their workforces relocating to other regions.

The GRI Process for Creating Regional Critical Infrastructure Resilience Governance Models



Nationally, overcoming these challenges requires a new model that allows disparate groups to coordinate regional response and recovery plans. GRI worked with relevant stakeholder groups to identify attributes of successful governance structures and public-private roles within those structures that can promote resilience across regional lifeline infrastructures. The six critical elements of this process are outlined below

1. *Leverage a neutral convener to empower an open regional conversation about a critical but sensitive topic.*

Taking effective action to create regional infrastructure resilience requires an all-hands-on-deck effort. Every sector, public and private, has exclusive information and unique requirements. No single agency can represent the region. But, substantive discussion and assessments of recent catastrophic disasters are potentially burdened with political sensitivities, local animosities, defensiveness about past performance, and bureaucratic turf issues. To a lesser extent, the same conditions may be present in discussions of preparation for predicted events. Add to this the challenges of handling sensitive security and proprietary information and the challenge of building a willing collaboration of these disparate groups becomes sufficiently daunting to deter action. Yet, inaction is not an option.

A convener with the relevant expertise can bring stability and confidence to the process. Specifically, the convener must bring several demonstrable attributes to the task:

It must be neutral and objective. The convener cannot have overt and polarizing equities in the region. While any objective academic or non-governmental organization can fulfill this requirement, in ideal conditions a trusted agent from outside the region would collaborate with a co-convener within the region who can provide deep regional knowledge. A regional college or university is usually well suited to be an in-region co-collaborator. In building and exercising this model, GRI collaborated with the University of South Carolina who served as a co-convener for flooding in that state; the University of North Carolina as the co-convener for flooding there; and the Pacific Northwest Economic Region (PNWER) for the Cascadia megaquake scenario. In Boston, the Massachusetts Emergency Management Agency (MEMA) leveraged

GRI to establish a neutral and objective environment for a discussion amongst key public and private sector stakeholders. The key is possessing objectivity and neutrality and relevant domain expertise.

The convener should also possess deep experience in the field of disaster resilience derived from a close study of what has worked and not worked in building regional resilience. It must demonstrate thought leadership in catastrophic event assessment and pre-event disaster planning. It should be able to marshal a cadre of experienced engineers and modelers who can lend their expertise to the technical aspects of the discussions. Above all, it should include experienced practitioners – real people who have lived through and made decisions in the chaotic circumstances associated with responding to and recovering from major disruptive events.

The convener must also have expertise in managing collaborative problem solving. Individuals, businesses, public officials, and non-profit organizations inevitably have widely divergent views of any given problem and they possess competing equities. The convener must be able to successfully overcome these barriers for reaching consensus in order to achieve practical, implementable solutions.

2. ***Employ a well-understood recent disaster or a well-modeled predicted event to baseline the challenges that stakeholders will need to understand and overcome.***

To be able to identify infrastructure resilience challenges, mitigation needs and planning gaps, stakeholders must have a clear understanding of the conditions that necessitate resilience. They need a context within which to place their resilience thinking. It is very difficult to identify specific measures for building resilience without connecting it in some way to a realistic event that exposes likely and serious life-safety and economic risks. Resilience stakeholders need to be able to visualize the effects of disasters and work through some "what/if" discussions that can inform the approaches they take in response.

Using a contemporary event that everyone is familiar with can be a helpful way to animate and inform planning. But care must be exercised to not use an event that is so recent that there is an incomplete understanding of what actually occurred. Stakeholders may not be able to agree on the "big picture" of what happened because there may have been insufficient time for complete discovery and analysis. Using a recent event to understand and baseline challenges may also provoke defensive responses as stakeholders, particularly those in the public eye, react to actual or perceived deficiencies in performance. In these cases, the neutrality and objectivity of the convener becomes critical in ensuring a full, scientifically-based analysis and presentation of the event and is what drives the discussions in an open and collaborative manner.

Using a model to examine a future predicted event has all the challenges of writing about the future. Stakeholders will want to examine the basis of the predictions, the assumptions and science behind the model and the objectivity of the modeler. The model itself must be sufficiently complex to accurately present the most likely conditions following the disaster, but simple enough to be understandable and useful to a diverse group of participating stakeholders. It must allow them to project their organizations into the model and use its revelations to evaluate their planned actions and understand how the actions of other stakeholders will affect their response and recovery.

For both the Boston and Puget Sound projects, GRI was able to create meaningful stakeholder interaction and analysis of regional infrastructure challenges using predictive models and analysis. The model used in Boston (Paul Kirshen, 2006) examined coastal flooding likelihoods for major urban areas across the U.S. and found the Boston Metro area's exposure to 100-year flood events to be particularly high. Using this information, GRI and Northeastern University worked with a model designed by the Sasaki Design Group to help local leaders and planners visualize the flooding threat to key energy and transportation assets. The Sasaki team modeled the Boston-Metro area for sea level increase under two cases, demonstrating the vulnerability of low-lying areas to inundation and flooding. While the Sasaki model was created to help planners visualize future effects of sea-level rise, it is built on assumptions which can serve as analogs for current flood risk from Superstorm-Sandy-like events. The Sasaki model was able to show how 7-feet of flooding at high tide would inundate the low-lying areas of the city where many critical assets are located. Accordingly, it was able to represent conditions that were a reasonable approximation of the storm-surge associated with a Superstorm Sandy-like event on Boston. These assumptions were the basis for the hypothetical disaster scenario used with stakeholder workshops.

In the Puget Sound, GRI used the work that formed the underlying foundation for the FEMA Multi-State Cascadia Rising exercise in 2016. The assumptions used in this exercise were based on models well accepted in the region and already used for local planning and exercises. Using this previously validated data, GRI was able to convene discussions with public and private stakeholders around a 90th percentile megaquake scenario on the northern half of the Cascadia Subduction Zone with the epicenter near Seattle. Using a model and scenario already accepted by regional stakeholders, the workshop was able to create meaningful interactions on planning gaps and questionable planning assumptions in the transportation and energy infrastructures.

3. ***Scale the challenge to manageable proportions by selecting two or three critical functions (systems or systems of systems) and evolving the final governance structure over time.***

According to Presidential Policy Directive 21 (PPD 21), the federal government identifies critical infrastructure as:

"those 'systems and assets' whether physical or virtual, so vital to the United States that the incapacity or destruction of such systems and assets would have a debilitating impact on security, national economic security, national public health or safety or any combination thereof."

The Department of Homeland Security has identified 16 critical infrastructure sectors. Alas, simultaneously analyzing 16 infrastructure sectors with overlapping systems and assets to identify the planning gaps in response plans by multiple public and private regional stakeholders is a task sufficiently daunting to deter any region from attempting it. GRI's solution to this challenge is to "scale and evolve."

Taking a maximum of two or three critical infrastructure sectors makes the task manageable without the danger of becoming stove-piped in a single sector and completely negating the opportunity to uncover obvious but previously unrecognized dependencies and interdependencies among sectors, infrastructures, and systems. Detailed analysis of Superstorm Sandy indicated that the energy, transport, communications, water, and health sectors were all seriously compromised during the event. These sectors are clearly foundational where disruptions cascade quickly into other sectors. Indeed, energy and transport are so foundational to disaster recovery that GRI believes it important to tackle them first and used these as the basis for discussions in the Boston and Puget Sound case studies.

In Boston, stakeholders were quickly able to discern that damage from the model-predicted storm surge would cause major damage to four significant power generation stations, at least 22 electric substations in the distribution grid, a large liquid natural gas terminal and an oil reserve terminal. The ability to quantify and visualize this level of damage, allowed stakeholders to begin to envision functional impacts that were beyond the capability of the model and that would severely affect their organization's recovery as well as the wider region. This was also true of the disruptions to the transport systems where the model predicted major damage to mass transit infrastructure, highways, tunnels and port facilities. Much more importantly, however, by examining these two functions against accepted model predictions, stakeholders were able to see the interconnections, dependencies and interdependencies among the various systems that provide energy and transportation. The same results were demonstrated using the same two infrastructure sectors in the Puget Sound case study.

Beginning the process with two or three critical infrastructure sectors where the overlaps and interdependencies are quickly exposed and easily discerned by the stakeholders allows regional processes to gain early success, build working collaborations, and establish the foundations for future analyses of other more difficult sectors.

4. ***Identify and engage the relevant regional stakeholders to include public officials, private corporations and relevant associations. As far as possible, leverage existing regional organizations, associations and collaborations.***

No regional process can be complete without the ability to get the right mix of stakeholders involved in the process. Mapping the key stakeholders that are involved with all the relevant sectors is critical. These will include public officials, private business owner/operators, trade and industry associations, customers (e.g., major users of the infrastructure) and non-profit advocacy groups and service organizations. Deep regional knowledge and relationships are key. In almost all cases, this requires having credible, regional sponsors who are willing to serve as co-conveners and recruit participants. Without these critical regional partners, outside organizations will have great difficulty establishing the relationships that result in participation at appropriate levels, with all the relevant stakeholder groups represented. As noted earlier, GRI has used local universities, public officials, and regional associations as partners in applying this model.

Stakeholder mapping begins at the top. While it is critical to map and obtain the participation of as many of the relevant stakeholders as possible from each of the sectors to be assessed, getting participants who understand organizational plans for disaster response and recovery for the critical infrastructure sectors is key. However, to be effective, these participants must know that they possess the active support of the decisionmakers that they report to. Governors, mayors, and senior corporate executives must empower their representatives to share information, collaboratively identify gaps and vulnerabilities, recommend practical solutions and bring those recommendations to appropriate officials who can make decisions. Without this active engagement and support, regional resilience processes may be successful in identifying problems, but they can never be successful in devising and implementing solutions.

Every metropolitan area and every region is replete with special purpose organizations chartered and working to solve problems. In most cases they are single purpose or single jurisdiction entities. They may be formed to advance a certain goal, such as economic development, or they may exist within only a specified jurisdiction – a town or county. Occasionally, they may also be regional in their scope. However, even regional economic planning councils usually only include a small subset of government or government agencies as members. However, identifying and convening existing organizations that possess important relationships and domain expertise to participate in regional resilient infrastructure planning is likely to prove to be a more effective and timely approach than trying to create new organizations from scratch. GRI has successfully integrated regional planning bodies, transportation and energy trade associations, public agencies and special interest groups into regional collaborations. All participants share a willingness to collaborate and focus on identifying and solving resilience challenges.

5. ***Use existing plans to validate and baseline the regional challenge as the basis for action.***

Response and recovery planning by governments and private companies is usually required by policy or regulation. There are usually requirements that these plans be regularly updated. However, too often these planning efforts are undertaken in an uncoordinated fashion. Still, these existing plans can provide a helpful stepping-off point for creating and validating regional baselines.

It is not uncommon to find that existing plans will have been developed in isolation. While cities or counties develop response and recovery plans with regional conditions in mind and with some understanding of state plans, it is unusual to find carefully coordinated planning where response and recovery plans (in the few cases where recovery plans exist) have been examined or tested in a regional context. This lack of coordination causes significant planning gaps among jurisdictions and may cause complete failure when the gaps exist between public planners and private infrastructure owner/operators. Without comparing plans as openly as possible, it is simply impossible to identify the interdependency requirements of infrastructure system recovery. Each entity, public and private, in the absence of knowledge about what is in the other plans end up making assumptions about adjacent infrastructure recovery capacities, capabilities, and priorities. Without facts, those assumptions can be seriously flawed and lead to catastrophic response and recovery failures.

Matching existing plans may be the only way to find and document regional infrastructure recovery interdependencies and recovery challenges. It is also a time-consuming and difficult undertaking made more challenging by the need to share sensitive or proprietary information. Crafting a way to exchange this type of information in order to objectively map and share the most problematic regional challenges is a key task of the convening body.

6. ***Collaboratively develop practical, affordable, regionally-tailored solutions through consensus and experience.***

The GRI process is designed to facilitate this goal. The only purpose of building the type of collaborative process described here is to achieve practical regional solutions that can be readily implemented. Given the inherent complexity of the enterprise, for any regional approach to succeed at building greater disaster resilience for critical infrastructure, it must be viewed by the participants as empowered, collaborative, iterative, and objective. For it to be sustainable: (1) there must be buy-in and ongoing support by the most senior level stakeholders; (2) it should begin with 2-3 clearly critical regional functional areas with others added over time to address the issue of complex interdependencies; (3) the right participants need to be identified and enlisted; and (4) existing regional groups, plans, and structures should be leveraged to the maximum extent.

Future Exploration

If followed, the principles and processes detailed above can lead to the development of regional plans that will enhance any region's ability to respond more effectively and recover more rapidly. Stakeholders are led through a facilitated process to discover unidentified interdependencies, erroneous assumptions, and unrecognized planning gaps between the public and private sectors and among the private sector owner/operators. At a minimum, it will facilitate enhanced coordination across jurisdictions and across infrastructure sectors which represents a significant step forward.

What continues to be missing, however, are decision-support tools that help planners to objectively visualize the extent of potential disruptions and determine the optimal course of action for speeding recovery. The goal should be to provide them with the means to move beyond a heavy reliance on assumptions, anecdotes and history. Developing these tools that can be readily adapted for use by decision makers in multiple regions is an essential research imperative.

Without prejudicing future research, GRI's experience would suggest that resilience assessments should assign primacy to maintaining functions rather than on infrastructure assets. In general, what communities are most interested in is having access to functions; e.g., energy, mobility, health care, and communications. Priority should be assigned to finding creative ways to provide those functions even when major assets are damaged or destroyed in a disaster. What is important is having access to essential functions that meet minimal needs during times of crisis and a capacity to rapidly restore full and even enhanced function following crisis. An emphasis on the continuity of functions (services) in the face of disruptive events, also ensures that planners are especially mindful of critical interdependencies. No function relies on only one system, and the assessment of any function requires the examination of the interplay of all systems that contribute to that function.

Assessing the resilience of a function requires first understanding the current capacity for infrastructure systems to provide it under normal operating conditions. Since disruptions will vary and affect functions differently, an assessment should identify the vulnerability of each function to these differing disruptions. This assessment of functional vulnerability may be similar to, but clearly will be more complex than, the risk assessment approaches that are in common use. And finally, since the availability of resources is always critical to resilience, having an understanding of which resources are at hand to cope with a disruption and which need to come from outside is key.

Developing and amplifying this research thread is an important requirement in creating infrastructure resilience on a regional scale.

About the Global Resilience Institute at Northeastern University

The **Global Resilience Institute (GRI)** at Northeastern University (globalresilience.northeastern.edu) is committed to informing and advancing societal resilience around the globe. Communities, companies, and countries can thrive only if the systems and networks that underpin our daily lives, whether physical, technological, or social are able to better withstand, recover from and adapt to the inevitable shocks and disruptive events of the 21st century.

Established in 2017, one of the Institute's core activities is to learn from global disruptions and through partnering with other leading academic research institutions, nonprofits and the public and private sectors, use what is learned to help devise and apply practical, interdisciplinary solutions to resilience building challenges.

A core focus of the Global Resilience Institute's mission is to support practitioners by identifying and advancing best practices that help to ensure lifeline infrastructure systems are able to adapt to, better withstand, and more rapidly recover from disruptive events. To this end, GRI leverages its expertise to study real-world threats, apply lessons learned, and provide recommendations for cross sector regional resilience building efforts.

This project, funded through the Department of Homeland Security's Critical Infrastructure Resilience Institute at the University of Illinois Urbana-Champaign, aims to identify challenges to resilience governance at a regional level.

Rising Above: Building Resilience in the Energy and Transportation Sectors of the Metro-Boston Region

Executive Summary

Boston, like most coastal urban areas, has become increasingly concerned about the potential impacts of inundation and flooding. Boston created space for much of its growth in the 19th and 20th Centuries by filling in wetlands, mudflats, and areas adjacent to its harbor. This newly created land tends to be just a few feet above current high-tide levels. Fortunately, during the 20th Century, the major storms that made landfall near and around Boston did so at low tide or near low-tide, sparing the metro area from disastrous flooding. But there is no guarantee that Bostonians will continue to be this lucky going forward. Further, coastal urban areas such as Boston has a growing exposure to the risk of flooding due to the combination of acres of impermeable surface, increased structural density, rising sea levels, and increasingly frequent extreme rain events.

A 2007 study examining the likelihood of coastal flooding for major urban regions across the United States found the Boston-Metro region's vulnerability to major flood events will rise significantly over the next 30 years, causing what had been estimated to be "100-year floods" to take place every 8 to 30 years.[1] The economic consequences of these floods will also drastically increase due to recent urban development on real estate in and around the Boston waterfront that is most vulnerable to inundation. CoreLogic's 2016 study of housing structures at risk from flood and inundation found Massachusetts and the Boston-Metro region to be 8th and 13th respectively in highest possible reconstruction recovery costs for homes destroyed by hurricane-related flooding in the US.[2] According to a study reported in *Nature* in 2013, Boston ranked 8th among the 130 largest coastal metropolises in the world in likelihood of catastrophic flooding and resulting financial loss (current average annual loss of $237 M rising to $730+ M by 2050).[3] There is little doubt that the Metro Boston region should be taking action to mitigate this increasingly costly threat and enhancing their plans for responding and recovering to major flood events. Key to guiding those efforts will be capitalizing on infrastructure mapping and scenario modeling solutions that are informed by the latest environmental forecast data. This will allow decision-makers to reach informed decisions about assets at risk and the most effective actions that will protect assets at risk and mitigate threats. Like any major city, Boston is dependent on systems of critical infrastructure that are owned and operated by private and public-sector entities that are outside of its direct control. Additionally, even though these systems are interdependent, these entities typically craft their plans for managing disruptive events independent of one another. This translates into there being a high risk of cascading failures when major disasters occur with resultant substantial and costly delays in overall community recovery. In short, the dearth of governance frameworks for managing the complex interdependencies that are inherent to critical infrastructure systems, complicates a metro-region's ability to understand in advance the severity of the risk it faces, the likelihood of consequences, and the necessary actions to mitigate or manage the risks.

The Global Resilience Institute at Northeastern University partnered with the Massachusetts Emergency Management Agency (MEMA) and the Boston Office of Emergency Management (OEM) to examine the threat that a major

1 Kirshen et al. "Coastal flooding in the Northeastern United States due to climate change." Mitigation and Adaptation Strategies for Global Change. 4 Dec. 2007. Web. https://link.springer.com/content/pdf/10.1007%2Fs11027-007-9130-5.pdf.

2 H. Botts, Ph.D. et al. "2016 CoreLogic Storm Surge Report." June 2016. Web. http://corelogic.maps.arcgis.com/apps/MapJournal/index.html?appid=0cd57ed426974442ac928615931803cd.

3 Hallegatte et al. "Future flood losses in major coastal cities." Nature. 18 Aug 2013. Web. https://www.nature.com/articles/nclimate1979.

flooding event would bring to two critical infrastructure systems – energy and transportation. This assessment was conducted by convening a diverse group of public and private leaders to examine the impacts to energy and transport assets in the Metro Boston region. The participants were selected from stakeholders, owner/operators, and governmental entities with an operational or oversight role of the liquid fuel, electrical power, port and surface transportation infrastructures. Altogether, over 60 stakeholders participated in the resilience-building task force.

Participant deliberations were framed around a hypothetical, but scientifically reasonable, scenario of a Sandy-like storm striking Boston at high tide bringing with it a seven-foot storm surge. The scenario used a realistic timeline of less than 24 hours' notice that the storm would strike the Metro Boston region. Using a combination of storm-model visualization, stakeholder interviews and workshop discussion, the GRI/MEMA/OEM team led the participants through three workshops to evaluate likely impacts of such a storm to include the risk of cascading failures associated with the interdependencies between the energy and transport sectors. Once consensus was reached on what was likely to go wrong, the participants were tasked with identifying the actions that should be taken in order to enhance resilience.

The resilience task force identified four major findings and multiple recommended actions to address the impacts of the storm scenario:

Finding 1: A Superstorm Sandy-like event in the Metro Boston area would severely impact the liquid fuel, electrical power, and transport systems that the region depends on for mobility and energy.

Finding 2: Current public and private response and recovery plans are not up to the task of adequately addressing a major regional disaster.

Finding 3: The overlap of public/private responsibilities and authorities for these infrastructures validates the need for a new comprehensive cross-sector approach to metropolitan area disaster recovery planning.

Finding 4: Both the private and public sector participants identified existing associations that could be leveraged to help address some vulnerabilities, but a more comprehensive and sustained effort would be required, given the magnitude of the stakes and challenges involved.

Each of these findings was accompanied by several recommended actions necessary to address the gap or vulnerability and thereby strengthen resilience of the infrastructure and the city's function.

Introduction

Boston's Challenge

Boston, like most coastal urban areas, has become increasingly concerned about the potential impacts of inundation and flooding. Boston created space for much of its growth in the 19th and 20th Centuries by filling in wetlands, mudflats, and areas adjacent to its harbor (see Figure 1). This has the twin adverse effects of removing some of the natural barriers to storm surge while simultaneously placing critical infrastructure in low-lying, flood-prone terrain. While major tropical storms are not as commonplace in the northeast as in the nation's southeast and Gulf of Mexico regions, the Metro Boston area has experienced major hurricanes with associated highs wind and storm surge in the past, and it will experience them again in the future.

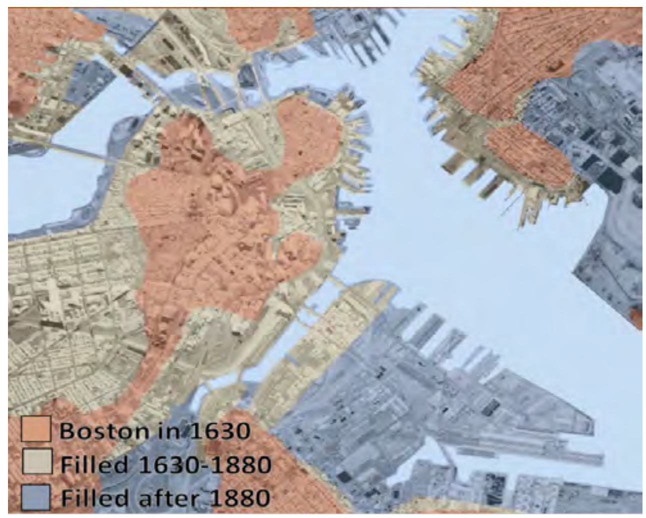


Figure 1. Boston Natural Fill and Infill Since 1630

Under current "normal" conditions, Boston has a nine-foot tidal range. In the 20th century, the city was fortunate that the major hurricanes that made landfall did so when the tides were low, sparing the Metro Boston area from disastrous flooding. Experts may debate the exact range of sea level rise over the coming decades, but coastal urban areas such as Boston already appear more and more vulnerable to the risk of flooding. This is due to the combination of the continued development that is reducing the amount of permeable surfaces, increased building density on and near the city's waterfront, rising sea levels, and increasingly frequent extreme weather events. When Superstorm Sandy roared through the Mid-Atlantic region in 2012, it brought with it 11 feet of surge to lower Manhattan. Such a deluge would have been even more destructive if it struck the Metro Boston region.

A 2007 study examining the likelihood of coastal flooding for major urban regions across the United States found that the Metro Boston region's exposure to "100-year" flood events will rise significantly over the next 30 years, causing the 100-year flood level to occur with a frequency of every 8 to 30 years.[4] Not only is the Metro Boston region more likely to incur extreme high-water events, but the economic consequences will drastically increase since so much new development has been undertaken in areas that are vulnerable to inundation. A study reported in *Nature* in 2013 ranks Boston as 8th among the 130 largest coastal metropolises in the world both in terms of the likelihood of catastrophic flooding and the resulting financial loss (current average annual loss of $237 M rising to $730+ M by 2050).[5]

It is clearly an urgent imperative for the Metro Boston region to take actions which will mitigate this increasingly costly threat and to develop robust plans to respond and recover from flooding incidents when they occur. Key to guiding those efforts will be capitalizing on infrastructure mapping and scenario modeling informed by the latest environmental forecast data. This will allow decision-makers to reach informed decisions about assets at risk and the most effective actions that will protect these assets and mitigate the threat. Like any major city, Boston is dependent on systems of critical infrastructure that are owned and operated by private and public-sector entities that are outside of its direct control. Additionally, even though these systems are interdependent, these entities typically craft their plans for managing disruptive events independent of one another. This translates into there being a high risk of cascading failures when major disasters occur with the resultant substantial and costly delays in overall community recovery. In short, the dearth of governance frameworks for managing the complex interdependencies that are inherent to critical infrastructure systems, complicates a metro-region's ability to understand in advance the severity of the risk it faces, the likelihood of consequences, and the necessary actions to mitigate or manage the risks.

Examining the Vulnerability of Critical Systems

The Global Resilience Institute at Northeastern University partnered with the Massachusetts Emergency Management Agency (MEMA) and the Boston Office of Emergency Management (OEM) to examine the threat that a major flooding event would bring to two critical infrastructure systems – energy and transportation. The interest in undertaking this effort was motivated in no small part by a recognition that Boston was vulnerable to the same kind of destructive consequences that the Metro New York region experienced from Superstorm Sandy in 2013. Specifically, the damage to the liquid-fuel, electrical power, maritime transportation, and mass-transit sectors from that storm and the associated challenges it presented to the region's recovery, spurred MEMA and OEM leaders to develop more comprehensive regional plans for managing the potential for similar impacts should a major hurricane bring storm surge to Boston.

In order to examine flooding impacts on these two critical infrastructures, GRI staff, in consultation with MEMA and OEM, proposed to work with informed stakeholders to evaluate the vulnerability of key energy and transport assets to coastal storm surge flooding. The participants were selected from stakeholders, owner/operators, and governmental entities with an operational or oversight role of the liquid fuel, electrical power, port and surface transportation infrastructures. Altogether, over 60 stakeholders participated in the resilience-building task force (see *Appendix A* for a list of participants).

As preparation for the stakeholder workshops, resilience researchers from the Global Resilience Institute developed questionnaire protocols to guide interviews with selected participants. The interviews were constructed to build a foundation of knowledge about: 1) the awareness by owners/operators and government entities of the flooding risk to key energy and transport assets; 2) the status of any planning to mitigate the impacts of storm surge; 3) the stakeholders' understanding of interdependent effects on multiple infrastructure sectors caused by a major flooding event; and 4) the capacities and resources that could help the region to recover more rapidly from disruption to these two critical systems.

4 Kirshen et al. "Coastal flooding in the Northeastern United States due to climate change." Mitigation and Adaptation Strategies for Global Change. 4 Dec. 2007. Web. https://link.springer.com/content/pdf/10.1007%2Fs11027-007-9130-5.pdf.

5 Kirshen et al. "Coastal flooding in the Northeastern United States due to climate change." Mitigation and Adaptation Strategies for Global Change. 4 Dec. 2007. Web. https://link.springer.com/content/pdf/10.1007%2Fs11027-007-9130-5.pdf.

This stakeholder engagement was guided by a hypothetical, yet realistic, disaster scenario that helped to frame the interviews with contextualized information and allowed interviewees to more clearly visualize the cascading effects that a major flooding event would generate. The scenario was built around a seven-foot storm surge striking the Metro Boston area at high tide with as little as 24-hour notice. The short warning time frame was informed by base historical data that shows major hurricanes move up the East Coast with indeterminate trajectory relative to Boston until the storm passes Cape Hatteras on North Carolina's Outer Banks. Once passing Cape Hatteras, storms then typically move at speeds of 35 miles per hour (mph), which translate into a forecast window of less than 24 hours for accurately predicting when a hurricane will make landfall in New England. Given this historic pattern of incoming storm arrival and timing, this scenario assumes an 18-hour interval between trajectory certainty and storm strike in the Boston area. **Appendix B** presents a copy of the disaster scenario developed and the accompanying interview protocol used to garner data on the likely impacts to the energy and transport sectors.

Visualizing a Metro Region's Vulnerability

In addition to gathering data via individual interviews and conducting background research from available open sources, the GRI team also looked for ways to help participants visualize the potential impacts on key energy and transport infrastructure assets in the Metro Boston region. Local climate experts had already begun working with the Sasaki Design Group on a model that could help local leaders and planners visualize the threat associated with future sea level rise. The Sasaski team modeled the Metro Boston region for sea level increase under two cases, both of which highlighted the vulnerability of low-lying areas to inundation and flooding. While the Sasaki model was created to help planners visualize *future effects* of sea-level rise, it is built on assumptions which can serve as analogs for *current* flood risk associated with coastal storm surge. Specifically, the Sasaki model has constructed maps showing potential flooding effects of a storm surge of five feet at high tide on top of a projected risk of two feet of sea level by 2050, conditions which offer a reasonable approximation of the impact of seven feet of storm surge from a Superstorm Sandy-like event should it happen in Boston today. These assumptions were the basis for the hypothetical disaster scenario used with stakeholder interviews.

The GRI team then interviewed key stakeholders on assets, operational decisions regarding system preparation and shutdown, plans to mitigate damage, and plans for system recovery following the storm. Information gathered from the stakeholder interviews as well as additional background research helped to build a picture of the risk to current energy and transport assets as well as the severity of functional disruption.

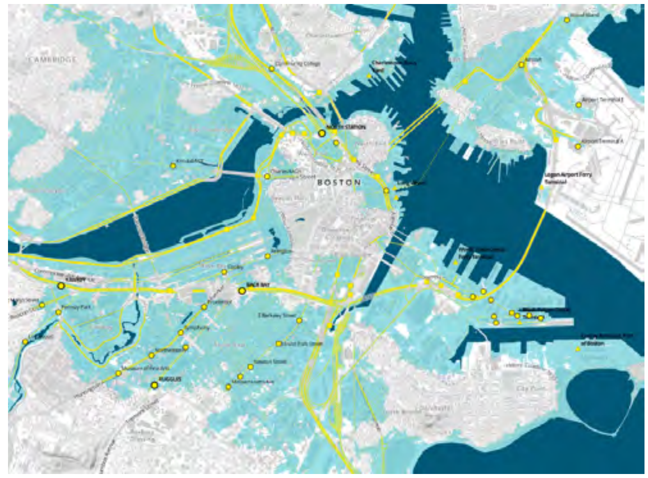


Figure 2. Sasaki Model Prediction of Metro Boston Flooding from 7-foot Storm Surge Event

Results from the Sasaki model indicate that much of the Boston downtown area is vulnerable to coastal storm surge (Figure 2 above). Based on the Sasaki visualizations alone, the coastal perimeters of the historic downtown would experience flooding, as would the Fens, Back Bay, and South End areas. North of the Charles River, low- lying land far into Cambridge would also experience flooding along with substantial regions of East Boston, Chelsea, and Winthrop. Such extensive flooding across the Metro region would mean widespread damage to buildings, infrastructure, and civic function.

Figure 3 below depicts the transportation assets that would be adversely affected by flooding created in the Sandy-like storm scenario. Such a seven-foot storm coming onshore at high tide would, at minimum, result in flooding to both the Callahan and Sumner tunnels, cause major damage to Conley Container Terminal, and flood mass transit stations in East Boston and downtown. In the face of such a storm it is likely that the U.S. Coast Guard Captain of the Port would order the closing of the Port of Boston to all maritime traffic until the damage to the waterfront could be assessed, debris could be cleared from the harbor, and hazardous waste spills could be documented and contained. As a result, liquefied natural gas (LNG) shipments in to Boston would be suspended, potentially impacting the natural gas supply for the Mystic Generating Station, the largest power station in Massachusetts. Additionally, many downtown roads would be under water, necessitating a stop to all vehicular traffic into and out of the urban center.

Not only would the transportation system be seriously compromised in its functional capacity, but energy assets would also be inundated by such a storm. Figure 4 below depicts the energy infrastructure flooded by a seven-foot surge at high tide. At least 20 electric substations would sustain major damage as well as the Mystic Generating Station, the Distrigas LNG Terminal, the Revere Irving Oil Terminal, and substations in Back Bay, South Boston, and East Boston. Recovery of energy system functionality depends at least in part on the ability to move people and resources (e.g. LNG) necessary to restart energy assets. With transport functions also compromised, the return of either system to full functionality would be seriously complicated under this scenario.

With results from the background research, stakeholder interviews, and scenario visualization as a basis for examination and discussion of potential interdependent impacts, the GRI/MEMA/OEM team convened the stakeholders in three workshops in November 2016, January 2017, and March 2017. The purposes of these workshops were to:

1. Determine if the public and private sector officials had played an operational or oversight role of key energy and transportation assets agreed with the forecasted effects indicated by the Sasaki visualizations. Stakeholders were also asked to identify additional and more specific effects than those predicted by the Sasaki model.
2. Identify cross-sector, interdependent functional disruptions that would likely occur under such a scenario.
3. Share the operational preparation and response measures that owner/operators would likely take if confronted by this storm scenario.
4. Identify gaps and vulnerabilities not addressed by current plans and authorities.
5. Recommend actions to speed recovery in the face of flooding impacts.

In addition to these objectives, the final workshop also focused on designing a path forward from these informal discussions to a formal task force who could lead to a program of actions that would strengthen the resilience of Metro Boston's critical infrastructure.

Workshop Takeaways

In all, participants indicated the usefulness of the scenario-based analysis and the value of undertaking a cross-sector discussion. Participants also believed that it would be important to develop an actionable strategy at the Metro Boston regional level for strengthening the resilience of lifeline infrastructures particularly given the likelihood of future extreme storms and sea level rise. Participants agreed on four major findings as a result of their deliberations and a number of actions that energy and transport stakeholders could take to improve the resilience of energy and transport systems and overall resilience of the Metro Boston area.

Key Takeaway 1: *A Superstorm Sandy-like event in the Metro Boston region would severely impact the liquid fuel, electrical power, and transport systems that the region depends on for mobility and energy.*

As with much of the northeast, geography and history have translated into Boston focusing much of its preparedness energies for managing the more commonplace low- and mid-level disruptive events. It has not had recent experience dealing with a Sandy-scale event because the three significant hurricanes that made landfall on the Boston area over the past century did so at or around low tide. However, changing conditions in climate, land use and the condition of existing infrastructure clearly require plans and actions for dealing with a more catastrophic flooding event.

The workshop provided an opportunity for key stakeholders to consider the kinds of impacts on infrastructure that the New York Metro region experienced during Superstorm Sandy. The Sasaki visualization graphics helped them to understand that the Metro Boston region has analogous vulnerabilities. The result were discussions that yielded a deeper understanding among all the participants of the ways that damage to key assets in one sector would have consequences for other assets. Importantly, it led them to reassess the assumptions they had been making about their capacity to respond to and recover from a major flooding event.

Specifically, the storm surge impacts that the Sasaki model points to left little doubt that there would be significant damage to critical energy and transportation systems essential to the functioning of the Metro Boston region. Within the energy sector, four significant power generation stations, including the Mystic Generating Station with 1,968 mega-watts of generation capacity, are in the projected flood zone. Further, at least 30 electric substations in Back Bay, South Boston and East Boston would face the risk of flooding. The Metro Boston area transportation systems would also be profoundly disrupted. The modeled storm resulted in flooding to the Callahan and Sumner Tunnels, major damage to the Conley Container Terminal and flooding of three important MBTA subway stations (*Aquarium, Wood Island*, and *South Station*), and numerous smaller stations within the MBTA system. These mass transit disruptions would have major implications for daily function of the city.

Workshop participants confirmed that much of the storm surge damage predicted by the model could well occur, while also envisioning additional functional impacts. For instance, they pointed out that backup generators might go offline if the disruptions to the transport sector translated into delays in the delivery of the fuels they need to run on. Inundation at the Revere Irving Oil Terminal would also make it difficult to bring in external sources of fuel to resupply quickly exhausted reserves.

Participants also pointed out that they can significantly reduce damage if they are able to carry out pre-storm protective measures for exposed assets. These include shutting down power transformers and substations in flood zones and installing temporary flood protection measures for the Callahan and Sumner Tunnels. However, they also acknowledged that executing most of these measures would require more than 24-hour lead times, though an accurate warning of an imminent hurricane strike may be as little as 18 hours. Further, in the event of a mandatory evacuation order, power and important transportation assets such as the Callahan and Sumner Tunnels would need to be fully operational to support the movement of the population from low-lying areas. This could translate into leaving Department of Transportation crews with no time to undertake measures to safeguard them from flood damage.

A major flood event would also involve considerable disruption to the seaport including damage to waterside terminals, oil and hazardous materials spills in the harbor, and floating debris and damage to aids to navigation. The result would likely be a days-long restriction on vessel traffic to Boston, including energy shipments of liquid fuels. Damage to the Port's main container terminal would compromise Boston's ability to receive containerized relief supplies by sea. Likely damage to the Distrigas LNG terminal would disrupt LNG shipments to Boston and, consequently, affect electrical power generation given the reliance of the Mystic Generating Station on a steady supply of natural gas.

In short, the Sasaki visualization tool proved to be helpful in highlighting the degree to which much of Boston's most critical energy and transportation infrastructure is highly exposed to storm surge. Still, while the tool is very helpful in showing that key assets are likely to be exposed to flood waters, the tool is unable to estimate how high actual flood levels would be at any given location. In other words, the model does not have sufficient granularity to determine whether the flood level would be at a nuisance level or a destructive one. Electrical substations with even low-lying

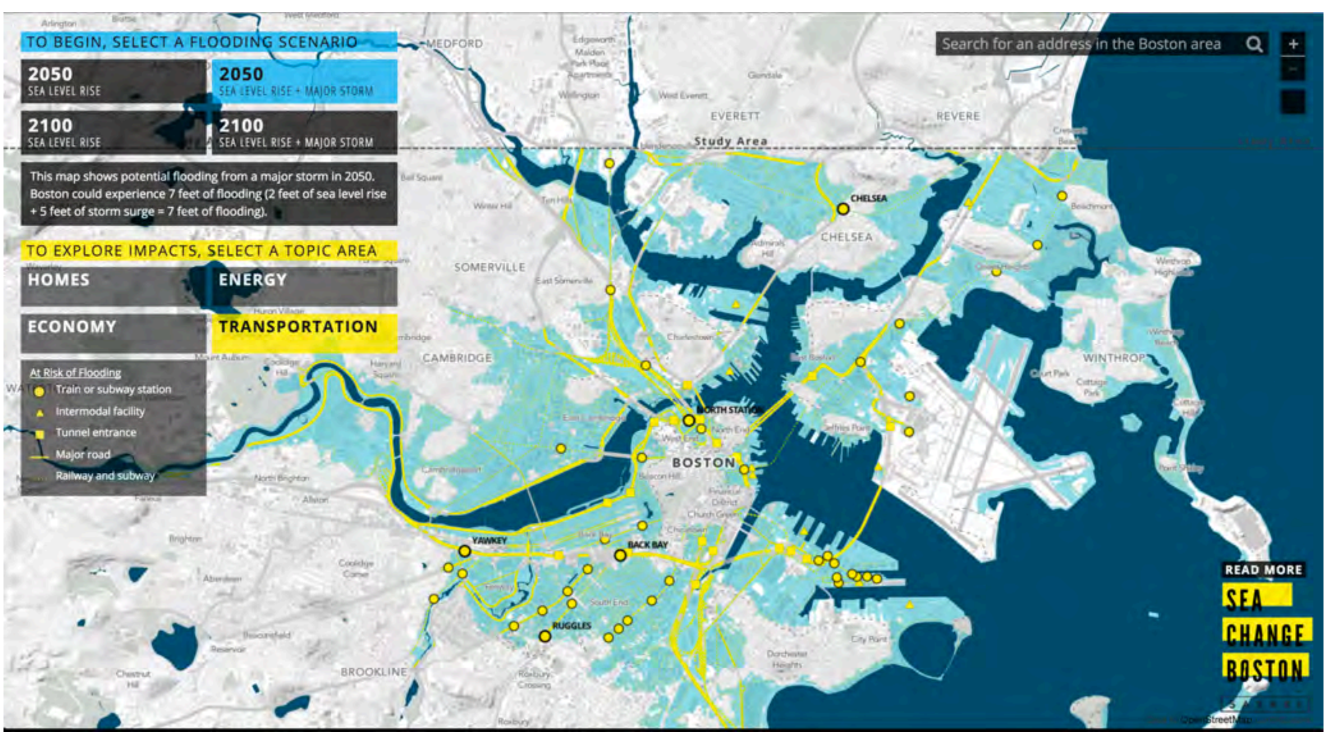


Figure 3. Transportation Assets Disrupted by a Sandy-like Storm Striking Boston at High Tide

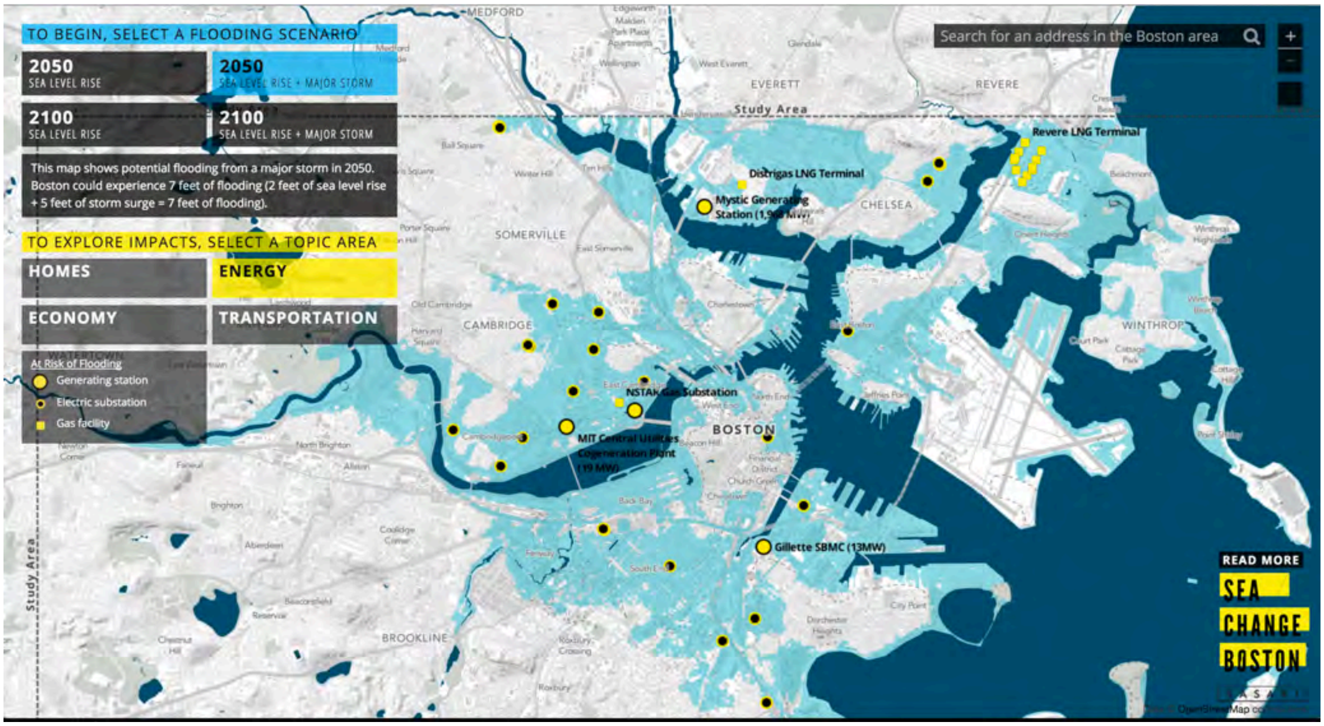


Figure 4. Energy Assets Affected by Sandy-like Storm Event

containment walls may be able to withstand a moderate level flooding, but if the Callahan and Sumner Tunnels are breached, water would pour in until they are full.

The model provides only limited insight into the interdependency issues as well. For instance, the model shows that the runways and taxiways at Boston Logan International Airport are on fairly high ground, but the likely loss of the subway line to the airport along with the flooding of the Tunnels and approach roads to East Boston would make the airport virtually inaccessible. Individual losses of critical energy and transportation assets would cause an interruption to Boston's daily life and commerce. Multiple losses would almost certainly be catastrophic because of this issue of infrastructure interdependence. Damage to transportation systems that preclude the shipment of liquid fuels would also impact the energy sector. Alternatively, a shortage of diesel fuel and electrical power would disable the mass transit system and the ability for emergency vehicles and repair crews to operate.

During such an event, the interdependency between the energy and transportation sectors will also result in cascading failures in the communications, health, water, and other sectors that are critical to the Metro Boston region's economic, social and commercial functions. Importantly, the impacts would not just be local; Boston serves as a hub for much of New England's fuel deliveries so the entire region would be impacted by a long-term disruption of the port.

Loss of the transportation and energy systems would affect every aspect of daily life. Given these stakes, there is an urgent need for greater cross-sector planning and coordination amongst critical infrastructure owners and operators and the public agencies that oversee them.

Key Takeaway 2: *Current public and private response and recovery plans are not up to the task of adequately addressing a major regional disaster.*

Every responsible agency and private owner/operator of critical infrastructure has a disaster immediate response and recovery plan. These plans tend to address the specific system or part of a system for which the agency or owner is responsible. Electric distribution authorities know how to restore power, departments of transportation know how to clear and repair roads, and gas utilities know how to repair pipelines and relight customer appliances. The challenge is that these systems ultimately depend on each other to function effectively. Fully restoring a critical system is not the same as restoring a critical function. There is not a single system providing essential services in the Metro Boston area that operates and sustains itself independently.

These systems and functional interdependency challenges extend beyond any given metro region. Most of lifeline infrastructure functions are regulated, owned, operated and sustained at the local and state levels, but rely on systems that are much further away. LNG is brought into Boston from around the world on ships, pumped into

Boston from national distribution points by pipeline, and distributed to customers by pipeline and truck. Electricity is generated from as far away as Canada and distributed over bulk transmission lines into a regional retail distribution system. Each system owner/operator's response and recovery plans must acknowledge the regional, national, and even international dependencies of the systems.

Planning for response and recovery in this environment requires a careful assessment of potential disruptive event scenarios and detailed knowledge of critical systems and their interdependencies. It requires knowing how systems relate to functions, where systems are most likely to fail, and what assets are required to restore them. There are at least two critical elements in creating this level of knowledge.

In many cases, disaster plans are based on historical information and corporate memory. Officials responsible for critical infrastructure functions and system owners and operators must be supported by analytic models that can provide realistic assessments based on current science of potential destructive events whether natural or human-induced, quantify likely outcomes, and identify functional and systemic failure points. While there are numerous risk models that focus on individual systems, it is not clear that there are adequate models for examining critical infrastructure function failures, dependencies and interdependencies on a regional level readily available to decision-makers at the local level. Additionally, while most critical system operators are supported by models that examine their specific system, it is unlikely that the information produced by those models is readily and routinely shared with other system operators on whom they are dependent.

Information sharing is critical and there is wide agreement among public officials, government agencies and private businesses of this importance, particularly during disaster response. There is significantly less emphasis on sharing the same level of information when planning for disruptions. Some information is highly security sensitive when aggregated and is often highly restricted. Some information is proprietary and guarded carefully. Both of those reasons for not sharing information are valid. This reluctance or inability to share critical data about systems performance, however, amplifies the challenges of critical pre-disaster planning and effective coordination in responding and recovering from disasters when they occur.

Given the dependence of critical functions on multiple critical systems, the interdependence of critical systems, the lack of adequate supporting analytic models and the difficulty of information sharing, it is highly unlikely that any public official or system operator currently has a plan that will survive contact with a significant disaster.

Key Takeaway 3: *The overlap of public/private responsibilities and authorities for these infrastructures validate the need for a new comprehensive cross-sector approach to metropolitan area disaster recovery planning.*

Because the Metro Boston area's critical functions are composed of many interdependent systems controlled by a broad array of public and private owners and operators, there is a clear need for a multi-faceted, cross-sector approach to disaster recovery planning. No one agency can understand the totality of the infrastructure resilience challenge nor can they independently devise an effective plan for assuring regional disaster recovery. To be effective, however, any collaborative effort must have the authority to operate and must be able to share information in as transparent a manner as possible.

The most successful collaborative planning effort would be one that is convened by an authority with the capacity to elicit willing, active cooperation from all the necessary participants. There is no known way to compel participation by all relevant parties. The convening authority must be one that is seen to have the objective of creating an unbiased, objective disaster recovery plan that serves the public interest. It should have sufficient stature and authority to compel public agency participation and persuade private sector participation. Each participating agency and organization should also have the support of the top leadership within that agency or organization to participate and to act on the sponsor's behalf. Without this senior involvement and support, the planning effort will not be productive. To support the process, the convening authority must designate an organization to manage and facilitate the process in a similarly objective and unbiased manner.

Participants in the collaborative planning process must feel comfortable in sharing information and data necessary to developing a comprehensive and operable plan. Some of this data will be sensitive; some will be proprietary. The convening authority and its facilitator organization must craft information sharing protocols that allow planning to proceed while also safeguarding sensitive and proprietary data in a way that inspires trust.

The outcomes of an authoritatively convened and empowered collaborative planning process would be:

- An actionable understanding of storm surge impacts to the Metro Boston region's energy and transportation infrastructure functions along with a set of potential actions that would mitigate damage and accelerate recovery.
- A comprehensive plan or inserts to existing plans to guide near- and long-term actions.

- A compelling set of briefings for state and local decision-makers, public and private, to secure approval and authorization to act on identified vulnerability reduction actions.

Given the fact that planning for disaster in the Metro Boston area has been occurring for years albeit largely by entities operate independent of one another, problems identified might be subjected to these questions:

- Is the problem recognized by an appropriate decision-making authority? If not, the planning group will need to work to brief the appropriate decision-maker(s) and convince them that a problem exists.
- Is there already a plan to eliminate or mitigate the vulnerability that causes this problem? If there is no existing plan to address the vulnerability, then the planning group facilitates and guides the development of a plan.
- If there is an existing plan to eliminate or mitigate the vulnerability, is it adequate to resolve the problem? As part of the evaluation process, the planning group must also address the adequacy of existing plans. If plans are present but outdated, or overly simplistic to the extent that they will not address the problem presented by the planning scenario, the planning group will need to facilitate and guide appropriate revisions to the plan.
- Is the existing plan adequately funded? If there is an existing plan to address the vulnerability, the planning group must evaluate the adequacy of funding to support the plan and recommend additional means or sources of funding, if necessary.

Key Takeaway 4: *Both the private and public sector participants identified existing associations that could be leveraged to help address some vulnerabilities, but a more comprehensive and sustained effort would be required, given the magnitude of the stakes and challenges involved.*

Participants in the three day-long workshops strongly advocated a collaborative process for achieving substantive progress both in advancing the Metro Boston area's understanding of the risk that major flooding poses to the energy and transportation sectors, and for creating plans for mitigating those risks. They also identified several actions that each participant could take to further the effort.

Participants expressed a willingness to undertake a campaign within their own organizations and across their associated networks to raise awareness of the flood risk and the need for collaborative action. This included briefings with organizational leaders, discussions at internal training processes, and outreach through associations that they are affiliated with. Collectively, these efforts promise to help socialize the concept of collaborative disaster recovery planning and identify additional participants who can contribute their expertise and resources toward advancing critical infrastructure resilience.

Most of the participants routinely attend conferences and workshops in the normal course of their duties. These conferences were identified as an important way to spread an understanding of the challenges the Metro Boston region faces from a major flood event, and for facilitating collaborative planning activities.

There was consensus that a one-day workshop specifically targeted at senior government policy officials and at C-suite level owners and operators with the energy and transportation sectors would be helpful to in garnering support for a sustained effort to address the resilience imperative.

While each of these initiatives is important, real success will only be possible if there is a formal Metro Boston region steering committee that is chartered and empowered by the top political and industry leaders, to work together on producing a critical infrastructure disaster recovery plan. GRI offered to host and facilitate such a steering committee should it be established.

Appendix A

Northeastern University
Global Resilience Institute

Metro-Boston Kick-off Meeting on Managing Critical Infrastructure Interdependencies

Tuesday, November 1, 2016 at the George J. Kostas Research Institute for Homeland Security

9:30 am	**Check-in** *Coffee and pastries served*
10:00 am	**Welcome** *Dr. Stephen Flynn, Northeastern University* *Mr. Kurt Schwartz, Director, MEMA* *Ms. Rene Fielding, OEM Director, City of Boston*
10:20 am	**Agenda Overview** *Dr. Robin White, Meridian Institute*
10:25 am	**Framing the Metro Boston Flooding Disaster Scenario** *Learning from Superstorm Sandy* *Dr. Stephen Flynn* *Dr. Evan Kodra, CEO, RisQ*
11:00 am	**Discussion: Getting the Issues and Challenges Right** *Dr. Robin White and Dr. Stephen Flynn*
11:15 am	**Panel 1: Understanding Vulnerabilities and Safeguarding Energy and Transport Assets** *Dr. Stephen Flynn, Interlocutor* *Panelists:* *Ms. Robbin Peach, Massport* *Mr. John Martin, MBTA* *Mr. Stephen Parenteau, National Grid*
12:00 pm	**Audience Response to Panel 1 Discussion** *Dr. Robin White and Dr. Stephen Flynn*
12:10 pm	**Lunch** *Pick up food for working lunch*

12:20 pm	**Panel 2: Cross Sector Coordination – Port of Boston as Example** *Mr. Peter Boynton, CEO, Kostas Institute, Interlocutor* *Panelists:* *Mr. David Waldrip, First Coast Guard District* *CDR Brad Kelly, USCG, Deputy Commander Sector Boston* *Capt. F. Bradley Wellock, Massport, Maritime Regulatory Affairs* *Mr. Paul DiGiovanni, Reinauer Transportation/Boston Towing*
1:15 pm	**Audience Response to Panel 2 Discussion** *Dr. Robin White and Dr. Stephen Flynn*
1:30 pm	**Identifying and Reducing Barriers to Infrastructure Insurance** *Dr. Erwann Michel-Kerjan & Dr. Howard Kunreuther* *The Wharton School, University of Pennsylvania*
1:50 pm	**Break** *Coffee and beverages available*
2:05 pm	**Governance Approaches to Address Interdependent Infrastructure Resilience** *Dr. Stephen Flynn, Dr. Matthias Ruth, & Dr. Auroop Ganguly, Northeastern University*
2:20 pm	**Assessing the Risk of the New England Electric Sector: Regional Resilience Assessment Plan Preliminary Findings** *Mr. Kim Erskine, Region 1, DHS Office of Infrastructure Protection*
2:30 pm	**Discussion of Next Steps for Advancing the Resilience of the Boston Metro Energy & Transport Infrastructure Sectors** *Dr. Stephen Flynn*
2:55 pm	**Concluding Thoughts** *Mr. Kurt Schwartz* *Ms. Rene Fielding*
3:00 pm	**Adjourn**

Northeastern University
Global Resilience Institute

Mayor's Office of
Emergency
Management
Martin J. Walsh
Mayor

Kick-off meeting on
Interdependent Critical Infrastructure Hurricane Preparedness :
Safeguarding the Energy and Transportation Sectors in the Metro-Boston Region

November 1, 2016 | Participant List

Participants

Daniel Abreau
Infrastructure Development and Recovery Team
U.S. Dept. of Homeland Security

Daniel Aldrich
Professor, Political Science
Northeastern University

Scott Andrews
Assistant Director, Rail Transit Safety MA Dept. of Public Utilities, Transportation Oversight Division

Udit Bhatia
PhD Student, Sustainability and Data Sciences Laboratory
Northeastern University

Peter Boynton
CEO
Kostas Research Institute for Homeland Security
Northeastern University

Cody Carneiro
MassDOT Security and Emergency Management Coordinator
MassDOT Security and Emergency Management

Sean Cornelius
Research Scientist
Northeastern University

Chad Council
GIS Analyst
FEMA-Response Division

Robert Creedon
Director Security & Emergency Management
MassDOT

Mark Cutter
Asst. Branch Chief; Waterways Management
U.S. Coast Guard

Ghebre Daniel
Assistant Director, EPD
MA Dept. of Public Utilities

Emma DeSimone
Program Manager, Metro Boston Homeland Security Region
City of Boston Office of Emergency Management

Paul DiGiovanni
Quality Assurance Manager
Reinauer Transportation Companies LLC

Steve Dodge
Associate Director
Massachusetts Petroleum Council/API

N**oah Dormady**
Assistant Professor
John Glenn School of Public Affairs Ohio State University

Warren Edwards
Executive Director, Community and Regional Resilience Institute
Meridian Institute

Ryan Ellis
Assistant Professor, Communication Studies
Northeastern University

Kim Erskine
Region 1, DHS Office of Infrastructure Protection
U.S. Dept. of Homeland Security

Aron Ezaz
Sr. Grant and Administrator Manager
Center for Resilience Studies
Northeastern University

Rene Fielding
Director, Office of Emergency Management at City of Boston
City of Boston Office of Emergency Management

Stephen Flynn
Director and Professor
Center for Resilience Studies
Co-Director, Kostas Research Institute for Homeland Security
Northeastern University

Auroop Ganguly
Associate Professor
Civil and Environmental Engineering
Northeastern University

Ed Gaynor
Captain
U.S. Coast Guard

Connor Goddard
Assistant Director
Center for Resilience Studies
Northeastern University

Chris Grasso
Research Manager
Center for Resilience Studies
Northeastern University

MaryBeth Groff
Chief of Staff
MA Emergency Management Agency

Robert Hallowell
Associate Staff
MIT Lincoln Laboratory

Hanieh Hassanzadeh
Research Scientist
Northeastern University

Daniel Kaniewski
Vice President, Global Resilience
Air Worldwide

Bernie Kelly
V.P. of Supply Operations
Global Companies

Brad Kelly
Deputy Sector Commander
U.S. Coast Guard

Rob Kistner
Sec Boston Inspections Division
U.S. Coast Guard

Rich Klein
Port Recovery
U.S. Coast Guard

Evan Kodra
CEO and Data Scientist at SDS Lab, PhD Alumnus
risQ

Howard Kunreuther
James G. Dinan Professor of Decision Sciences & Public Policy
The Wharton School

Vaishali Kushwaha
PhD Student, Law and Public Policy
Northeastern University

James Lally
Partner Emeritus, Kleiner Perkins Caufield & Byers
Global Companies

Joshua Laufer
PhD Student, Law and Public Policy
Northeastern University

Tim Leshan
Vice President, Government Relations
Northeastern University

John Lyle
Operations Manager
Swissport Fueling

Scott MacLeod
Mitigation & Disaster Recovery Section Chief
Massachusetts Emergency Management Agency

John Martin
Senior Director; Engineering & Maintenance Systems
Massachusetts Bay Transportation Authority

Joanne McBrien
Supervisor of Reliability and Strategic Planning, Energy Assurance Supervisor
Massachusetts Dept. of Energy Resources

Matt McCann
Regional Director, Region 1- New England
U.S. Dept. of Homeland Security

Joanne Mendes
Executive Director
New England Convenience Store and Energy Marketers Association

Erwann Michel-Kerjan
Executive Director, Wharton Risk Management and Decision Processes Center
The Wharton School

Steven Miller
Supervisor, Environmental Management and Sustainability
MassDOT

Daniel Modricker
Regional Senior Advisor
U.S. Dept. of Homeland Security

Eric Morgan
Technical Staff
MIT Lincoln Laboratory

Tim Morin
Coordinator of Emergency Services
MassDOT Highway Operations

Lauren Morris
Counsel, Department of Public Utilities
MA Department of Public Utilities

George Naccara
Chief Security Officer
Massachusetts Port Authority

Donald Nelson
Public Utilities Engineer
Department of Public Utilities

Galen Nelson
Interim Senior Director -Innovation and Industry Support
MA Clean Energy Center

Steven Nider
Infrastructure Development and Recovery team
U.S. Dept. of Homeland Security

John Norden
Director of Operations
ISO New England

Dave O'Connell
Chief of Prevention
U.S. Coast Guard

Christine Packard
Deputy Director at Massachusetts Emergency Management Agency
Massachusetts Emergency Management Agency

Courtney Page
PhD Student, Political Science
Northeastern University

Christopher Paglia
Director - US Business Resilience & Continuity Management
National Grid

Stephen Parenteau
Lead Program Manager, New England Electric Emergency Planning
National Grid

Robbin Peach
Program Manager of Resiliency
Massachusetts Port Authority

Len Polizzotto
Executive in Residence
Kostas Research Institute for Homeland Security
Northeastern University

Jeffrey Putnam
MA Dept. of Public Safety

Paul Regan
Operational Planner
FEMA-Response Division

Joseph Rigney
State Tunnel Engineer
MassDOT

MaryBeth Riley-Gilbert
Climate Change Resiliency Specialist,
Dept. Of Environmental Affairs
Massachusetts Bay Transportation
Authority

Brian Ritzinger
Public Utilities Engineer
MA Dept. of Public Utilities

Matthias Ruth
Professor and Director
School for Public Policy
Northeastern University

Kurt Schwartz
Director
Massachusetts Emergency Management
Agency

Travis Sheehan
Senior Infrastructure Advisor
Boston Planning and Development
Agency (BPDA)

John Stanley
Contingency Planner
U.S. Coast Guard

Nancy Stevens
Director
Consumer Division
MA Dept. of Public Utilities

Matt Stuck
Resereve Chief of Staff
U.S. Coast Guard

Andy Sugimoto
Captain
U.S. Coast Guard

Kathleen Theoharides
Director of Climate and Global Warming
Solutions
MA Office of Energy and Environmental
Affairs

Gina Tonn
Post-doc
The Wharton School

Angie Valencia
Executive Assistant
Center for Resilience Studies Northeastern
University

David Waldrip
Port Security Specialist and Marine Transportation System Recovery Coordinator
U.S. Coast Guard

Thomas Walker
Port Security Specialist
U.S. Coast Guard

Brad Wellock
Manager Maritime Regulatory Affairs at Massport
Massachusetts Port Authority

Robin White
Senior Mediator and Program Director
Meridian Institute

Scott White
Maritime Safety, Security, & Preparedness
U.S. Coast Guard

Sarah White
Massachusetts Port Authority

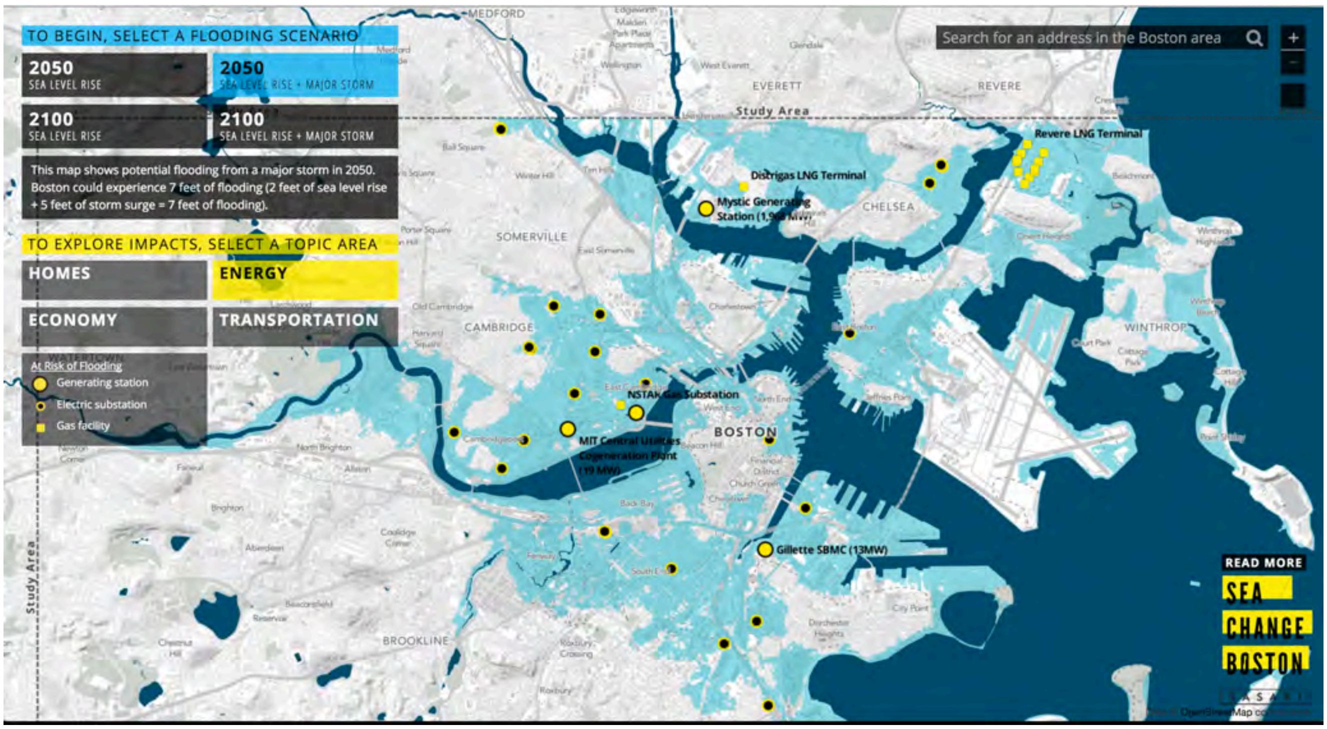
Felix Zemel
Chief of Inspections, Building Division
MA Dept. of Public Safety

Appendix B

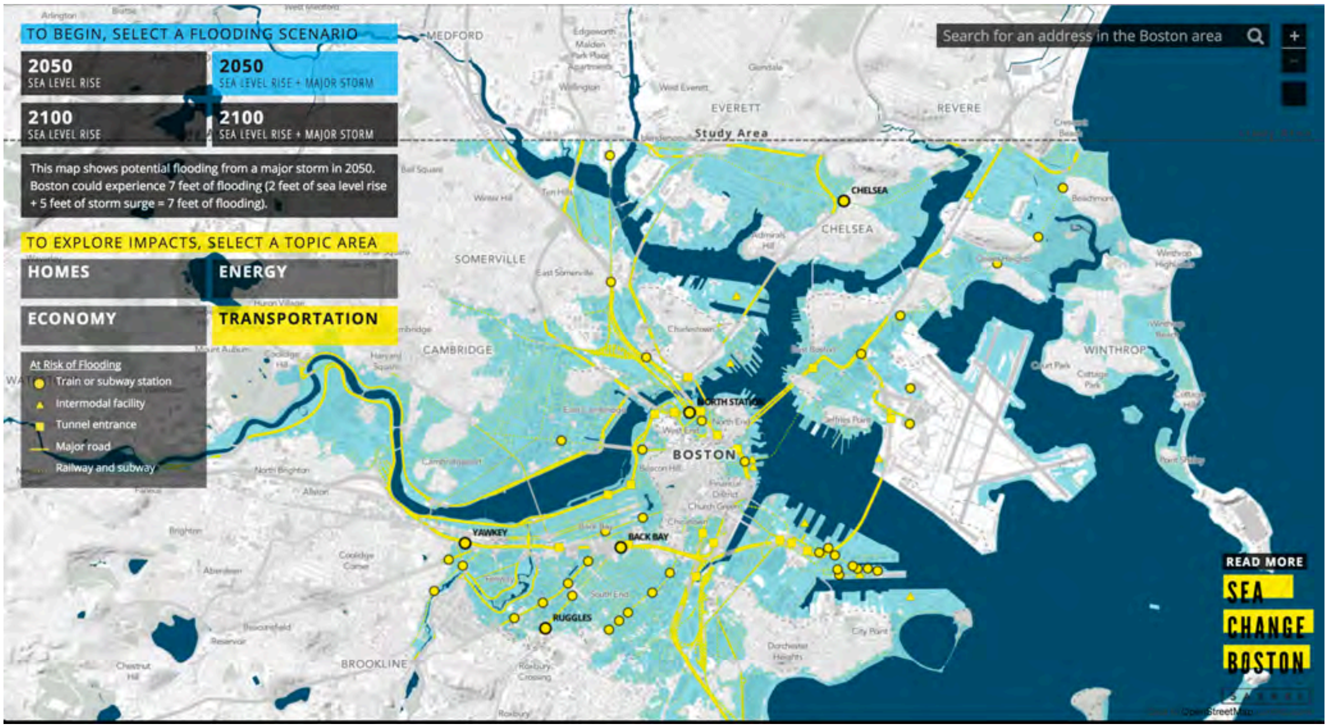
Scenario Description

In order to provide context for interviews, the below disaster scenario will be provided to the Metro Boston region infrastructure stakeholders. The purpose of providing this scenario project is not to focus on or debate any of its details, but rather to use the scenario as a starting point for conversations about the decision-making and prioritization processes embedded in the operation and governance of critical infrastructure, and for thinking about how these processes could be improved to strengthen the resilience of the cities and regions that rely on their dependable, interdependent functionality.

On early Wednesday morning, September 21, 2016, Hurricane Christina – a Category 1 storm with storm surge of seven feet – makes landfall on the South Shore of Massachusetts. Unlike other major hurricanes in the 20th century that came ashore at low tide, Christina arrives when the tide is high in Boston Harbor. The storm's path had been unpredictable up until it was offshore of Cape Hatteras, North Carolina. The storm track then moved north at a speed of 30 mph, providing emergency planners with only 18 hours' notice prior to landfall. The resultant storm surge and its impact on the Metro Boston transportation and energy sector is shown on the inundation maps below:



Energy sector assets exposed to flooding by "Hurricane Christina"



Transport sector assets exposed to flooding by "Hurricane Christina"

The hurricane causes major damage to the Mystic Generating Station, the Distrigas LNG Terminal, the Revere Irving Oil Terminal, and substations in Back Bay, South Boston, and East Boston. It results in flooding to both the Williams and Sumner Tunnels, major damage to Conley Container Terminal, and flooding of the Aquarium Station, Wood Island, and South Station. The U.S. Coast Guard Captain of the Port has ordered the closing of the Port of Boston to all maritime traffic until debris can be cleared from the harbor and oil spills can be documented and contained. As a result, all LNG shipments in to Boston have been suspended. The Governor has ordered all roads closed to all but emergency vehicles in the vicinity of the City of Boston.

In short, the storm has simultaneously caused substantial damage to both the energy sector and transport sector for the Metro Boston region. The challenge for infrastructure owners and operators and government officials is to organize efforts to speed their recovery.

Cascadia Subduction Zone Megaquake Critical Infrastructure Interdependencies Workshop

Executive Summary

This report is a part of the Global Resilience Institute's (GRI) ongoing effort to develop a governance framework that would enhance the resilience of critical infrastructure systems in major metro regions across the country. Critical infrastructure is owned and operated by a diverse set of stakeholders from both the public and private sectors. Transportation, energy, water, telecommunications, and other critical infrastructure sectors have also evolved from localized assets to networks that invariably sprawl across multiple local jurisdictions and often span multiple states and even national jurisdictions. This reality makes it extremely difficult to understand and manage the complex interdependences amongst these infrastructure sectors. One consequence is that important vulnerabilities within and among these sectors only become apparent when they are revealed in the aftermath of a disaster. The remedy for addressing this situation requires identifying a new framework that advances regional cross-sector collaboration. To this end, GRI partnered with the Pacific Northwest Economic Region (PNWER) to convene key stakeholders of two highly interdependent critical infrastructure sectors: Transportation and energy. In the absence of a recent major disaster to expose the interdependency challenges associated with this sector, GRI and PNWER have framed this work around a highly realistic scenario involving a major earthquake along the Cascadia Subduction Zone.

The Cascadia Subduction Zone (CSZ) is an 800-mile long fault line where the Juan de Fuca tectonic plate is locked against the North American plate just off the Pacific Coast, stretching from northern California to British Columbia. Geologists have determined that over the last 10,000 years, a megaquake has occurred in the CSZ on average every 243 years; the last megaquake to take place in the CSZ was 317 years ago in 1700. Though the interval between quakes varies, researchers have suggested there is a significant chance of a megaquake occurring in the CSZ before 2060. Recent megaquakes around the globe have proven the deadly potential of these rare events, claiming hundreds of thousands of lives in the last 15 years alone. Important to this project, events such as the 2011 Fukushima nuclear meltdown have illustrated the destruction a megaquake can cause to critical infrastructure and the long-lasting effects it can have on communities.

In 2016, FEMA conducted a regional exercise in the Pacific Northwest which simulated the aftermath of a Cascadia megaquake and consequent tsunami. The exercise scenario focused on the region's immediate response to the earthquake, simulating how stakeholders would provide life safety and emergency management operations across six "core capabilities": communications, public health and medical, mass care services, situations assessment, critical transportation, and operational coordination. Following the exercise, several organizations conducted additional exercises to evaluate how they would recover their systems and establish a more detailed estimate of recovery timeframes and requirements.

GRI and PNWER expanded on the Cascadia Rising and other recent exercises. Specifically, GRI conducted an in-depth examination of how the interdependencies between the energy and transportation sector would present governance challenges that affect the region's ability to recover in the weeks and months following the devastating earthquake. While the scope of FEMA's initial exercise was limited to the United States, GRI's approach includes British Columbia, which is exposed to the same effects of a megaquake as Washington and Oregon, and also has extensive linkages with the energy and transportation networks across the Cascadia region. This effort culminated with a workshop held by GRI and PNWER in Seattle in September 2017.

In order to determine the possible impacts to energy and transportation infrastructure in the region and identify critical information requirements, GRI staff, in consultation with PNWER, engaged with key stakeholders in the region. These stakeholders included infrastructure owners and operators, public emergency managers, and very importantly, major employers in the region. The information gathered from these conversations informed a regional workshop that included participants from the public and private sectors at the city, state, provincial and national levels in both the U.S. and Canada.

The primary goal of the Seattle September 2017 workshop was to facilitate a greater awareness and understanding amongst these stakeholders of the information gaps and potentially unrealistic planning assumptions that would undermine the capacity of the region to manage cascading failures and slow recovery when the megaquake strikes the region. The workshop was built around a series of breakout sessions which addressed various aspects of infrastructure systems resilience, focusing on energy and transportation interdependencies.

Ultimately, workshop participants uncovered for key takeaways and recommended actions to address the impacts of the megaquake scenario:

Key Takeaway 1: *Regional stakeholders are often unaware of the critical information gaps that affect their planning, response, and recovery efforts. These "unknown unknowns" limit how effectively they are able to cope with interdependency challenges.*

Key Takeaway 2: *Current frameworks for building resilience encourage stakeholders to examine infrastructure sectors on a sector-by-sector basis. However, the inherent interdependence associated with critical infrastructure sectors necessitates that regions approach their infrastructure sectors as a system of systems.*

Key Takeaway 3: *Current economic, jurisdictional, and legal hurdles hamper stakeholders' abilities to share critical information or provide a disincentive for organizations to do so.*

Key Takeaway 4: *Stakeholders from the public and private sector acknowledge the long-term implications of a slow recovery process, but find it difficult to coordinate in advance their collective capacities to accelerate that process.*

Participants' recommended actions were designed to provide actionable solutions to information sharing challenges and be a guide on how to leverage existing regional coordinating bodies towards resilience building efforts.

The Cascadia Subduction Zone Megaquake

Introduction

On July 25, 2015, an article written by Kathryn Schulz entitled "The Really Big One" was published in *The New Yorker*. Schulz' comprehensive examination of both the likelihood and consequence of a 9.0 magnitude in the Cascadia Subduction Zone (CSZ) poses to the Pacific Northwest Region captured considerable public attention. The article would go on to win the Pulitzer Prize for Feature Writing.[1]

As Schulz highlighted, the CSZ is an 800-mile long area where the Juan de Fuca tectonic plate is locked against the North American plate just off the Pacific Coast from northern California to British Columbia.[2] The abutment of these plates makes the area prone to a subduction zone earthquake, which occurs when hundreds of years of pressure causes one plate to slide under the other, causing the ground to violently shake and in the case of the CSZ, suddenly drop about 6 feet along the fault line.[3] For the residents of the Pacific Northwest, this would mean the destruction of lifeline infrastructure, severe shortages of vital resources, and tens of thousands of injuries and fatalities.

According to Japanese records, which have been kept on tsunamis over the past 1,400 years, scientists have discerned that the most recent CSZ earthquake occurred on January 26, 1700.[4] Thanks to modern geological technology, researchers at Oregon State University now know that there have been 41 megaquakes in the CSZ region over the last 10,000 years, meaning they occur every 243 years on average. Just under half of them have been full margin ruptures which carry the highest risk of producing a megaquake of the magnitude laid out in the Schulz article, though a localized rupture could be just as devastating for regions near the epicenter.[5] While

1 Schulz, Kathryn. "The Really Big One: An earthquake will destroy a sizable portion of the coastal Northwest. The question is when." New Yorker. Jul 2015. Web. http://www.newyorker.com/magazine/2015/07/20/the-really-big-one.

2 FEMA. "Cascading Rising Scenario". FEMA. 2016. https://www.fema.gov/media-library-data/1462203815175-6b989e683e8c2d34864f007fbde2c3fd/CR2016Flyer.pdf.

3 Schulz, Kathryn. "The Really Big One: An earthquake will destroy a sizable portion of the coastal Northwest. The question is when." New Yorker. Jul 2015. Web. http://www.newyorker.com/magazine/2015/07/20/the-really-big-one

4 Schulz, Kathryn. "The Really Big One: An earthquake will destroy a sizable portion of the coastal Northwest. The question is when." New Yorker. Jul 2015. Web. http://www.newyorker.com/magazine/2015/07/20/the-really-big-one

5 Goldfinger, C., Nelson, C.H., Morey, A.E., Johnson, J.R., Patton, J., Karabanov, E., Gutierrez-Pastor, J., Eriksson, A.T., Gracia, E., Dunhill, G., Enkin, R.J., Dallimore, A., and Vallier, T., 2012, Turbidite event history—Methods and implications for Holocene paleoseismicity of the Cascadia subduction zone: U.S. Geological Survey Professional Paper 1661–F. http://pubs.usgs.gov/pp/pp1661/f

the average time between quakes does vary, the study published by Oregon State places the probability that a full margin rupture – likely a 9.0 magnitude – will occur at about 10% and a rupture at the southern end – likely an 8.0 magnitude – at about 33% by 2060. In either case, the potential dangers of such a significant megaquake are clear and present. In 2004, the tsunami from a 9.1 magnitude earthquake killed 228,000 people in Indonesia.[6] Several years later, a 9.0 magnitude earthquake killed 18,000 people in Japan and triggered the Fukushima nuclear power plant disaster, the long-term effects of which are still not fully understood.[7] Both of these earthquakes happened on the same series of subduction zones that circle the Pacific Ocean, known as the "ring of fire", on which the CSZ is located.[8]

The 2016 FEMA Cascadia Rising Exercise

In June 2016, FEMA held a regional functional exercise named Cascadia Rising to simulate the Pacific Northwest's ability to response to a CSZ megaquake such as the one described in Schulz' *New Yorker* article. To conduct this simulation, FEMA chose to examine a 90th percentile scenario involving a megathrust earthquake along the Cascadia Subduction Zone fault line. The scenario and impacts to the region were based on a 2011 simulation developed by the National Infrastructure Simulation and Analysis Center Homeland Infrastructure Threat and Risk Analysis Center (HITRAC), which is part of the Department of Homeland Security's Office of Infrastructure Protection.[9] FEMA's exercise brought together hundreds of participants from public agencies in the states of Washington, Oregon, Idaho as well as the federal government and tribal organizations. Additionally, 15 private sector organizations and the American Red Cross participated.

FEMA's exercise scenario focused primarily on the region's immediate response to the earthquake, simulating how stakeholders would undertake life-safety and emergency management operations across six "core capabilities": communications, public health and medical, mass care services, situations assessment, critical transportation, and operational coordination. Following the exercise, several organizations, including the Bonneville Power Administration, conducted additional exercises to evaluate how they would recover their respective systems and establish a more detailed estimate of recovery timeframes and requirements.

Vulnerabilities of the Energy & Transportation Sectors

To further explore the Pacific Northwest's regional critical infrastructure resilience planning principles and process, the Global Resilience Institute (GRI) in partnership with the Pacific Northwest Economic Region (PNWER), conducted a workshop designed to expand on the Cascadia Rising and other recent exercises. The workshop provided an in-depth examination of the interdependencies between the energy and transportation sector and their implications for the region's ability to manage the post-megaquake recovery effort. Building from the process developed during GRI's examination of the governance challenges associated with the Metro Boston region's ability to manage a severe flooding event, GRI developed a brief scenario of the likely damages to the energy and transportations functions to frame the workshop discussions. The megaquake damage prediction presented by GRI was informed largely by the scenarios developed by FEMA and NISAC for the Cascadia Rising exercise. However, it also drew from an extensive array of studies and literature produced by scientists, emergency managers, and infrastructure owners and operators throughout the region. The scenario can be found in full in **Attachment A**.

In determining the damages to the energy and transportation sectors in the Pacific Northwest that framed the workshop, GRI diverged from FEMA's scenario in two primary ways. First, GRI determined that discussions around planning and recovery assumptions should also involve engaging key stakeholders in Canada. The Vancouver-Metro region shares with the Pacific Northwest the same vulnerability to a Cascadia megaquake. Additionally, the energy and transportation sectors it relies on are connected to and operate across the U.S.-Canada border. Indeed, each

6 FEMA. "Cascading Rising Scenario". FEMA. 2016. https://www.fema.gov/media-library-data/1462203815175-6b989e683e8c2d34864f007fbde2c3fd/CR2016Flyer.pdf.

7 World Nuclear Association. "Fukushima Accident." World Nuclear Association. Oct 2017. Web. http://www.world-nuclear.org/information-library/safety-and-security/safety-of-plants/fukushima-accident.aspx

8 Schulz, Kathryn. "The Really Big One: An earthquake will destroy a sizable portion of the coastal Northwest. The question is when." New Yorker. Jul 2015. Web. http://www.newyorker.com/magazine/2015/07/20/the-really-big-one.

9 FEMA. "Cascadia Rising 2016 Exercise Scenario". FEMA. Jan 2015. Web. 16 June 2017. https://assets.documentcloud.org/documents/3149654/Cascadia-Rising-2016-Exercise-Scenario.pdf

day resources, personnel, and information moves across the border in order to maintain the functionality of these critical systems. As a result, a disruption on either side of the border could quickly cascade to the other, since they are such closely coupled systems.

In framing the workshop, GRI also identified the importance of placing special emphasis on the energy sector in general, and its fuel component specifically. As described in GRI's scenario below, fuel production, refining, and transportation infrastructure in the Pacific Northwest operates largely in isolation of the rest of the United States given the region's physical separation from the East by the Cascade mountain range. Further, the concentration of American petroleum refineries for the region in Puget Sound creates a significant vulnerability for the entire Pacific Northwest. Following a megaquake, there would be significant fuel shortages that would be difficult to redress. This widespread lack of fuel, in turn, would have a major impact on the region's ability to execute its current response and recovery plans. Likewise, the fuel and energy sector's challenges would be compounded by the limited ground, rail, and air mobility infrastructure that would be available following a 9.0 magnitude earthquake. "Ownership" and responsibility for each of these challenges to the energy and transportation sectors is currently fractured across local, state, provincial, and national public and private stakeholders. The result is a significant governance challenge in assuring the kind of cross-sector collaboration that would be required to support post-megaquake recovery in the Pacific Northwest. Currently, there is no formal effort underway to address this governance challenge.

The Global Resilience Institute's Project Approach

Project Purpose

This workshop was conducted to expand the GRI study of regional governance models in disaster planning, response and recovery. Among the key imperatives for resilience building is the need for stakeholders from across disciplines and sectors to collaborate ahead of major disasters to identify and address governance and planning challenges. As systems of all types become increasingly interdependent and span multiple jurisdictions, as well as the public and private sectors, it is necessary to assess vulnerability and plan jointly at the regional level. The threat of a CSZ megaquake and the potential damages that it would cause illuminate the challenges of stove-piped planning and the dangers of response without a resilient recovery lens.

The workshop examined the current state of regional planning in the Puget Sound area including Vancouver, BC. In this examination, GRI sought to expand its understanding of the principles required to create regional planning processes and models that could operate above the local jurisdictional level but below the federal or state level. An additional major goal was to fully incorporate not only the private sector infrastructure owner/operators but their major customers as well. This focus acknowledges that full regional economic recovery cannot occur until the region's major businesses are back in operation.

Workshop Preparation and Data Gathering

This workshop is the result of an ongoing collaboration between the Global Resilience Institute (GRI) and the Pacific Northwest Economic Region (PNWER) funded by the Department of Homeland Security's Critical Infrastructure Resilience Institute (CIRI) at the University of Illinois Urbana-Champaign. Building from workshop and steering committee processes developed and refined in the Metro Boston region, GRI served as a neutral third-party convener to gather the diverse group of stakeholders required to address governance challenges in the face of a CSZ megaquake. GRI developed a specific disaster scenario based off the FEMA simulation and GRI's own research into the specifics of the energy and transportation systems in the region. This scenario served to frame the workshop's discussions around a possible set of circumstances that decision makers would have to navigate in the aftermath of a major earthquake.

Several months prior to the workshop, GRI held an exercise design committee meeting at PNWER's annual summit in Portland, Oregon. This committee meeting brought together 25 regional stakeholders from the public and private sectors. The purpose of the exercise committee was to ensure that the September workshop was informed by input from multiple sectors and jurisdictions and included the consensus of key regional stakeholders. Leveraging the members of this committee and the PNWER participants, GRI was able to access infrastructure owners and operators, governance networks, and essential private industry organizations. The workshop design was further informed by interviews and conversations with about a dozen individuals from the region who represented organizations that had been identified as integral to regional planning and governance. Among these interviewees were representatives from the rail, electricity, and oil industries, emergency managers at the state and local levels, and major employers in the Pacific Northwest.

The exercise design committee meeting and interviews helped to develop the primary themes for the September workshop: Critical information gaps and assumptions that would affect the Pacific Northwest's ability to plan for, respond to, and recover from a major earthquake. Given these key themes, GRI identified both the primary "producers" of information before a disaster, such as infrastructure owners and operators and response planners, as well as the "consumers" of information, such as emergency managers and industry stakeholders. Predictably, none of the stakeholders interviewed were solely "producers" or solely "consumers" of critical information, but rather each one produced – or already held – information and made decisions based solely on what they knew. Because each system and each decision maker does not operate in a vacuum, none of the stakeholders could realistically produce or hold all of the information on their own. The critical information gaps that did exist required emergency planners to build assumptions, both explicit and implicit, into their emergency response and recovery plans. Overcoming these information gaps, which were usually byproducts of dependencies and interdependencies between organizations and systems that functioned without coordinating their decisions, was the key driver of the September workshop. GRI and PNWER wanted to facilitate an interactive workshop that fostered the cross-sector dialogue necessary for planning recovery *before* a major disaster, so as to improve the capacity for the region to coordinate efforts under extreme duress *during* or *after* a major earthquake.

Workshop Design

A primary goal of the Seattle workshop was to foster dialogue among stakeholders and support their efforts to develop a tailored governance solution for the Puget Sound and Cascadia regions to close their critical information and coordination gaps. Achieving this goal required the workshop to be interactive and solution oriented. GRI drew upon its earlier work in the Metro Boston region where GRI examined the planning challenges associated with managing the risks to the energy and transportation infrastructures from a major flooding event. For the Cascadia, GRI workshop examined the planning gaps created by multiple jurisdictions. Specifically, it brought together participants who spanned local, state, provincial and national jurisdictions from Oregon to British Columbia. These participants were tasked with working with people they do not typically interact with outside their specific sector (either energy or transportation) to identify what information they need, who has it, and what barriers there are to sharing it with other stakeholders.

Two breakout sessions that constituted the majority of the workshop, each of which was followed by an in-depth discussion among all the participants. (For the full agenda see **Attachment B**.) In the first breakout session, the participants were divided into four working groups: Private sector infrastructure owners and operators; public sector infrastructure owners and operators; public sector emergency planners and managers and; private sector and non-profit industry stakeholders. Groups were asked to answer the following questions to be reported out to the entire audience after working group discussions:

1. **Critical Information Requirements:** What elements of information do you need (that you do not have) to ensure your plan is adequate to allow rapid recovery to normal operations?
2. **Required From:** Who has or is likely to have the critical information you require before (planning), during (responding), and after (recovering) a disaster?
3. **Assumptions:** In the absence of this information, what assumptions must you make (or have you made) in planning, responding, or recovering to ensure that you return to normal operations?
4. **Critical Dependency or Interdependency:** What critical dependency or interdependency is revealed by these critical information requirements?

Following the breakout session, the workshop participants listened to and discussed the outputs from the other groups, observing how needs and capacities differed between sectors. These discussions were designed for participants in different roles across the emergency preparedness, response, and recovery spectrum to begin to identify where planning gaps or assumptions exist explicitly and implicitly. Explicit gaps exist when a stakeholder knows that information is unavailable or inaccessible and makes an assumption accordingly – a "known unknown." Implicit gaps, on the other hand, occur when a stakeholder does not have a critical piece of information that would alter their ability to execute response and recovery plans, but the stakeholder is unaware that the piece of information exists or is relevant to their plans. This first full-workshop discussion served to begin the cross-sector dialogue that revealed such challenges.

Once identified, these challenges were the focus of the second breakout session.

In the second session, working groups were reorganized to include an approximately equal number of representatives from each of the first working groups. These new working groups sought to begin to formulate solutions to the issues identified in the first session by addressing the following questions:

Using one of the critical information requirements developed in session one's answer:

1. Does the information required to address this critical information requirement exist? Where?
2. What systemic process, procedure, and/or capability can be put into place to ensure the exchange of this critical information?
3. What legislative or regulatory changes would be required to implement this information exchange process or procedure?

Groups explored these questions for several of the key issues discovered in the first working group session. Following the second breakout session, the attendees reconvened to discuss some of the solutions proposed within the groups. While these issues were, of course, much more complex than a short discussion could solve, the participants engaged, often very candidly, with stakeholders from other sectors about what types of problems they would face, their needs, and how it would affect others in the room.

Workshop Findings

Based on the discussions held at GRI's Seattle workshop, interviews with regional stakeholders, and in-depth research of the critical infrastructure systems in the Pacific Northwest, GRI identified key takeaways that other regions should consider when undertaking resilience building initiatives.

Key Takeaway 1: *Regional stakeholders are often unaware of the critical information gaps that affect their planning, response, and recovery efforts. These "unknown unknowns" limit how effectively they are able to cope with interdependency challenges*

As the understanding of the risk of a major earthquake in the CSZ has become more clearly and widely understood, regional stakeholders have created plans for responding and recovering. However, these plans have generally been created within individual organizations or among stakeholders within the same sector or jurisdictional boundaries. This is a serious limitation given that the CSZ megaquake scenario makes clear the degree to which such a disaster would involve a wide geographic region and affect all critical systems simultaneously. Further, as systems continue to grow increasingly interconnected, including cyber-connected, so as to generate greater efficiencies and cost reductions, vulnerabilities increase. In fact, while the 9.0 magnitude quake that was posited for this workshop would devastate the entire region, even a more localized major disaster could ripple through the entire region as well.

An example that frequently arose during interviews and at the workshop, was that fuel was critical for each stakeholder's response and recovery planning. With the workshop's stated focus on the transportation and energy sectors, it quickly became clear that the loss of refined fuel would render the other stakeholders unable to conduct their response and recovery operations as planned. This is problematic because the Pacific Northwest's refined fuel supply comes almost entirely from four refineries along the Puget Sound, and is then transported by pipeline to Oregon and British Columbia. Almost all those refineries would be seriously damaged by a megaquake. Compounding the issue of fuel shortages, the seismic damage to highways, pipelines, and rail could make it difficult to move even the limited supply of refined fuel to areas in need, and would in turn make it more difficult to bring necessary repair equipment to the refineries, storage tanks, and terminals.

This situation presents a striking example of the complexity of orchestrating the response and recovery of even just two critical infrastructure systems. On an operational level, stakeholders from the public and private sectors would both be conducting recovery efforts following a megaquake. The success, or even the feasibility of one organization's efforts relies on their decision-makers having a common operating picture from which they can base actions. The reality, however, is that such a shared operational awareness rarely exists. In the rare instances where it does at a local level, aggregating the information at a regional level can be arduous and time consuming. Workshop participants expressed that in many cases, they would be providing information to regional coordinating bodies for their sector or to state or national emergency management agencies. While consolidating information in this manner may make information sharing easier, several significant challenges were noted:

1. Regional coordinating bodies are often organized to oversee a specific infrastructure sector, or operate within defined jurisdictional boundaries at the local, state, and provincial levels. Participants from the energy sector expressed high confidence that they would be able to communicate with one another, with several layers of redundant communications systems and relationships between organizations. However, recovering the energy infrastructure would requires critical information about the transportation sector that is not currently available to them. This includes such details as which roads are accessible and when and how much fuel for backup generators might be available. Participants agreed that cross-sector efforts to coordinate communication protocols or pool information had been limited to individual efforts between organizations, and only a small number of these interactions had happened so far.

2. Even when information is consolidated and accessible, it is likely to require considerable dialog among multiple stakeholders about what to do in the event that the information confirms catastrophic losses. For instance, one state transportation authority outlined their estimate that there would likely be only 10% operational capacity for bridges in a particularly critical area. He went on to explain that his agency's ability to determine the exact amount of bridge availability and to provide any estimate of recovery timeframes was dependent on their ability to muster enough inspectors to perform assessments. While it is useful for other agencies to be aware that they should plan with the assumption that the transportation system will be operating a one-tenth of normal levels, participants were unable to determine how that limited capacity would be allocated following an earthquake. It was clear that multiple stakeholders had factored into their plans that they would be receiving priority access to whatever remaining transportation infrastructure that was available. It was also clear that those plans would collectively substantially overtax what little functional capacity remained with respect to the transportation sector after the megaquake.
3. Participants also expressed concern that there is the potential for *too much* information following a major disaster. This highlights a persistent, and often overlooked challenge. In addition to the challenge of knowing where information is consolidated and how to access it, organizations must know what the most helpful information is to share with other stakeholders and coordinating bodies. The danger, as described by the attendees, is that immediately following a major earthquake, there would be such a desire to share information and situation reports that stakeholders would end up inundating emergency managers with information that is not relevant or critical to the task at hand.

Because stakeholders often are not aware of the gaps in their own information, they can unintentionally build assumptions into their plans. One participant illustrated these implicit assumptions by describing a recent disaster where emergency food resources needed to be distributed to the affected communities. Though the emergency managers and regional coordinators had shared information and supply chain logistics information, they had not consulted the food retailers in the region. They had never considered that large retailers would supply emergency food in exchange for restoration priority. Realizing this critical gap and implicit assumption led emergency managers to reach out to a large food retailer to assure that there will be closer collaboration in the event of disaster. The FEMA Cascadia Rising exercise similarly built in an implicit assumption by not factoring in fuel shortages into their disaster scenario. In the absence of a coordinated regional planning effort, these types of "unknown unknowns" often do not manifest themselves until after a disaster occurs and significantly reduces a region's ability to respond resiliently.

Key Takeaway 2: *Current frameworks for building resilience encourage stakeholders to examine infrastructure sectors on a sector-by-sector basis. However, the inherent interdependence associated with critical infrastructure sectors necessitates that regions approach their infrastructure sectors as a system of systems.*

Presidential Policy Directive 21 (2013) emphasizes the need to secure our nation's critical infrastructure in the face of increasingly disruptive events, and identifies building resilience as a key mechanism for doing so. Further, PPD-21 recognizes the interconnectivity of infrastructure systems and acknowledges the need to strengthen resilience in an "integrative, holistic manner."[10] However, in practice, this integrative approach has not been realized and the traditional tendency continues to be to manage and provide oversight of infrastructure sectors in silos. The Department of Homeland Security has defined a total of 16 critical infrastructure sectors for which "Sector Coordinating Committees" have been stood up for each. Management of these Sector Coordinating Committees, in turn, are assigned to the individual federal department or agency that has historically been connected to a given sector.[11] While this public sector engagement with owners and operators within a sector is important, it does not address the need at the regional and community levels to approach resilience building efforts as an integrative process. Further, most oversight by the public sector is established at the local and state levels when the critical infrastructure systems themselves typically sprawl across multiple jurisdictions within any given major region.

10 "Presidential Policy Directive: Critical Infrastructure Security and Resilience." The White House Office of the Press Secretary. Feb 2013. Web. https://obamawhitehouse.archives.gov/the-press-office/2013/02/12/presidential-policy-directive-critical-infrastructure-security-and-resil

11 Office of Infrastructure Protection. "Critical Infrastructure Sectors." U.S. Department of Homeland Security. July 2017. Web. https://www.dhs.gov/critical-infrastructure-sectors#

The typical public policy response to address the issue of stovepipes that are misaligned with the function to be managed is to create a new central organization with the authority and breadth to collect information and to provide some level of operational direction at the systems level. One of the three imperatives for implementing PPD-21 was to direct DHS to accomplish the former by enabling "effective information exchange by identifying baseline data and systems requirements."[12] At the regional level, energy companies have proven to be quite adept at organizing themselves by establishing Regional Mutual Aid Agreements (RMAGs) with other energy companies. Attendees from the electrical power sector emphasized that they have detailed plans on how they would pool resources and work with the federal government on recovery in the aftermath of major power outages. However, the workshops that GRI has convened in Boston and Seattle make clear that the kind of regional coordination that exists for the electrical power sector is the exception to the rule for other infrastructure sectors. Further, there are only nascent efforts to address the infrastructure interdependency issue at the regional level.

Regions clearly need planning frameworks that better integrate information and coordinate multi-sector response and recovery planning. The recognition of this imperative is well understood. Participants at the workshop highlighted several instances where they had worked with partners to better understand each other's plans. However, they also acknowledged that a limiting factor is that resilience building efforts too often rely primarily on the shared commitment of individual leaders as opposed to a formal organizational structure. Unfortunately, when any of these individuals leave because of promotions, retirements, or job changes, these collaborative efforts often suffer as a result.

The most promising way for accomplishing this is to leverage existing regional coordinating bodies and repurpose them to support resilience efforts before, during, and after major disasters. Organizations such as PNWER which have a strong network of regional stakeholders across the public, private, and non-profit sectors are exemplars of this.

One particularly promising model is the Marine Transportation Safety Recovery Unit (MTSRU) developed by the U.S. Coast Guard and managed by the Captain of the Port. The MTSRU is both an emergency operations center and database for information that can inform multi-jurisdictional decisions, and help prevent operators from working at cross-purposes. However, MTSRU members are currently largely limited to stakeholders who operate in narrow geographic space of the waterfront even though they depend on infrastructure systems that extend beyond a given harbor. If its strength as a cross-sector coordinative body could be expanded to a wider geographic reach, it could play an enhanced role in supporting regional information sharing and response and recovery operations.

Key Takeaway 3: *Current economic, jurisdictional, and legal hurdles hamper stakeholders' abilities to share critical information or provide a disincentive for organizations to do so.*

Participants at the workshop expressed that, while the principle of sharing critical information before a disaster is one for which they see great value, there are often barriers that make it difficult to accomplish in practice. Attendees highlight that these barriers were particularly pronounced when it came to cross-sector communications across the public and private sectors.

The need to establish more unified pre-disaster communication and the current disincentives to doing so, proved to be one of the most frequently mentioned barriers to achieving greater resilience. A common impediment was the difficulty private sector partners faced when sharing sensitive information with government agencies. One emergency manager from the State of Washington expressed mixed feelings about the state's current public disclosure rules. While as a private citizen he understood the benefits of a high level of transparency for promoting greater government accountability, in his official capacity, it presented problems when it came to asking many private sector organizations to share information. Companies are legitimately concerned that information that ends up in the public domain may reveal vulnerabilities that could be exploited by criminals or terrorists or have competitiveness implications. Workshop attendees from the private sector also mentioned that some collaborative efforts to gather aggregate data could potentially run afoul of anti-collusion provisions embedded in anti-trust laws.

12 "Presidential Policy Directive: Critical Infrastructure Security and Resilience." The White House Office of the Press Secretary. Feb 2013. Web. https://obamawhitehouse.archives.gov/the-press-office/2013/02/12/presidential-policy-directive-critical-infrastructure-security-and-resil

In many instances, the sharing of data is managed through informal arrangements that are difficult to scale. For instance, Seattle City Light and Amazon recently met to examine their emergency plans and figure out how each would work with the other. An important outcome of this meeting is that Amazon came away with a much clearer picture of what they should expect for electricity following a major disruption, and can account for it in their plans. Previously, Amazon had assumed that they would have a level of power that did not match Seattle City Light's projections. However, any organization that wanted a similar meeting would have to approach Seattle City Light on their own initiative. One emergency management department similarly stated that anyone who wished to collaborate was welcome to come to their office. However, there was no structure to facilitate and sustain that engagement across all the stakeholders who would potentially benefit from more information sharing.

Just as vulnerabilities often only manifest themselves following a major disaster, the benefits of initiating and maintaining collaboration across sectors are not often easy to recognize until the process actually begins. Ongoing communications to stakeholders can provide near-term benefits to include identifying ways to improve operational efficiencies. These potential positive outcomes came to light as the natural product of having such a diverse group of practitioners in the room. This made the workshop, as one participant noted, a very positive preliminary step towards encourage more frequent interactions among key stakeholders who will need to work together in the aftermath of a major disaster and who can also clearly benefit from knowing and working with each other prior to a disaster.

Key Takeaway 4: *Stakeholders from the public and private sector acknowledge the long-term implications of a slow recovery process, but find it difficult to coordinate in advance their collective capacities to accelerate that process.*

Finally, the workshop participants acknowledged that the disastrous effects of the CSZ megaquake could linger for weeks and even months if recovery efforts are not well planned in advance. Most of the region's top employers, including Amazon, Boeing, and Microsoft, are international, knowledge-based companies that may find that they have to relocate their headquarters and most of their employees if the region's infrastructure did not recover soon enough for them to resume business. Companies expressed concerns that a longstanding lack of infrastructure would mean that their employees – especially those who rely on public transit – would be unable to commute to work, move back into their homes, and otherwise resume their daily lives. One private sector participant acknowledged that, while they have strong roots in the region, eventually their obligations to their shareholders would require them to move their corporate facilities elsewhere. This has occurred to communities such as New Orleans after Hurricane Katrina, when companies and people leave a region after a disaster, they rarely return.

Despite the clear challenges that a CSZ earthquake would present for the region, virtually all the private sector participants described that their clear preference was to remain in the region. Accordingly, they were committed to doing what they could to help accelerate post-quake recovery. One modest example of how the private sector could be a force multiplier for emergency managers was provided by a representative from Starbucks. He pointed out that Starbucks has thousands of local stores and internal communication channels, which could be mobilized to provide data and observations about post-quake damage as managers went to assess the condition of their stores. This method for producing real-time data falls outside of traditional strategies that relies primarily on emergency responders to do these assessments. Amazon also expressed the ability to use both its physical assets and its data to help facilitate a strong recovery. In fact, Amazon demonstrated this ability by delivering vital supplies following Hurricane Maria's devastation in Puerto Rico.

One of the primary barriers to more effectively mobilizing all the potential assets that a community could bring to a recovery effort were that emergency management systems were not calibrated to receive offers of help. Emergency responders are limited in the amount of information they can receive, assess, and act on. Regulations and public safety protocols may also limit their ability to leverage volunteers who lack formal training and credentials. The best way to overcome these issues is to work out these arrangements in advance to include putting in place "Good Samaritan" rules.

Conclusion

It was evident from the workshop discussions that stakeholders' abilities to satisfy their critical information requirements will play a key role in determining how effectively regions are able to respond to and recover from major disasters. Regional governance structures must be designed to facilitate the flow of the "right" information among interdependent sectors over multiple jurisdictions. Participants identified challenges caused by a lack of information, including gaps and assumptions in recovery plans, but also emphasized that information overload is a risk that must be managed. Ensuring access to information necessitates that stakeholders coordinate before a major disruption, not only to share the data that each of them already possesses, but to also communicate their needs to other organizations that other may be in a position to redress. Identifying in advance potential cascading failures that are inherent to interdependent infrastructure systems will also play an important role in reducing the number of unanticipated challenges responders encounter immediately after the major earthquake.

Successfully implementing the governance structures that facilitate effective information sharing faces a number of hurdles. On one hand, participants expressed a strong interest in collaborating and noted that some of them had already begun the process. However, the reality that regions face is that these partnerships are often between individual organizations or limited to siloed sectors. This is because current frameworks for collaboration do not place enough emphasis on the interdependencies between organizations and sectors and instead try to solve them on a sector-by-sector basis often within established formal political jurisdictions even if a sector is spread across multiple jurisdictions. This coordination, which often is structured from the "top down," rarely captures the needs of the individual owners, operators, and responders who need access to information that is outside of their immediate control. Additionally, governance structures often overlook the capacity for stakeholders such as private industry to contribute directly to recovery efforts. This untapped potential for industries and civil society to provide information and resources to support regional recovery is a potential windfall for professional emergency managers. Establishing a framework that helps to address the challenges and opportunities associated with overlapping jurisdictions, interdependencies, and hidden capacities, is an urgent imperative for building resilience so that a region can quickly get back on its feet and adapt to future challenges.

The goal of the workshop organized and facilitated by GRI and PNWER was to initiate a conversation between stakeholders that would lead to actionable governance solutions to the critical information requirements that the Cascadia Region would face following a major earthquake. In this regard, the GRI-PNWER workshop is not an end in itself, but is the first step towards bringing together different sectors and identifying existing capacity in the region that could be leveraged to act as future conveners. PNWER's Blue Cascades VII, a functional exercise that seeks to continue the work done at FEMA's Cascadia Rising exercise, will be held in March 2018. Using the information gathered and lessons learned from the September 2017 workshop, PNWER will be well-positioned to advance regional planning for post-megaquake recovery. The inclusion of the private sector in the discussion and the focus on interdependencies between the energy and transportation sector can also serve as a model for future public-private efforts to bolster a region's resilience.

Attachment A

Northeastern University Global Resilience Institute

Pacific NorthWest Economic Region

Cascadia Subduction Zone Megaquake
Critical Infrastructure Interdependencies Workshop

September 28, 2017
Double Tree Suites by Hilton, Seattle Southcenter
16500 Southcenter Parkway
Seattle, WA 98188

Background

The Pacific Northwest Economic Region (PNWER) will conduct the Blue Cascades VII Exercise in March 2018. This table-top exercise will focus on the recovery of the central Puget Sound region from a mega-quake caused by a disruption in the Cascadia Subduction Zone and will examine the criticality of significant, large, independent infrastructures deemed essential to regional recovery as identified by the Homeland Security Region 6 Critical Infrastructure Working Group. PNWER partnered with the Global Resilience Institute (GRI) of Northeastern University to assist in the development of the exercise around three areas: long-term regional recovery, critical energy and transportation interdependencies and cascading failures, and the integration of private businesses into planning, response and recovery.

Workshop Goals

- To confirm and refine a plausible scenario with respect to the potential impacts of CSZ Mega-quake on energy and transportation that should inform the design and execution of Blue Cascades 7 to be conducted in March 2018.
- To identify the extent to which lessons learned from major disruptions to the energy and transport infrastructures derived from Superstorm Sandy and other recent major disasters might usually inform post-disaster recovery planning in the Cascadia region.

Workshop Design

The workshop will be a highly-interactive day-long event with approximately 60 public sector and private sectors participants from British Columbia, Washington, and Oregon. The agenda is organized to facilitate a cross-sector (transportation and energy) discussion that will help to identify requirements for and inhibitors of these critical lifeline infrastructures. The workshop participants will work collaboratively on identifying potential interdependencies among critical infrastructure systems as well as untested assumptions that may lead to gaps in current plans. Working group results will help inform the design of Blue Cascades 7 and provide basic understanding of the most critical interdependency challenges in the energy and transportation sectors.

– Workshop Read Ahead –

In framing these workshops, we begin with the idea that: *The lack of timely, accurate information before, during and after a crisis causes planners and emergency managers to make frequent but often inaccurate assumptions about infrastructure availability and capacity leading to almost insurmountable friction and substantially slowing recovery. Therefore, accurate and timely information flow focused on intention and capability would substantially reduce the need for assumptions, optimize planning, facilitate management and speed recovery.*

Participants will be asked to consider these questions in two separate working group sessions:

Session 1:

Concentrating on the energy and transportation sectors:

- What information do emergency managers require of public and private sector infrastructure owners and operators to ensure public sector response and recovery plans support the rapid restoration of critical energy and transportation infrastructures? What inhibits the exchange of this information?
- What information do public and private sector infrastructure owners and operators require of emergency managers to support rapid restoration of critical energy and transportation infrastructures? What inhibits the exchange of that information?

Session 2

Using the information requirements developed in Session 1:

- Does the information required by the public and private sectors exist? Where?
- What systemic processes, procedures and capabilities can be put in place to ensure this exchange of vital information?
- What legislative or regulatory changes would be required to implement these information exchange processes or procedures?

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The Cascadia 90th Percentile Mega-quake Scenario

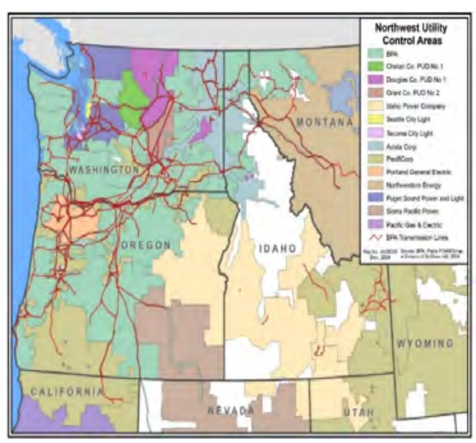
The scenario described below highlights how the interdependencies of the energy and transportation sectors with other infrastructure could potentially impact on recovery in the event of a 9.0-magnitude Cascadia Subduction Zone (CSZ) Megaquake. The Global Resilience Institute at Northeastern University and Pacific Northwest Economic Region (PNWER) have identified lifeline infrastructure systems that are likely to be damaged or disabled following the megaquake that will result in cascading failures that will have consequences for the entire Cascadia region. This scenario is informed by the June 2016 "Cascadia Rising" exercise conducted by FEMA to simulate the response to a 90th percentile scenario involving a megathrust earthquake along the CSZ fault line. While the precise damages sustained cannot easily be predicted, this scenario represents a realistic outcome following a megaquake of this magnitude.

Refineries

Four refineries on Puget Sound and one in Tacoma provide 90% of Washington and Oregon's refined fuel, as well as about 20% of British Columbia's refined fuel. In order to provide refined products to the region, these refineries are dependent on collocated marine terminals, rail, and pipelines. Without operational roads and intermodal transportation systems, employees and resources would be unable to enter or exit the refineries. British Columbia can only supply 30% of its refined fuel needs, relying on Washington and Alberta for the rest.

This scenario posits that in the aftermath of the 9.0 magnitude Cascadia Subduction Zone Earthquake, all five refineries will sustain moderate damage rendering them inoperable for 7-10 days due to loss of electrical power. Two refineries will sustain extensive damage to equipment or storage tanks, rendering them inoperable for 18-21 days. One refinery will be completely destroyed resulting in a total failure of all elevated pipes and/or total collapse of storage tanks with the associated hazmat spills into the environment.

Fuel and Energy Transmission



The majority of electrical transmission in Washington and Oregon is expected to be inoperable. This scenario posits that emergency repairs would take between 7 and 51 days, depending on geographic location, while full restoration would require a month to over a year through the region.

The Trans Mountain Pipeline and Puget Sound Pipeline System transports both crude and refined fuel to British Columbia and Washington; as much as 90% of B.C.'s fuel supply is dependent on this pipeline. In this scenario, damage in Puget Sound will prevent crude oil distribution for at least as long as the terminals are closed. The Olympic Pipeline originates at the Puget Sound refineries and transports 90% of Washington's and 68% of Oregon's refined fuel, as well as all of the

– Cascadia Megaquake Scenario –

fuel for SeaTac International Airport and Portland International Airport. The pipeline ends at the Critical Energy Infrastructure Hub on the Willamette River in Oregon, which contains 90% of the state's fuel, as well as other infrastructure for the transportation and transmission of fuels and energy.

The pipeline will be completely inoperable for at least 30 days due breaks and leaks, caused by liquefaction, ground displacement, and pump station damage. The loss of power and damage to lifeline roads and bridges will compound recovery challenges. In addition to fuel shortages at power generation plants and fuel stations, SeaTac and Portland International Airports only have capacity for 2-3 days of reserve fuel.

Transportation

Most primary and secondary roads along the I-5 corridor to the coast will be rendered impassable, including numerous bridge collapses along the I-5 putting many coastal communities between the Puget Sound and Oregon in near isolation with respect to ground transportation, as well as complicating the transportation of emergency workers and supplies along the I-5 corridor.

Vulnerable communities and mass transit dependent residents will be unable to access transportation Residents in both Vancouver and Seattle are dependent on ferries to reach the outlying islands; blockages to waterways and damage to marine facilities will render these inoperable and prevent access for emergency responders and repair equipment.

The CEI Hub is built on liquefiable soil, and is accessed by seismically vulnerable bridges along the Willamette. This scenario posits a partial collapse of the St. John's Bridge upstream of the CEI Hub and severe damage to the counterweights required for the Burlington Northern Rail Bridge to transport fuel by rail to the Hub.

Ports and Airports

Port facilities along the coast are designated as staging areas and likely to be significantly damaged due to flooding, debris, and underwater landslides. Debris in channels will result in closures pending Coast Guard inspections and necessary dredging. This may necessitate extensive work and machinery to restore operation that will take between 6-10 weeks to complete.

SeaTac International Airport moves 45.7 million people and 366,000 tons of cargo each year. In addition to liquefaction and seismic damage to airport facilities, fuel supplies and intermodal access will be prevented, closing the airport for 7-10 days and limiting air operations for at least 30 days.

The Portland International Airport is a designated staging area during an emergency for storage and coordination of emergency personnel and supplies. The runways are highly susceptible to liquefaction, and the whole facility risks flooding due to its proximity to levees. In this scenario, full runway reconstruction would take up to 10 months.

The Vancouver International Airport carries 22.3 million passengers and 281,018 tons of cargo each year. It relies on a pipeline from the Chevron refinery and barges for fuel, as well as supplementary trucks from the Washington refineries each day. This scenario posits limited damage to airport facilities, but fuel shortages from refinery, pipeline, and road closures.

Attachment B

Northeastern University
Global Resilience Institute

Pacific NorthWest Economic Region

Cascadia Subduction Zone Megaquake
Critical Infrastructure Interdependencies Workshop

September 28, 2017
List of Participants

Barrett Adams-Simmons
Regional Sector Outreach Coordinator
DHS Infrastructure Protection, Region 10

Bruce Agnew
Director
Cascadia Academy

Michael Allen
Household Hazardous Waste Specialist
Metro Regional Government

Tristan Allen
Private Sector and Infrastructure Program Manager
WA Emergency Management Division

Jim Ammons
Director of Business Continuity
Nike

Phil Anderson
Associate Director of Research and Innovation
Global Resilience Institute

Don Ashmore
Public Utilities Fleet Manager
City of Tacoma

CAPT Mike Balding
Deputy
USCG Sector Puget Sound

Jasmir Basi
Regional Director for Transportation Security and Emergency Preparedness
Transport Canada

Robert Bavier
Director, Hazardous Materials Management
Union Pacific Railroad

Jason Biermann
Emergency Management Director
Snohomish County

Mimi Bolaffi
Contingency and Planning, Port Security Division
USCG Sector Puget Sound

Andrew Bochman
Energy Sector Security Stratgist
Idaho National Laboratory

Christine Boynton
Communications and Media Manager
Global Resilience Institute

Roy Brower
Director, Solid Waste Compliance and Cleanup
Metro Regional Government

Laura Bruno
Regional Planning Coordinator
Regional Disaster Preparedness Organization (RDPO)

CDR JoAnn Burdian
Coast Guard House of Representatives Liaison
U.S. Coast Guard Office of Congressional Affairs

– Participants List –

Noe Isaac Cavazos
Logistics Readiness Officer
U.S. Pacific Command

Jennie Clinton
Senior Risk Manager
Microsoft

Linda Crerar
Director
Center of Excellence for Homeland Security
Emergency Management

Liz Dalton
Global Lead, Energy and Climate Resilience
One Concern, Inc.

Marcus Deyerin
Training and Exercise Coordinator
King County DOT Training and Exercise

Robert Dick
Assistant Deputy Minister
Transport Canada

Jim Earl
Sales
Lynden Transport

Warren Edwards
Distinguished Senior Fellow
Global Resilience Institute

Jim Floyd
Deputy Director, Global Security
Bill & Melinda Gates Foundation

Stephen Flynn
Founding Director
Global Resilience Institute
Northeastern University

Wendy Freitag
Academic Director for the Master in
Infrastructure Planning and Management
University of Washington

AJ Geiss
Crisis Manager
Amazon

Don Gesch
Transmission and Distribution Assistant
Manager
City of Tacoma

Barb Graff
Director
City of Seattle Office of Emergency
Management

Christopher Grasso
Program Manager
Global Resilience Institute

Branden Hardenbrook
Deputy Director
Pacific Northwest Economic Region

Mike Harryman
State Resilience Officer
Office of Oregon Governor Kate Brown

Chris Hartinger
Enterprise Crisis Manager
Starbucks

Chad Hawkins
HazMat Rail Program Coordinator
Oregon State Police – Office of the State
Fire Marshal

Marcie Hedman
Assistant Power Manager T&D Electrical
Services
City of Tacoma

Kurt Hodge
Transportation Manager
Safeway

Eric Holdeman
Director
Center for Regional Disaster Resilience,
Pacific Northwest Economic Region

John Holdsworth
Program Manager - Planning
Snohomish County Emergency Management

Ryan Hruska
Research Scientist, Infrastructure Analysis
Idaho National Laboratory

LCDR Darwin Jensen
Chief of Prevention Department
US Coast Guard Puget Sound

Gil Kerlikowske
Distinguished Senior Fellow
Global Resilience Institute

Lis Klute
Northwest Regional Emergency Manager
Amtrak Emergency Management and
Corporate Security

Jerry Koenig
Emergency Management Strategic Advisor
Seattle City Light

Suzanne Lemieux
Manager
American Petroleum Institute

Michael Lennington
Analyst-in-Charge / Senior Analyst
Government Accountability Office

Ann Lesperance
Director, Northwest Regional Technology
Center
Pacific Northwest National Laboratory

Nathan Magee
Organizational & Leader Development
OC/T
Joint Base Lewis-McChord

Jason Marquiss
Deputy Director
Washington State Emergency Management
Department

Patrick Massey
Regional Director, Region X
Department of Homeland Security,
Infrastructure Protection

Curry Mayer
Emergency Management Director
City of Bellevue

Deb Moller
Principal Consultant
Moller Consulting

Matthew Morrison
Chief Executive Officer
Pacific Northwest Economic Region

Steve Myers
Senior Program Manager
Pacific Northwest Economic Region

Daniel Nibouar
Disaster Debris Planner
Metro Regional Government

Jason Osleson
Operations Analyst
Department of Homeland Security

Jonna Papaefthmiou
Planning, Policy, and Communications
Manager
Portland Bureau of Emergency Management

– Participants List –

Ron Perkio
Manager, Transportation Security Options
Transport Canada

Sandra Pinel
Stakeholder Outreach
Department of Homeland Security, NPPD

Chris Polit
Emergency Management Training and Exercises Section Chief
US Army

Evan Reis
Executive Director
US Resiliency Council

Laura Ritter
Lead Security Policy Advisor
Exelon

Maria Robson
PhD Research Assistant
Global Resilience Institute

Tom Sampson
Chief
Calgary Emergency Management Agency

Helmut Steele
Company Security Officer
Washington State Ferries

CAPT Linda Sturgis
Sector Commander
US Coast Guard Sector Puget Sound

Sangeeta Varty
Senior Risk Manager – Business Continuity
Amazon

Nate Weigel
Program Coordinatro
Pacific Northwest Economic Region

Robin White
Executive Director
Global Resilience Institute

Rick Williams
Columbia Region Director
Leidos Maritime Solutions

Edward Wood
Emergency Manager
Joint Base Lewis-McChord

Scott Zaffram
Federal Preparedness Coordinator and Acting Director, National Preparedness Division
FEMA Region 10