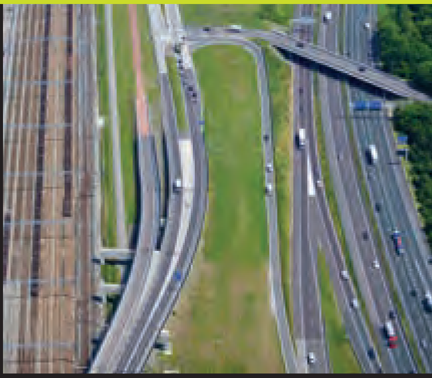
NATIONAL CLIMATE ASSESSMENT REGIONAL TECHNICAL INPUT REPORT SERIES

CLIMATE CHANGE AND INFRASTRUCTURE, URBAN SYSTEMS, AND VULNERABILITIES

Technical Report for the US Department of Energy in Support of the National Climate Assessment



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Climate Change and Infrastructure, Urban Systems, and Vulnerabilities

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About This Series

This report is published as one of a series of technical inputs to the Third National Climate Assessment (NCA) report. The NCA is being conducted under the auspices of the Global Change Research Act of 1990, which requires a report to the President and Congress every four years on the status of climate change science and impacts. The NCA informs the nation about already observed changes, the current status of the climate, and anticipated trends for the future. The NCA report process integrates scientific information from multiple sources and sectors to highlight key findings and significant gaps in our knowledge. Findings from the NCA provide input to federal science priorities and are used by U.S. citizens, communities and businesses as they create more sustainable and environmentally sound plans for the nation's future.

In fall of 2011, the NCA requested technical input from a broad range of experts in academia, private industry, state and local governments, non-governmental organizations, professional societies, and impacted communities, with the intent of producing a better informed and more useful report. In particular, the eight NCA regions, as well as the Coastal and the Ocean biogeographical regions, were asked to contribute technical input reports highlighting past climate trends, projected climate change, and impacts to specific sectors in their regions. Each region established its own process for developing this technical input. The lead authors for related chapters in the Third NCA report, which will include a much shorter synthesis of climate change for each region, are using these technical input reports as important source material. By publishing this series of regional technical input reports, Island Press hopes to make this rich collection of information more widely available.

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Contents

CHAPTER 1 INTRODUCTION

CHAPTER 2 BACKGROUND

CHAPTER 3 FRAMING CLIMATE CHANGE IMPLICATIONS FOR INFRASTRUCTURES AND URBAN SYSTEM

CHAPTER 4 URBAN SYSTEMS AS PLACE-BASED FOCI FOR INFRASTRUCTURE INTERACTIONS

CHAPTER 5 IMPLICATIONS FOR FUTURE RISK MANAGEMENT STRATEGIES

CHAPTER 6 KNOWLEDGE, UNCERTAINTIES, AND RESEARCH GAPS

CHAPTER 7 DEVELOPING A SELF-SUSTAINED CONTINUING CAPACITY FOR MONITORING, EVALUATION, AND INFORMING DECISIONS

Preface

In connection with the U.S. National Climate Assessment scheduled to be completed in 2014, the U.S. Global Change Research Program (USGCRP) and the National Climate Assessment Development and Advisory Committee (NACDAC) invited technical inputs. Many of the most substantive inputs were sponsored by USGCRP agencies, reflecting the knowledge and experience represented by their programs. The technical inputs were due to be submitted by March 1, 2012.

The U.S. Department of Energy (DOE) produced three technical input reports: Climate Change and Infrastructure, Urban Systems, and Vulnerabilities; Climate Change and Energy Supply and Demand; and Climate and Energy-Water-Land system interactions. All three reports were based in part on a major national workshop of experts from a wide variety of communities of knowledge and experience, and all three reports were peer-reviewed. This book provides the content of the first of these reports to a broader audience.

The author team would like to acknowledge the inspiration, leadership, guidance, and support of Bob Vallario, Director of the Integrated Assessment Research Program of DOE's Climate and Environmental Systems Division, Office of Biological and Environmental Research, Office of Science. Without Bob's knowledge and perspectives on everything from the subject areas to the expert communities, the technical input export could not have been produced and delivered on schedule; and he has continued since the report was delivered to put its scientific content to use; not only in the National Climate Assessment but in a wide variety of other program efforts related to DOE's missions. Although he is not listed as an author of this technical report, he is in every way a full partner of the report's authors and their commitments to advance knowledge about the report's topics.

List of Figures

List of Tables

Executive Summary

This technical report on "Climate Change and Infrastructure, Urban Systems, and Vulnerabilities" was prepared for the U.S. Department of Energy by the Oak Ridge National Laboratory in support of the U.S. National Climate Assessment (NCA). Prepared on an accelerated schedule to fit time requirements for the NCA, it was a summary of the currently existing knowledge base on its topic, nested within a broader framing of issues and questions that need further attention in the longer run (also see the on-line version of the report, which includes figures in color: http://www.esd.ornl.gov/eess/NCAInfrastructure.shtml).

The report arrived at a number of "assessment findings," each associated with an evaluation of the level of consensus on that issue within the expert community, the volume of evidence available to support that judgment, and the section of the report that provides an explanation for the finding.

Cross-sectoral issues related to infrastructures and urban systems have not received a great deal of attention to date in research literatures in general and climate change assessments in particular. As a result, this technical report breaks new ground as a component of climate change vulnerability and impact assessments in the U.S., which means that some of its assessment findings are rather speculative, more in the nature of propositions for further study than specific conclusions that are offered with a high level of confidence and research support. But it is a start in addressing questions that are of interest to many policymakers and stakeholders.

A central theme of the report is that vulnerabilities and impacts are issues beyond physical infrastructures themselves. The concern is with the value of services provided by infrastructures, where the true consequences of impacts and disruptions involve not only the costs associated with the clean-up, repair, and/or replacement of affected infrastructures but also economic, social, and environmental effects as supply chains are disrupted, economic activities are suspended, and/or social well-being is threatened.

Current knowledge indicates that vulnerability concerns tend to be focused on extreme weather events associated with climate change that can disrupt infrastructure services, often cascading across infrastructures because of extensive interdependencies – threatening health and local economies, especially in areas where human populations and economic activities are concentrated in urban areas. Vulnerabilities are especially large where infrastructures are subject to multiple stresses, beyond climate change alone; when they are located in areas vulnerable to extreme weather events; and if climate change is severe rather than moderate. But the report also notes that there are promising approaches for risk management, based on emerging lessons from a number of innovative initiatives in U.S. cities and other countries, involving both structural and non-structural (e.g., operational) options.

More specifically, the report's assessment findings are as follows. In each case, the report includes further information to support the finding.

Regarding implications of climate change for infrastructures in the United States, we find that:

- Extreme weather events associated with climate change will increase disruptions of infrastructure services in some locations
- A series of less extreme weather events associated with climate change, occurring in rapid succession, or severe weather events associated with other disruptive events may have similar effects.
- Disruptions of services in one infrastructure will almost always result in disruptions in one or more other infrastructures, especially in urban systems, triggering serious cross-sectoral cascading infrastructure system failures in some locations, at least for short periods of time
- These risks are greater for infrastructures that are:
    - Located in areas exposed to extreme weather events
    - Located at or near particularly climate-sensitive environmental features, such as coastlines, rivers, storm tracks, and vegetation in arid areas
    - Already stressed by age and/or by demand levels that exceed what they were designed to deliver
    - These risks are significantly greater if climate change is substantial rather than moderate

Regarding implications of climate change for urban systems in the United States, we find that:

- Urban systems are vulnerable to extreme weather events that will become more intense, frequent, and/or longer-lasting with climate change
- Urban systems are vulnerable to climate change impacts on regional infrastructures on which they depend
- Urban systems and services will be affected by disruptions in relatively distant locations due to linkages through national infrastructure networks and the national economy
- Cascading system failures related to infrastructure interdependencies will increase threats to health and local economies in urban areas, especially in locations vulnerable to extreme weather events
- Such effects will be especially problematic for parts of the population that are more vulnerable because of limited coping capacities

Regarding implications of climate change for infrastructure and urban system risk management strategies in the United States, we find that:

- Risks of disruptive impacts of climate change for infrastructures and urban systems can be substantially reduced by developing and implementing appropriate adaptation strategies
- Many of the elements of such strategies can be identified based on existing knowledge
- In most cases, climate-resilient pathways for infrastructure and urban systems will require greater flexibility than has been the general practice, along with

selective redundancy where particular interdependencies threaten cascading system failures in the event of disruptions

- Revising engineering standards for buildings and other infrastructures to accommodate projected climate change is a promising strategy
- In some cases, especially if climate change is substantial, climate-resilient pathways will require transformational changes, beyond incremental changes.

Regarding implications of climate change for infrastructure and urban system research needs in the United States, we find that:

- Improving knowledge about interdependencies among infrastructures exposed to climate change risks and vulnerabilities will support strategies and actions to reduce vulnerabilities
- The challenge is to recognize that, although uncertainties about climate change and payoffs from specific response strategies are considerable, many actions make sense now, such as developing monitoring systems to support assessments of emerging threats to infrastructures and urban systems
- A high priority should be given to verifying and validating the report's assessment findings, especially where the current evidence is not strong.

Regarding a continuing assessment process for climate change and infrastructure and urban systems in the United States, we find that:

- A self-sustaining long-term assessment process needs a commitment to improving the science base, working toward a vision of where things should be in the longer term
- Capacities for long-term assessments of vulnerabilities, risks, and impacts of climate change on infrastructures and urban systems will benefit from effective partnerships among a wide range of experts and stakeholders, providing value to all partners

Chapter 1

Introduction

The third U.S. national assessment of climate change impacts and responses, the National Climate Assessment (NCA), includes a number of chapters summarizing impacts on sectors, sectoral cross-cuts, and regions. One of the sectoral cross-cutting chapters is on the topic of *urban/infrastructure/vulnerability* implications of climate change in the U.S.

As a part of the NCA effort, a number of member agencies of the U.S. Global Change Research Program provided technical input regarding the topics of the NCA chapters. For the *urban/infrastructure/vulnerability* topic, the U.S. Department of Energy (DOE) is one of the responsible agencies; and this report was prepared for DOE by the Oak Ridge National Laboratory (ORNL) in support of the NCA. DOE's interest grows out of a longstanding research focus on energy infrastructures and their relationships with other infrastructures and systems, such as water and land, led by the Climate and Environmental Systems Division of the Office of Science.

Unlike many of the other chapters, which have equivalents in previous national assessments, this particular topic is appearing in NCA for the first time. In past assessments, cross-sectoral issues related to infrastructures and urban systems have not received a great deal of attention; and, in fact, in some cases the existing knowledge base on cross-sectoral interactions and interdependencies, at least as represented in published research literatures, appears to be quite limited. Studies dating back as far as 1982 (Lovins and Lovins, *Brittle Power*) have, however, pointed to the vulnerability of large, complex infrastructures to large-scale failures, and this underlying concern has grown in recent years (e.g., Villasenor, Brookings, "Securing an Infrastructure Too Complex to Understand," September 2011).

As a result, this technical report breaks new ground as a component of climate change vulnerability and impact assessments in the U.S., which means that some of its assessment findings are rather speculative, more in the nature of propositions for further study than specific conclusions offered with a high level of confidence. But it is a welcome start in addressing questions that are of interest to many policymakers and stakeholders.

For broader issues related to social as well as infrastructural aspects of climate change vulnerabilities and risk management strategies in urban areas, this technical report should be read in conjunction with a second technical report on U.S. Cities and Climate Change: Urbanization, Infrastructure, and Vulnerabilities, supported by NASA. For more attention to energy/water/land use interactions, see an additional technical report on that topic, also supported by DOE.

All of the technical reports to the NCA were prepared on a highly accelerated schedule. As an early step in organizing the NCA, a workshop was held in November 2010 to discuss sectoral and regional assessment activities. Out of that workshop came a number of further topical workshops and a working outline of the NCA 2012 report, including sectoral, regional, and cross-cutting chapters. In the summer of 2011, a number of USGCRP agencies stepped forward to commission technical input reports – each with at least one expert workshop and with a submission deadline of March 1, 2012, condensed into a period of eight months or less. Meanwhile, the advisory committee for the NCA (NCADAC) has appointed author groups for the report chapters, who incorporated the technical input in a draft NCA report to be submitted to the U.S. Congress by early 2014 (see www.globalchange.gov).

This report benefited from a scoping workshop on July 20, 2011, and an expert workshop November 9-10, both in Washington, DC. A final draft of the full report was sent to eleven distinguished external reviewers, eight of whom provided extensive comments and suggestions that were incorporated in this document.

The report includes substantial sections on "framing climate change implications for infrastructures and urban systems to climate change," considering both sensitivities to climate change and linkages among infrastructures, and on "urban systems as place-based foci for infrastructure interactions." These sections are followed by sections on implications for risk management strategies, research gaps, and developing a self-sustained assessment capacity for the longer term.

Chapter 2

Background

A. The Development Of The Report

1) OVERVIEW

This report is a summary of the currently existing knowledge base on its topic, nested within a broader framing of the issues and questions that need further attention in the longer run. The main constraint at this time is the limited amount of research that has been conducted and reported in the open literature on interactions between different categories of infrastructure under conditions of stress and/or threat. Given this rather severe constraint, findings in this report about climate change implications for infrastructures and urban systems are necessarily weighted somewhat toward research gaps and needs as contrasted with *specific* vulnerabilities; but a number of *general* assessment findings, reflecting a high level of consensus, add richness to NCA's understanding of cross-sectoral impacts and risks.

2) APPROACH

This report was developed by an author team led by ORNL under the oversight of DOE, with significant input from a range of expert communities at the two workshops in Washington, DC. Data, methods, and tools depended on available source materials and varied according to the topic and the resources that have been invested in each particular topic, except for one case study of climate change implications for urban infrastructures in Miami that was carried out by LANL and ORNL using critical infrastructure simulation and analysis tools developed initially for use by DHS. Judgments about report content, assessment findings, and levels of confidence reflect group consensus among the report authors, considering comments from selected external reviewers.

3) NCA GUIDANCE

The NCA adopted a range of types of guidance for the technical reports covering eight topics that are priorities for the 2014 report: risk-based framing; confidence characterization and communication; documentation, information quality, and traceability; engagement, communications and evaluation; adaptation and mitigation; international context; scenarios; and sustained assessment (www.globalchange.gov/what-we-do/assessment/nca-activities/guidance). The ability to respond to this guidance was limited by several factors. First, the content of the report is based as much as possible on available sources of technical literature, which varied considerably in their treatment of such issues as scenarios and confidence characterization. In most cases, in fact, the sources do not refer to climate change scenarios at all. Second, the nature of much of the source material, often qualitative and issue-oriented, severely limited any attempt to estimate quantitative bounds on probabilities. And third, the highly compressed time schedule for the technical report preparation process limited potentials for engagement and communication and made it difficult to impose top-down strictures on report authors.

Given a body of source material that is a highly imperfect fit with the NCA guidance, the report has made an effort to frame its assessment findings in broad contexts of risk-based framing, scenarios, and confidence characterization. Assessment findings are associated with evaluations of the degree of scientific consensus and the strength of the available evidence. Where appropriate, findings are also associated with two general scenario-related framings of possible future climate changes: (1) *"substantial"*, which is approximated by IPCC Special Report on Emission Scenarios (SRES) emission scenario A2, and (2) "*moderate*", which is approximated by scenario B1.

4) ASSESSMENT FINDINGS

Assessment findings are provided at the end of each major section of the report, including sections on risk management strategies; knowledge, uncertainties, and research gaps; and developing a sustained capacity for continuing assessments. The complete list of twenty assessment findings is included in the report's Executive Summary.

B. The Scope Of The Report

1) HOW "INFRASTRUCTURES" ARE DEFINED

For this study, the emphasis is on *built* infrastructures (as contrasted, for instance, with *social* infrastructures). Such infrastructures include urban buildings and spaces, energy systems, transportation systems, water systems, wastewater and drainage systems, communication systems, health-care systems, industrial structures, and other products of human design and construction that are intended to deliver services in support of human quality of life.

Experience over the past decade has shown vividly how vulnerable such infrastructures can be to the types of extreme weather events that are projected to be more intense and/or more frequent with future climate change. For instance, the Gulf Coast continues to be highly vulnerable to the effects of climate change despite rebuilding and new design features for infrastructure. While additional protection has been provided in the form of new levees and other structures; higher, stronger and better engineered roads and bridges; and more complete monitoring and communications equipment; the magnitude of the potential impacts of sea-level rise, storm effects and heat -- in conjunction with ongoing changes in the natural environment -- will continue to require attention and investment for a considerable time to come.

In 2008, the U.S. Global Change Research Program issued a "Gulf Coast Study" (SAP 4.7, 2008) that detailed the impacts of climate change on the central Gulf Coast from Houston to Mobile, AL. The study concluded that two- to four-feet of relative sea level rise were likely to occur in the region by 2050, including the continuing subsidence of

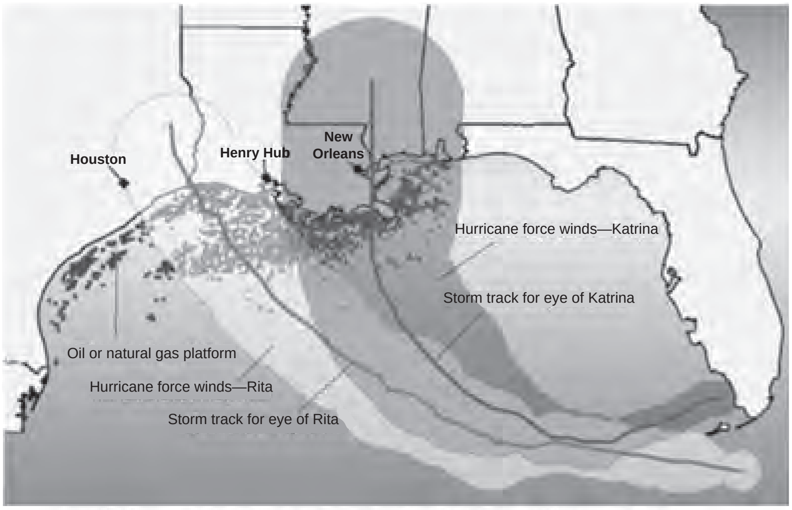


Figure 1 Path of Hurricanes Katrina and Rita relative to oil and natural gas production platforms

Source: GAO analysis of data provided by the National Weather Service and the Minerals Management Services.

the land mass (unrelated to climate change) (Figure 1). More recent estimates indicate that sea-level rise by 2100 may be twice as great as this study assumed, based at that time on lower projections by the IPCC in its Fourth Assessment Report in 2007.

Our expanding understanding of climate stressors is complemented by an enhanced understanding of how infrastructure and the services they provide are at risk. The *Gulf Coast Study* found that approximately 2,400 miles of major roads, 246 miles of railways, 3 airports and three-quarters of the freight facilities would be inundated by a four-foot rise in sea level. It further found that more than half of the major roads and all of the ports were susceptible to flooding from a storm surge of just 18 feet. By comparison, Katrina's surge was estimated at 28 feet at landfall. As stark as these direct impacts are, the ripple effects of damaged infrastructure on other essential services poses an even more complex set of challenges. In the ensuing analysis of impacts of Hurricanes Katrina, Rita and Ike, lessons were learned about the interdependence of various types of infrastructure and how interdependencies exacerbate the vulnerabilities of critical services. In this region, fuel supply, shipping and communications were all disrupted as a result of interruptions in transportation services.

As an example, three critical transportation conduits, the Colonial, Plantation and Capline pipelines, were knocked out by a power outage caused by Hurricane Katrina. The pipelines were shut down for two full days and operated at reduced power for about two weeks. These pipelines bring more than 125 million gallons of gasoline, diesel and jet fuel to the northeast seaboard each day. As a result of the energy failure, fuel shortages and price spikes resulted, affecting the transportation network (http://money.cnn.com/2005/09/01/news/economy/pipeline/index.htm). Gasoline price spiked as much as 40 cents per gallon (or about 25% in September 2005) and aircraft were in danger of being grounded for lack of fuel. In addition to the power outage, Katrina also caused damage to crude oil pipelines and refineries that reduced oil production by 19 percent for the year. Katrina also disrupted Mississippi River exports of the grain harvest. The South Louisiana port is the largest in the U.S. in terms of volume, generally due to grain movements; and there is no economically viable way to export the grain without this port. During Katrina, navigation down the Mississippi was disrupted by sunken vessels, electrical outages, and damage to port facilities. The timing was also of great concern: the perishable exports require transport by the early fall or spoilage can occur. Fortunately, the Coast Guard was able to clear the channels, power was restored, and the grain shipments were transported after significant delays of several weeks (http://text.lsuagcenter.com/en/communications/publications/gmag/Archive/2006/fall/Katrina+Disrupts+Mississippi+River+Grain+Transportation.htm).

Communications infrastructure also plays a crucial role in transportation and energy infrastructure and services. Houston TranStar provides multi-agency management of the region's transportation system as well as a primary resource from which to respond to incidents and emergencies. Its many transportation management services, including 730 closed circuit television cameras for road surveillance, dynamic messaging systems, centralized traffic management and accident communications systems, and synchronized traffic signals, depend heavily on advanced communications technology and electrical power (http://www.houstontranstar.org/about_transtar/). TranStar has also served as the "nerve center" of emergency management during the hurricanes. After Hurricane Ike, 2,200 of Houston's 2,400 traffic signals were dark and took almost three weeks to return to full operation. During Hurricane Rita, TranStar's website was accessed 14 million times during the event for up to the minute information on evacuation routes and shelters, which overwhelmed the communication service as about 2.5 to 3 million people attempted to evacuate. Evacuation routes were jammed and numerous deficiencies were identified. As a result, TranStar's web services have been upgraded, creating a redundant server in Arizona in case the Houston facility loses power, more wireless "hurricane-proof" cameras have been installed, and TranStar's coverage area was expanded beyond Houston's borders (http://www.houstontranstar.org/about_transtar/docs/Annual_2005_TranStar.pdf).

These examples demonstrate the interconnectedness of the transportation-energy and communications infrastructures and their joint vulnerabilities to extreme weather events. A failure to any of these interdependent systems can make a natural disaster much worse. It also shows the far-reaching impacts of such a failure.

2) HOW "URBAN SYSTEMS" ARE DEFINED

This report is particularly concerned with built/engineered systems in urban areas. Obviously, it includes interactions between these systems and social/political/institutional systems as well, but those systems are the focus of the other urban technical report mentioned above and are therefore not built specifically into the organizational structure of this report.

Within urban areas, infrastructure systems and services are defined by 1) large populations, 2) with tremendous economic and social activity, 3) in relatively confined geographic areas. Because of the importance of water to commerce as a source of cheap energy and transportation, many urban systems are close to the coasts, lakes or rivers. Economic activity is typically non-farm related, focused heavily on the manufacturing and service sectors of the economy. To accommodate these characteristics, urban systems are typically defined by heavily built-up environments and extensive infrastructure, to provide for the energy, clean water, transportation, and communication needs of the population. · These five core services are supplied by a collection of service providers in both the public and private sectors. Governance plays a key role in insuring the smooth and adequate provision of these services so that the health, economy and quality of life in the metropolitan area remain sound.

As noted in the 2009 state of knowledge report, *Global Climate Change Impacts in the United States (*GCRP, 2009*)*, urban areas face unique vulnerabilities to climate change, and the impact/vulnerability literature since 2007 has had a considerable focus on metropolitan areas. That urban areas have unique conditions and vulnerabilities has been the subject of a number of influential studies. For instance, Kirshen, et al. 2008 conducted a case study of the Boston area and found numerous interdependencies among infrastructure types vulnerable to climate effects.

Climate effects, such as sea level rise and storm surge, affect all infrastructures in the geographic vicinity with compounding impacts. Coastal flooding, for example, affects not only transportation services, , energy and communications, in the same geographic area. A major theme of a Boston case study is that "adaptation of infrastructure to climate change must also consider integration with land use management, environmental and socio-economic impacts, and various institutions." Amato et al., 2005, also found that energy demand could double by 2030 from air conditioner use and population growth; this increased demand would require new energy generation that is capital intensive and needs a long lead time. In 2011, the state of Massachusetts found that a sea level rise of 0.65 meters by 2050 could damage assets worth $463 Billion (Massachusetts Climate Change Adaptation Report, 2011).

New York City has had a major impact and adaptation effort underway for a number of years. In 2007, Jacob wrote that New York's role as a mega-city was linked to its highly developed infrastructure, particularly to transportation (Jacob, et al., 2007). The NYC metropolitan area has one of the largest transit systems in the world and there are more than 2000 bridges and tunnels in the City alone. With much of that infrastructure at elevations of only two to six meters above sea level, it is vulnerable to the effects of sea-level rise and storm surge. Jacob found that the damages from the most severe storms could exceed $100-200 Billion. In June 2010, Rosenzweig and Solecki, et al., as part of the New York City Panel on Climate Change that advises the City in climate concerns, proposed how a risk management response might be constructed (Rosenzweig, 2011b).

Major efforts have also been undertaken in other cities focused on one or more climate impacts. Based on evidence from the 1995 heat wave that took 800 lives in the city of Chicago, for example, Hayhoe developed a framework for quantifying climate impacts on urban energy and infrastructure (Hayhoe, K., et al., 2010). She found that mean annual temperature and the frequency of heat waves were key drivers and that Chicago's labor, maintenance and capital investments would be 3.5 times higher under a high emissions scenario than under a low one.

Riverine flooding is an issue in Portland, and Chang modeled the impact on travel delay using a suite of climate, hydrologic, hydraulic and transportation models in an integrated analysis (Chang, et al., 2010). Other urban areas which have efforts underway that address infrastructure components include San Francisco, Seattle and Miami. Finally a study of Copenhagen is relevant because of its economic scope. In 2010, Hallegatte et al. produced a methodology to model the direct and indirect economic impacts of storm surge and sea level rise from climate change (Hallegate, et al., 2011). Employing an input-output model, they examined production and job losses and duration of reconstruction activities, along with the benefits of upgraded defenses against flooding.

3) CLIMATE CHANGE VULNERABILITY AND IMPACT CONCERNS FOR INFRASTRUCTURES AND URBAN SYSTEMS

Climate change issues and concerns for infrastructures and urban areas focus on climate and weather parameters and/or events that are projected to change in magnitude or duration as a result of climate change. Vulnerabilities and risks are associated with changes in average temperature and temperature extremes, including heat and/or cold waves; changes in amounts and patterns of precipitation, including extreme rainfall events and flooding; changes in storm tracks, frequencies, and intensities; and sea-level rise. In many cases, variances and extremes are more salient for infrastructures and urban systems than are averages.

Table 1 summarizes several kinds of potential impacts from a study of climate change vulnerabilities in Boston. Box 1 provides an example from recent experience with a weather threat to energy infrastructure in the United States.

4) CLIMATE CHANGE ADAPTATION POTENTIALS FOR INFRASTRUCTURE AND URBAN SYSTEMS

Infrastructures and urban systems can reduce climate change risks, increase resilience to possible impacts, and reduce the magnitude and intensity of impacts by a range of adaptive behaviors: physical/capital equipment adaptations; technology and institutional adaptations; self-initiated "autonomous" adaptations and "planned" adaptations related to changes in external signals, requirements, and/or rewards; incremental adaptations without significant changes in existing systems and/or transformational adaptations that involve significant changes in systems or their locations.

Examples of possible adaptations to risks are depicted for Boston in Table 2 (also see Box 3 in Section V: Relating Adaptation and Mitigation).

5) CROSS-SECTORAL INTERACTIONS AMONG INFRASTRUCTURES

Although infrastructures and urban systems are often viewed individually – e.g., transportation or water supply or wastewater/drainage – in fact they are usually highly interactive and interdependent. Also drawn from the Boston case study, Table 3 illustrates interactions among infrastructures that might be affected by climate change, and Table 4 indicates possible sectoral adaptation strategies to reduce vulnerabilities and impacts across other sectors. More generally, the complexities of infrastructure interdependence are illustrated by Figure 2.

A number of experiences in the past decade have shown that such interdependencies can lead to cascading impacts through urban infrastructures that can result in unexpected impacts in communication, water, and public health infrastructure sectors, at least in the short term:

The Howard Street Tunnel fire in Baltimore, 2001

On July 18, 2001, a CSX freight train derailed in a through-route tunnel under Howard Street in Baltimore. This accident started a chemical fire that continued for more than

Table 1. Impacts on Environment, Economy, and Society

	System Impacts	Environment	Economy & Society
Energy	Summer More electricity demand. Also more brown-outs and more local emissions. Winter Less gas and heating oil. demand	Summer Also more emissions of pollutants. Winter Also fewer emissions of pollutants.	Summer Need to expand peak capacity. Also disproportional impact on elderly and poor. Increased energy expenditures, loss of productivity and quality of life. Winter Reduction in heating bills.
Health	Summer Slightly higher heat related mortality until about 2010. Also increased emission related illness.	N/A	Also stress on health care systems, loss of productivity, loss of quality of life.
Transportation Impacts Due to River and Coastal Flooding	Increased travel time . . . Loss of trips . . . More miles. More hours.	Also more emissions due to more travel miles.	Also loss of productivity and disruption of production chains.
River Flooding	Temporary loss of land and land activity.	More non-point source loads. Also extended floodplains, more, debris and more erosion.	Property losses. Also productivity and quality of life losses. In addition, see Transportation Infrastructure damage
Sea Level Rise	Permanent loss of some coastal land. Temporary loss of land and land activities.	Also wetland loss and erosion.	Property losses. Also productivity and quality of life issues. In addition, see Transportation infrastructure damage.
Water Supply	Less reliable local supply.	Higher or lower stream flows and water tables.	Also, productivity and quality of life losses.
Water supply	Less dissolved oxygen More non-point source pollution. Warmer water.	Also ecosystem stress and less biodiversity.	Also productivity property values and quality of life issues.

BOX 1

Wallow Fire Threat to the Springerville, AZ, Electric Power Generating Station

One threat to built urban infrastructures is increased exposure of critical assets or nodes to wildfires in areas forecast to receive lowered precipitation. An illustration of what these impacts might look like occurred in June 2011, when a major wildfire threatened the Springerville Generating Station. This station provides critical power into the Tucson Electric Power Company, the Salt River Project, and Tri State Generation and Transmission. As part of emergency response, the cascading impacts of the station's loss were modeled as the event unfolded. Consequence and forecast models tracked the wildfire threat and estimated the effects on the Arizona power grid if this generating station were to be taken off line.

Analysis indicated that there was enough power supply reserve in the grid to avoid a blackout in Tucson, but the modeled case illustrated one kind of vulnerability of an infrastructure to a weather-related extreme event that could cascade in a similar manner. On September 9, 2011, a transmission line near Yuma, AZ, tripped out due to high temperatures, starting a chain of events that led to shutting down the San Onofre nuclear power plant; and power was lost to the entire San Diego County power distribution system, serving approximately 7 million power customers. Power was out for 12 hours resulting in sewage releases and disruptions to city water distribution (see text below).

Figure 2 An illustration of infrastructure interdependencies

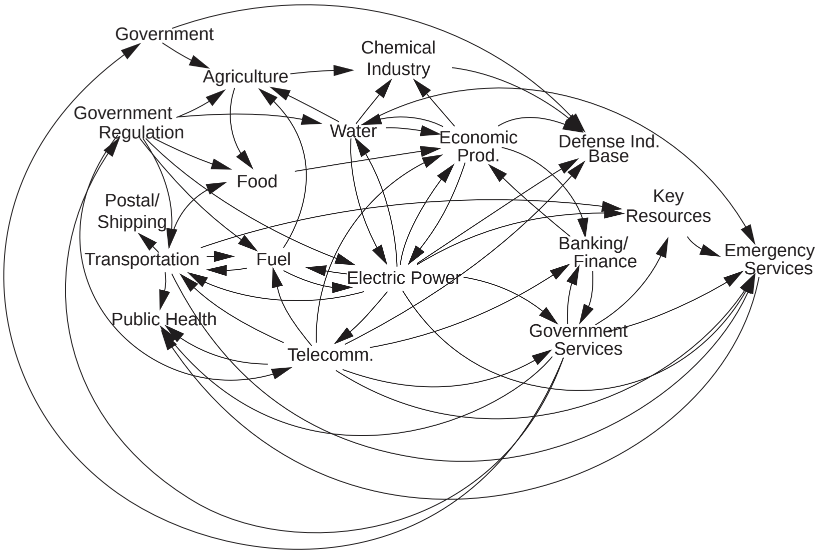


Table 2. Adaptation Impacts on Environment, Economy and Society, and Mitigation in Boston

	Sector Adaptation Strategy	Environment	Economy & Society	Mitigation
Energy	Both expand capacity and conserve.	In different locations, either increase or decrease emissions.	Rate changes. Growth and loss of some energy management. subsections	Energy conservation and use of renewables for replacement and new capacity will reduce GHG emissions.
Health	Install air conditioning, Improve and expand health services. Implement early warning systems.	More urban heat effects unless energy conservation.	Air conditioning (AC) expenses. Better health care system.	AC expansion may require more energy use (see Energy). Urban heat island effect reduction.
Transport	Expand public transport. Increase road network redundancy.	Reduce emissions and congestion. If coastal roads minimized, might allow landward migration of coastal wetlands under sea-level rise.	More reliable transport network.	Public transportation will reduce GHG.
River Flooding	Flood proofing. Retreat. Increase recharge to reduce amount of surface runoff.	Retreat and increased recharge have positive environmental benefits.	Less flooding damages and overall less homeowner expenses. More recharge will lead to more water supply.	Greenways may result in carbon sequestration, less urban heat islands, more shade. Denser development may result in more efficient energy and other resources uses.
Sea Level Rise	Flood proofing. Protection in high density developed areas. Retreat.	Fewer coastal uses are positive for environment.	Less flood damage and overall less homeowner expenses. More recharge will lead to more water supply.	If wetlands can be re-established, similar to river flooding
Water Supply	Demand management. Joint regional systems.	If less water demand, improved water quality.		Less energy use in water supply.
Water Quality	Management-point source pollution and other loads. Increase discharge.	Improved water quality.	Possible rate changes.	If vegetation part of stormwater management, then carbon sequestration less urban heat island, more shade. If denser development, then more efficient energy and other resource uses.

Table 3. System interactions – climate change impacts in Boston

	Energy	**Health**	**Transport**	**River Flooding**	**Sea Level Rise**	**Water Supply**	**Water quality**
Energy	Summer: More electricity demand. Also more brown-outs and more local emissions. Winter: Less gas and heating oil demand.	Summer: Also decrease in air quality higher morbidity and mortality. Winter: Also air quality improvement	Summer Also (if energy shortages), loss of rail service, loss of traffic signals. Disruption of air traffic.	Not applicable (NA)	NA	Summer: Also increased cooling water needs.	Summer: Also more cooling water will impact water quality (local and blow down).
Health	NA	Summer: Slightly higher health-related mortality 2010. Also increased emission-related illnesses.	NA	NA	NA	NA	NA
Transport Impacts Due to River and Coastal Flooding	Increased energy demand due to more travel.	Also reduced public safety	Increased travel time. Loss of trips. More miles. More hours.	NA	NA	NA	NA
River Flooding	Possible disruption in local deliveries.	Increased pathogens in water supply .	Less trips and increased traffic delay. (see Transport section).	Temporary loss of land and land activity	Also will increase flooding impacts.	Also could flood water treatment plants and wells.	Also could flood wastewater treatment plants. More non-point scarce pollution.
Sea Level Rise	NA	NA	Less trips and increased traffic delay (see Transport section).	Also could increase river flood losses.	Permanent loss of some coastal land. Temporary loss of land and land activities.		Also could flood wastewater treatment plants and may impact any new desalination plants.
Water Supply	Also possible loss of local energy supply because of lack of cooling water.	Less reliable local supply could result in hydration and water quality problems.	NA	NA	NA	Less reliable local supply.	Times when more water withdrawal and thus less dilution.
Water Quality	Also warmer waters could result in less of local energy production.	Also increased illness due to exposure to water from diseases.	NA	NA	NA	More treatment necessary.	Less dissolved oxygen. Moe non-point source pollution. Warmer water.

Table 4. System Interactions – Adaptation in Boston

	Energy	Health	Transport	River Flooding	Sea Level Rise	Water Supply	Water quality
Energy	Both expand capacity and conserve.	In different locations, either reduce or improve air quality	More reliable public transport and traffic signals.	NA	NA	More reliable as less pumping power cuts. Possible competition with other water uses.	In different locations, either more or less cooling water demand.
Health	Increased energy demand in summer.	Install air conditioning. Improve and expand health services. Implement early warning systems.	NA	NA	NA	NA	NA
Transport	Reliable heating oil delivery. Lower transportation energy demand.	Reduce emissions. Fewer road deaths.	Expand public transportation. Increase road network redundancy.	N/A	N/A	N/A	Perhaps less runoff contamination.
River Flooding	Dense development, more efficient energy use.	If less flooding, less spread of some waterborne and related diseases.	If retreat, then benefit transport.	Flood proofing. Retreat. Increase recharge to reduce amount of surface runoff.	If increased recharge, then reduced coastal flooding in estuaries.	If increased recharge, then increased water supply.	If increased recharge, then improved fresh and coastal water quality. Retreat will result in improved NPS runoff.
Sea Level Rise	Less flooding of coastal plants.	Less injury and loss of life due to flooding.	If retreat, then transportation improved.	N/A	Flood proofing. Protection in high density developed areas. Retreat.	Less flooding of coastal plants.	Less flooding of coastal plants.
Water Supply	More water available for cooling.	More reliable supply.	N/A	N/A	N/A	Demand management. Joint regional system.	If less water demand, improved water quality.
Water Quality	N/A	Less water pollution related diseases.	N/A	N/A	N/A	Reduced need for water treatment.	Managing non point source pollution and other loads increase discharge.

five days. By the end of the first day, a water main ruptured, flooding streets in the downtown area for five days. Fire and water effects damaged an electric power cable, leaving 1200 buildings without electricity. The accident also destroyed a communication system fiber-optic cable passing through the tunnel, slowing Internet service in the Northeast; and train, bus, and boat transportation were also disrupted (http://www.fra.dot.gov/downloads/RRDev/brn1.pdf): pp. 2-18.).

The San Diego blackout on September 9, 2011

On September 9, 2011, power was lost to approximately 7 million power customers in San Diego (personal communication, SDG&E) and lasted for 12 hours. The blackout covered areas of Arizona, California and Mexico during the hottest portion of the day and temperatures in some parts of the outage area reached 115 degrees Fahrenheit. The causal sequence occurred over an 11 minute period when at least 20 events, some whose significance is still being determined, cascaded through the communication and power infrastructures beginning in Arizona. High temperatures and infrastructure stresses caused disruptions and impacts across urban infrastructures.

The blackout disrupted both emergency communications and the impacted population's ability to respond, curtail power demand, or be warned of unsafe conditions. Two hours into the blackout, SDG&E sent a warning to more than 17,000 customers: The City of San Diego posted a boil water notice for several neighborhoods. City officials issued the boil order based on reduced water pressure that allowed contaminated water to infiltrate the system. Pump failure led to a loss of pressure in pipes. The power outage caused several sewage pumping stations to go offline, releasing millions of gallons of sewage into lagoons and waterways.

One pump station started overflowing after losing power and spilled sewage into Los Penasquitos Lagoon and emptying into the ocean at Torrey Pines State Beach. The spill stopped 3-1/2 hours later when power was restored. A second pump station failed during the outage and discharged sewage that closed beaches from La Jolla to Solana Beach, and along the Silver Strand south of Coronado. In addition about 120,000 gallons spilled into the Sweetwater River from a pump station near Interstate 5 and state Route 54 and an even larger spill south of the Mexican border, where Baja California officials reported a pump station lost power and sent 3.8 million gallons of sewage into the Tijuana River.

When the power went out, two city sewage pump stations failed because they each relied on electrical feeds from two separate San Diego Gas & Electric substations and did not have onsite generators. Overall, 2.6 million gallons of sewage spilled in Los Penasquitos Creek and 870,000 gallons were released into the Sweetwater River and ultimately to San Diego Bay.

The power outage affected about 10 percent of the city's water customers, the result of not having emergency generators at each of the pump stations. Without electricity to power the city water pumps and water purification plants, many individuals lost access to clean drinking water.

The Northeast Blackout

Many issues observed in the San Diego outage of 2011 were also apparent in the August 2003 Northeast blackout. During this blackout, 50 million people in the Northeastern and Midwestern US and Ontario, Canada, lost electric power, but some of the most damaging effects came when water treatment plants and pumping stations were shut down, just as in San Diego. Areas throughout the region lost water pressure causing potential contamination of city water supplies. In Cleveland and Detroit, the water supply was severely diminished and contaminated because of inadequate emergency and back up power generators. Cleveland, Ohio; Kingston, Ontario and NewYork experienced major sewage spills into waterways. Cleveland, Ohio and Detroit, Michigan issued boil water orders affecting approximately 8 million people.

While some Northeast waste treatment plants overcame the loss of electricity and stayed in operation during the extended power outage, other areas were not as fortunate, as where power was lost at every water pumping station and treatment plant. Within hours of the blackout, water pressure in Cleveland had diminished and over one million customers were left without access to water. At the downtown pumping station, which is below sea level, water pressure remained for some time. However, treatment plants were still in the process of switching over to backup power, and they could not treat the water supply that was available. Three major wastewater treatment plants in Cleveland discharged millions of gallons of sewage into the Cuyahoga River and Lake Erie, polluting the beaches and causing serious environmental damage. While New York's gravity-fed drinking water system fared well, the wastewater treatment system spilled nearly half a billion gallons of untreated effluent into New York Harbor over two days because pumps were offline.

Although many cities believe they have adequate backup power in the case that one or two of the treatment plants and/or pumping stations are down by pulling power from separated substation and not investing in on-site power, they are usually unprepared for large-scale blackouts that cut off the whole city's power supply. Adapting to these more frequent events for treatment plants and pumping stations could include either powerful backup generators or on-site power generation with no reliance on the local electric grid. To be successful in a large-scale blackout, the generators must be capable of running entire stations, at least at partial load. In Cleveland and Detroit, most pumping stations did not have enough power to operate their pumps, and treatment plants took up to 15 hours to fully restore their power.

C. Emerging Contexts For Infrastructure And Urban System Implications Of Climate Change

As climate change emerges as an impact and response issue for infrastructure and urban systems, such issues are inevitably intertwined with other driving forces for change (IPCC, 2007). Cataloguing all of the changes that might be factors, and especially their interactions with each other and with climate change, is beyond the scope of this report; but especially important contexts include the following:

1) SOCIOECONOMIC AND LAND USE TRENDS

The U.S. Census Bureau and other sources project that the total U.S. population will grow from about 310 million in 2010 to more than 400 million in 2050, with most of the growth between now and 2030 being in the U.S. West and South, both of which will grow about 50% more rapidly than the national average. Economic activity is not projected more than one decade into the future; but the clear hope is that – along with total population growth – the average standard of living will also rise, which translates into a significant increase in the requirement for supporting infrastructure over the next two to four decades, much of it in areas of the country at risk from impacts of climate change.

Socioeconomic scenarios being used to frame NCA assessments are based largely on Bierwagen, 2010, which projects trends in housing density and impervious surface cover for the United States with reference to the SRES A1, A2, B1, and B2 scenarios. In the A2 case, which reflects more rapid development, the growth of population and economic activity is oriented toward the Southwest, South, and coastal Southeast and East. In the B1 case, which assumes more moderate development, the growth is more broadly distributed across the nation. All of the scenarios show major increases in urban and suburban housing: roughly doubling urban and suburban land area by 2100. Again, the infrastructure implications are formidable.

2) SECTORAL TRENDS AND CONTEXTS

Similarly, projections of long-term trends in sectors such as energy, transportation, water supply, wastewater and drainage, and communication infrastructures are either scarce or unavailable, beyond the world of futures research and proprietary sectoral forecasts by industry that may not address interdependencies. Most analysts agree that the national demand for infrastructure *services* will increase substantially over the next half-century; the question is whether service demands can be made in innovative ways that are less physical-structure intensive, associated with such potentials as information-technology rooted "smart" services and/or dematerialization. One key interaction will be between technological change – such as in energy and water-use efficiency and in highway transportation – and infrastructure revitalization, especially in regions and cities where much of the current infrastructure is aging and overstressed by demand levels it was not designed to meet. A second key interaction will be between infrastructure revitalization and financial resources. Many infrastructures that are in place half a century from now will have been installed between now and then; but the process of change implies major financial investments, especially by public sector institutions, in an era when the public willingness to pay is in question, either through taxation or rate increases.

One key issue is the aging of many built infrastructures in the United States, many of which date to urban and regional capital investments many decades ago, some more than a century ago. A recent study by the American Society of Civil Engineers (ASCE, 2011) reports that America's water and wastewater infrastructures are aging and overburdened, estimating that the effects of a failure to revitalize these infrastructures are likely to be dramatic in terms of losses to the national economy. It concludes that current spending is only about half of the needed investment, "which means that the U.S. must invest an additional $1.1 billion over the next five years." Similar concerns exist for bridges and other aspects of transportation infrastructure (see ASCE's Report Cards on the health of U.S. infrastructures).

Chapter 3

Framing Climate Change Implications for Infrastructures and Urban Systems

For more than half a century, climate change impact and vulnerability assessments have tended to focus on issues for natural (and human-managed natural) environments, where changes in climate parameters have direct effects on such systems as ecology and hydrology. Because human-built systems are so often designed in part to buffer human well-being from natural-environmental constraints, it was implicitly assumed that implications of climate change for human infrastructures could be treated as a lesser concern.

What we know now, however, is that human-built infrastructures are of particular interest to the US population and to decision-makers who respond to their needs and demands. Climate and weather events can directly affect services that most people care about, such as comfort, convenience, mobility, labor productivity, and security. In many cases, the greatest concerns are with population and service concentrations in urban areas, especially those located in vulnerable areas, which are often threatened by storms, floods, wildfires, droughts, heat waves, and other weather phenomena linked to longer-term climatic processes.

As a new topic for national climate change assessments in the U.S., any effort to develop findings about major implications of climate change for infrastructures and urban systems needs to start by outlining a general framework of thought.

A. Sensitivities Of Infrastructures And Urban Systems To Climate Change

Implications of climate change for infrastructures and urban systems can be examined by assessing historical experience with extreme weather events and by simulating future conditions, including both individual events and either a series of extreme events in a short time period (Figure 3) or the combination of an extreme weather event with another type of threat at the same time (Wilbanks and Kates, 2010).

1) EXAMPLES FROM HISTORICAL EXPERIENCE

Familiar examples from recent experience include Hurricanes Irene and Katrina.

Hurricane Irene combined direct infrastructure damage, flooding, and winds that did far more than topple trees and turn out the lights across the Baltimore area. The storm left sewage spills, forced beach closures and triggered warnings to stay away from the water. The worst problem came in the Baltimore Highlands area southwest of the city, where a ruptured sewer main poured about 100 million gallons of raw sewage into the lower Patapsco River in the first week. Power outages also led to more than a dozen

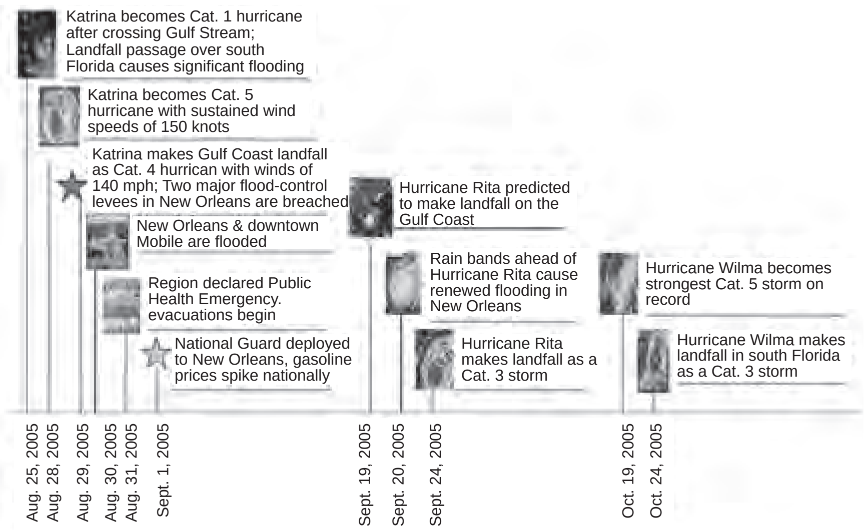


Figure 3 Infrastructure vulnerabilities to a rapid succession of extreme events

other sewage spills across the region. These spills continued for days after the initial storm passage illustrating that cascading impacts as restoration progressed were still working their way through the interdependent infrastructures.

As described above, Hurricane Katrina made landfall along the U.S. Gulf Coast on August 29, 2005, resulting in extensive flooding in the City of New Orleans, Louisiana, due to storm surge from adjacent Lake Pontchartrain and several levee failures (Colten, et al., 2008). These floodwaters had been partially pumped back into Lake Pontchartrain when the city experienced additional flooding and levee failures from Hurricane Rita on September 24, 2005. Floodwaters completely receded by October 11, 2005. Much of the flooding occurred in urbanized and industrial areas, fueling concerns that a public health crisis could result from exposures to chemically and microbiologically contaminated floodwaters.

Preliminary investigations in mid-September 2005 documented high levels of microbial and toxicant contamination in the New Orleans floodwaters. Floodwaters in New Orleans from Hurricanes Katrina and Rita were observed to contain high levels of fecal indicator bacteria and microbial pathogens, generating concern about long-term impacts of these floodwaters on the sediment and water quality of the New Orleans area and Lake Pontchartrain. Indicator microbe concentrations in offshore waters from Lake Pontchartrain returned to pre-hurricane concentrations within 2 months of the flooding.

2) SECTORAL PERSPECTIVES

A different perspective is provided by looking at interdependencies from the standpoint of particular kinds of infrastructure: in this case transportation and water.

Transportation (also see the NCA Technical Input Report on Climate Impacts on the U.S. Transportation Sector)

In 2008, two seminal works on the impacts of climate change on transportation infrastructure and services were issued within one day of each other. The first, the *Potential*

Impacts of Climate Change on U.S. Transportation, was released as Transportation Research Board Special Report 290 (Transportation Research Board, 2008). It clearly described how climate change is likely to affect transportation based on anticipated climate effects from the IPCC Fourth Assessment. It stated categorically that while impacts would vary by mode of transportation and region, they would be widespread and costly in both human and economic terms. It went on to recommend that transportation professionals incorporate climate change into their investment decisions and adopt strategic, risk-based approaches to decision making, among other things. Whereas this TRB report was general and non-specific on the impacts on transportation, the second was a case study that demonstrated and detailed many of the impacts in a specific region (see above). Commonly referred to as the *Gulf Coast Study* (SAP 4.7, 2008), the report bracketed likely future climate conditions between Houston, TX and Mobile, AL using the then latest and most inclusive techniques. As described above, the study found widespread vulnerability to sea level rise and storm surge: more than 2,400 miles of major roadway are likely to be permanently inundated by a sea-level rise of four feet (including subsidence) along with 246 miles of railways, 3 airports and three-quarters of the area's freight facilities. Even greater, but temporary, impacts are expected for short term flooding due to storm surges.

Reports on individual modes of transportation have been issued since 2008. Most recently, the Federal Transit Administration released its study on the impacts on transit facilities in 2011. Citing many urban examples, it provides a framework for transit agencies to assess their vulnerabilities. It notes, for example, that the most disruptive near term impact is likely to be intense rainfall that floods subway tunnels and low-lying facilities, bus lots, and rights-of-way. The report also identifies recent weather events that have disrupted transit service, including rail buckling in the Washington DC Metro and the Boston "T" and heavy rains in New York that shut down 19 major segments of the subway system. These examples illustrate the significance of severe weather events that are anticipated as a result of climate change.

Because of their apparent vulnerability and economic importance, ports have recently been an important focus of assessment studies. Nicholls, et al., (2008) ranked 136 port cities according to their vulnerability to coastal flooding. In 2009, the UN Conference on Trade and Development (UNCTAD) convened 180 experts from 60 countries to discuss, among other things, the potential impacts of climate change on maritime transport systems and supply chains, and issued a Summary of Proceedings (UN Conference on Trade and Development, 2009) UNCTAD has followed up this effort with a forthcoming book specifically focused on port impacts (Aerts, et al., 2011).

In the U.S., studies specifically on aviation have lagged behind those on other modes of transportation. One study by Pejovic, et al. (2009) statistically analyzed the weather events that caused delay at Heathrow Airport in London and then applied these models to future climate conditions. Studies of climate change vulnerabilities in New York City and Boston have noted vulnerabilities of coastal airports to sea-level rise and storm surges.

Given the rapidly evolving literature on transportation impacts, Koetse and Rietveld (2009) attempted to provide an overview of empirical findings in 2009. They found that demand patterns from tourism and agricultural production were likely to shift, causing secondary changes in transport patterns. They note that sea level rise and storm surge may be the most important direct consequences for transportation. However, while stating that the impacts are regional in nature, they also say that the impacts are "ambiguous" due to reported opposing effects on road safety and rail disruptions and the imprecision of climate output models. These are cited are research needs.

Water

A recent study by Freas, et al. (2010) clearly indicated that, based on the IPCC Fourth Assessment findings, climate change will affect the water cycle, and that water and waste water utilities will need to adapt infrastructure designs over a 20- to 40-year planning time frame. They estimate that addressing severe precipitation, water scarcity, snow melt and sea level rise effects through 2050 is a critical priority and will cost the nation from $448 to $944 billion in increased infrastructure and operating and maintenance expenses. An alternative view is provided by Rosenberg, et al., who attempted to address some of the known limitations of storm water run-off by employing historical records and regional climate models (based on two GCMs) to estimate extreme precipitation and determine design parameters (Rosenberg et al., 2009). Their analysis suggested that, while increases in extreme rainfall magnitudes were indicated, projections varied substantially by both model employed and region of the state. As a result, the range was too large to determine engineering design requirements. Nevertheless, the available evidence does suggest that current drainage infrastructure may be inadequate. Urban water managers are focused on water supply, wastewater management, water for recreation, water for ecosystems and associated services, storm water drainage, protection from coastal and river flooding, and river transport. Water managers in meeting these needs are not only dependent upon internal resources and interactions, but they also are influenced by those from outside. Examples of outside influences are federal and state regulations and institutions and water supply sources, water demands, floods, and pollution originating from outside their boundaries.

A dominant issue in some regions and urban systems is aging water infrastructure. In 2009, the American Society of Civil Engineers gave grades of D or D- to all aspects of water and wastewater management (dams, drinking water, levees, inland water ways, and wastewater). According to their study, $367.5 billion was needed in investment over the next 5 years. http://www.infrastructurereportcard.org/sites/default/files/RC2009_exsummary.pdf, accessed November 13, 2011). Impacts of this situation include growing operation and maintenance costs, inability to meet present and future demands, and health concerns (Grayman, 2009). As described in Daigger (2009) and others, however, aging infrastructure presents an opportunity to incorporate new planning paradigms into water management.

3) MODEL INTEGRATION PERSPECTIVES

A final perspective is in terms of challenges for model integration. One key example is integrating models of critical infrastructures with integrated assessment models (IAM).

Through its impact on infrastructure and on the economic activity the infrastructure supports, climate change can transiently or permanently reduce regional economic output, and thereby reduce regional employment over what it would be otherwise. Due to interdependencies of infrastructure systems, the reduction of output in one industry or the loss of one infrastructure can cause the reduction in the output in other industries or other infrastructures. We also observe cascading reductions in output across industries when key industries, such as transportation (e.g., ports), chemical (e.g., chlorine) and energy (electricity) sectors, suffer reduced output for an extended period. Figure 3 (above) shows some of the loops of interdependence across several infrastructures. The direct climatic impacts may include damage to productive capacity, whose stopgap repair can increase the future sensitivity to evolving climate change, or where resiliency-improving investments can insulate productive resources from future disruptions. The indirect impacts can be process changes in other industries or the diversification of supply chains.

Interdependencies can be interregional, for example, flooding in Thailand or cyclones in South Korea directly affect critical U.S. supply chains, e.g., computer hard drive manufacturing and precision component parts (note also implications of the Fukushima *nuclear power plant disaster). As a consequence, the ensuing effects of infrastructure response to* climate change can produce path-dependent influences on future economic conditions. Concomitant changes in production processes can change costs and the competiveness of local industries, leading to abandonment of facilities or the migration of the activities to other geographical areas. Some industries are more vulnerable to climate change events than others. Floods and snowstorms can quickly affect transportation systems, while droughts can have sizable impacts on agricultural and electrical generation systems. Assessments that neglect infrastructure vulnerability, interdependencies, and resilience miss fundamental elements of economic and societal risk.

Integrated assessment models (IAMs) are used extensively to evaluate climate change scenarios. IAMs currently focus on greenhouse gas (GHG) emissions and their mitigation in the context of economic growth. Adding infrastructure simulation capabilities would allow an assessment of adaptation as well as the quantifying risk to economies and societies. As such, infrastructure modeling is appropriately integrated assessment modeling because of the interaction between infrastructure adequacy and economic growth over time. In general, the current infrastructure models operate at different scales and have different computational requirements from most IAMs. For compatibility with IAMs, the analyses of infrastructure risks would need to be represented at regional levels with global coverage. Ultimately, there will be need for a hierarchical analytical capability that can describe the propagation of local effects to national and international implications – and the converse.

B. Infrastructure System Services

Although considerations of infrastructure often seem totally concentrated on physical structures, those structures are especially important because they are means to social ends. In other words, *services* and not *structures* are what are important to users and decision-makers.

When critical infrastructure and thus critical services are disrupted by climate effects in a metropolitan setting, cascading impacts can occur affecting part or all of the area, social and economic activity and the health and quality of life of the people themselves. These impacts can be viewed as three tiers of effects: 1) direct impacts on citizens and businesses, 2) impacts on service providers and business-to-business activities, and finally 3) regional or even national impacts.

A climate effect, such as severe weather event, will be experienced in all or part of a metropolitan area. As it is, services to consumers can be lost that reduce mobility affecting commuting patterns and possibly causing lost wages. Access to health care can be restricted for a time. Lighting, heating or air-conditioning can be lost by power outages. The flow of clean water for drinking and washing can be disrupted and disasters lasting days or weeks can disrupt solid waste removal. Businesses can be shuttered from a loss of power or flooding which will reduce sales and profitability. In serious events, hospitals can lose power or water raising critical health concerns.

An often unseen impact of service disruptions from severe weather (including climate-induced effects) is on business-to-business supply chains. Manufacturers need raw materials and parts, and likewise businesses in every sector of the economy rely on other firms to supply necessary inputs for their final products and economic livelihoods. For example, restaurants in the northeast have historically relied heavily on gulf coast shrimp just as auto manufacturers in Detroit have relied on parts from Mexico and elsewhere; a disruption in shrimp harvesting in Louisiana causes a hardship in Boston. In this way, service disruptions can create “ripple effects” throughout the economy, affecting much larger regions and even have national implications for highly concentrated services and major, long lasting disasters, especially as “just in time” supply delivery systems increase the emphasis on rapid responses.

It is worth noting that economic activity tends to be fluid both geographically and temporally. Economic demand can sometimes be pent-up and new markets for services can be found over time. Hence over long enough time periods and wide geographic regions, economists find that the impact of an individual disaster can be apparently absorbed by the broader economy as alternative sources of supply are found. But such aggregation over time and space masks real short-term effects on specific individuals and businesses. It ignores the need for cash flow and the time pressures for more optimal efficiency. And it ignores the price spikes that can occur due to shortages and loss of services.

While the effects of severe events spurred by climate change are most dramatic, incremental climate change has impacts as well. Over time, rising average temperatures and seas are projected to affect the demand for services. Agricultural products, for example, may come from different locations or disappear altogether, while others may appear from new locations. Over the long term, sea level rise could alter development patterns along the coasts. Such changes could give rise to the need for geographic relocation in infrastructure and services, as well as effects on their magnitude. Infrastructure will follow demand, but this movement will also necessitate investment. Shifts in population centers and altered patterns of agriculture will still require transportation, energy, communications, water supply and wastewater/drainage services. Where they do not exist or do not exist in sufficient quantity, new infrastructure will be necessary.

Infrastructure systems and the services they provide are highly interdependent in complex economies typified by urban areas. Because they are often co-located, they are subject to the same climate stressors, and damage to one will typically entail damage to others. The services also influence and rely on each other, and damage to one may reduce service in another. Integrated systems analysis should be conducted to determine the robustness and resilience of interdependent infrastructure services.

Many studies have demonstrated the impacts that climate change can have on the nation's infrastructure. Identifying the costs of these direct impacts is a crucial research need but tells only part of the story. The full scope of costs goes far beyond the actual damage to infrastructure. Recognizing the full costs of climate impacts is critical to the accurate identification of reasonable adaptation costs in order to avoid disruptive impacts.

The loss of or damage to infrastructure due to a natural disaster, whether a transportation, energy, water supply and wastewater/drainage, communications, or other structure, usually makes headlines. Such a loss can cost millions of dollars to replace or repair, or otherwise drain operating or maintenance budgets. Direct losses incurred by Hurricane Andrew in 1992 were estimated at $30 billion (NRC, 2009). Hurricane Katrina caused damages of $145 billion. In 2011 drought, heat waves, and wildfires damaged homes, agricultural and other structures across Texas, Oklahoma, New Mexico, Arizona, southern Kansas, and western Arkansas and Louisiana with combined losses over $10.0 billion (Haveman and Shatz, 2006). Note that these estimates are based on the value of the dollar at the time of the events.

Just as critical is the loss of service that the infrastructure and its operation provide to the economy, health, ecosystem and quality of life of American citizens. When infrastructure is damaged, it can affect people and communities in a variety of ways. Workers may not be able to get to their jobs resulting in lost wages. Businesses may close or lose sales with a loss of power. Supply chains can be disrupted causing shortages of goods and materials and can cause cascading "ripple" effects through the economy. Access to hospitals and loved ones may become more difficult or impossible with a loss of critical infrastructure.

The National Research Council noted in 1999 that these monetary and non-monetary losses are much more difficult to estimate, but a few examples are illustrative. The Port of Long Beach estimated the total cost of a 15-day closure to be $4.3 billion with no physical damages. In the winter of 2007-2008, Washington state's budget for maintenance had to be increased by $9 million to cover snow removal and related costs, but total economic losses were estimated as almost $75 million (Freight Transportation Economic Impact Assessment Report, 2008). And since 1936, the U.S. Army Corps of Engineers has invested more than $120 Billion in flood control projects which have estimated benefit to the economy in those areas of $706 billion (U.S. Army Corps of Engineers, 2009). These examples indicate that the direct costs of infrastructure damage represent only a fraction of the total economic impact of infrastructure service disruptions.

As we are adapted to our environment as it exists today, a changing climate has great potential to significantly affect the people, activities and even the geography of urban locations. It will do so by changing the natural environment through rising seas, more intensive storms, increased heat waves and other effects which change the landscape, damage the infrastructure of the built environment and disrupt critical services of urban areas. If appropriate adaptive measures are not taken, the end result of these disruptions will be reduced economic activity, health and quality of life.

Far from acting independently, service providers depend on each other to fulfill their roles (O'Rourke, 2007). The provision of energy, for example, generally depends not only on energy supply but also on transportation (to transport fuel and workers) and advanced communications. Transportation services used to assist energy services depend, in turn, on transportation infrastructure and energy (in the form of electricity or fuel) to power the transportation service. The same is true of communications and other types of services needed to provide adequate transportation. In urban areas and across the country, the provision of these services is an intricately interwoven web of infrastructure, users and suppliers.

The key point is that a service enabled by a critical piece of infrastructure can be disrupted by a variety of causes, including damage directly to it or to a necessary input for it. For example, an oil pipeline can be equally disrupted by a pipeline fracture or by loss of electric power that pumps product through it. Such service disruptions have implications on businesses and people, and affect the economy, health and quality of life in the metropolitan area. Unless appropriate adaptation measures are taken, service disruptions will become increasingly likely as climate effects intensify.

An increasing amount of research has addressed the sectoral impacts of climate change effects focusing on loss or damage to infrastructure or disruptions to operations. Permanent and temporary flooding, storm surge, and heat waves arising from a changing climate have been shown to incur likely impacts by damaging or undermining infrastructure and negatively impacting operations. Few studies, however, have analyzed the potential impacts from an interdependent or systems approach.

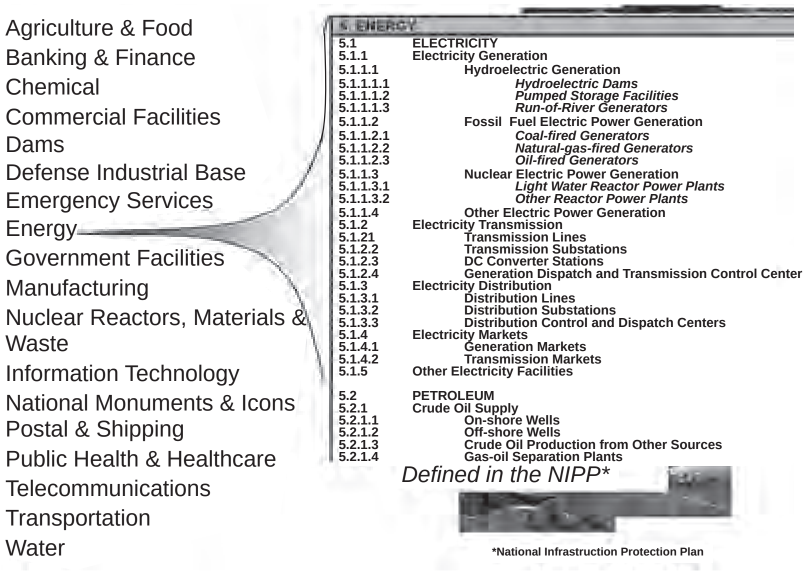
C. Linkages between Infrastructures

Anyone who considers infrastructures and infrastructure services under conditions of threats and stresses understands that any particular infrastructure is linked with other kinds of infrastructures as well; but capacities for modeling and analyzing such linkages have developed only recently in response to concerns about national security, and in many cases published research on the linkages has been scarce and spotty.

1) ANALYTICAL APPROACHES

A long tradition of research on disaster risk reduction and management has produced a rich menu of approaches for estimating potential losses from natural and other disasters (e.g., FEMA, 1997, and NRC, 1999). Among the currently available tools is *Hazus*, a standardized FEMA methodology. This base of knowledge and experience provides a backdrop for considering linkages among infrastructures subject to possible disasters.

Although open-literature published research literatures on connections and interdependencies among different types of infrastructure in the US are not generally well-developed, the national knowledge base is stronger than reference searches would indicate. For more than half a decade, under the sponsorship of the Department of Homeland Security (DHS) and other agencies concerned with US national security, a battery of analytical tools have been developed specifically to address infrastructure impacts of disasters. In particular, the National Infrastructure Simulation and Analysis Centers (NISAC) have developed capacities for modeling and analyzing cross-sectoral vulnerabilities of critical infrastructures to a variety of threats, including extreme weather events.



Agriculture & Food
Banking & Finance
Chemical
Commercial Facilities
Dams
Defense Industrial Base
Emergency Services
Energy
Government Facilities
Manufacturing
Nuclear Reactors, Materials & Waste
Information Technology
National Monuments & Icons
Postal & Shipping
Public Health & Healthcare
Telecommunications
Transportation
Water

5. ENERGY

5.1	ELECTRICITY
5.1.1	Electricity Generation
5.1.1.1	Hydroelectric Generation
5.1.1.1.1	*Hydroelectric Dams*
5.1.1.1.2	*Pumped Storage Facilities*
5.1.1.1.3	*Run-of-River Generators*
5.1.1.2	Fossil Fuel Electric Power Generation
5.1.1.2.1	*Coal-fired Generators*
5.1.1.2.2	*Natural-gas-fired Generators*
5.1.1.2.3	*Oil-fired Generators*
5.1.1.3	Nuclear Electric Power Generation
5.1.1.3.1	*Light Water Reactor Power Plants*
5.1.1.3.2	*Other Reactor Power Plants*
5.1.1.4	Other Electric Power Generation
5.1.2	Electricity Transmission
5.1.21	Transmission Lines
5.1.2.2	Transmission Substations
5.1.2.3	DC Converter Stations
5.1.2.4	Generation Dispatch and Transmission Control Center
5.1.3	Electricity Distribution
5.1.3.1	Distribution Lines
5.1.3.2	Distribution Substations
5.1.3.3	Distribution Control and Dispatch Centers
5.1.4	Electricity Markets
5.1.4.1	Generation Markets
5.1.4.2	Transmission Markets
5.1.5	Other Electricity Facilities
5.2	PETROLEUM
5.2.1	Crude Oil Supply
5.2.1.1	On-shore Wells
5.2.1.2	Off-shore Wells
5.2.1.3	Crude Oil Production from Other Sources
5.2.1.4	Gas-oil Separation Plants

*Defined in the NIPP**

*National Infrastruction Protection Plan

Figure 4 Interdependencies: A complex system-of-systems problem

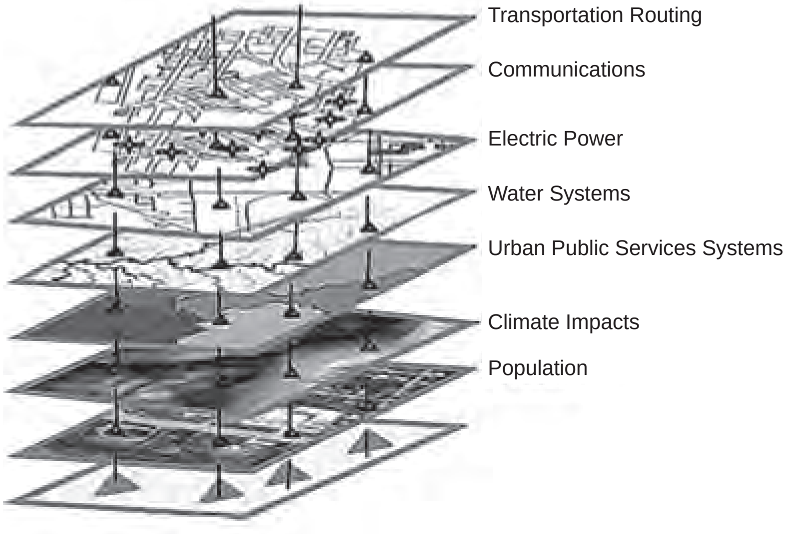


Figure 5 An interdependent system of systems approach

In general, these Critical Infrastructure Protection (CIP) approaches view infrastructure interdependencies as a complex system of systems problem, composed of individual infrastructures that are each defined by a number of components (Figure 4). These components of individual infrastructure sectors are linked with components of other infrastructure sectors in ways that can be identified; Figure 5 depicts these linkages via what the modeling community calls a “sandwich diagram.” In this way, interconnections can be modeled as pathways between interconnected components of infrastructure layers; Figure 6 illustrates these interconnections, which in infrastructure

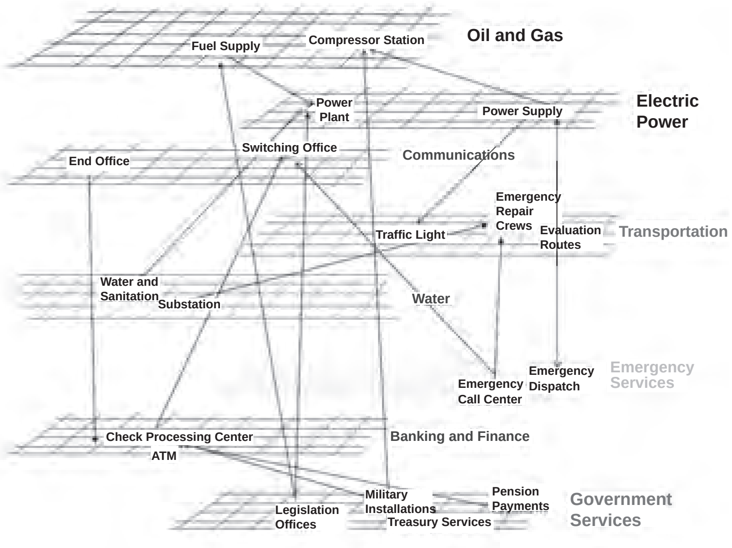


Figure 6 Infrastructure systems can be modeled as interconnected infrastructure layers

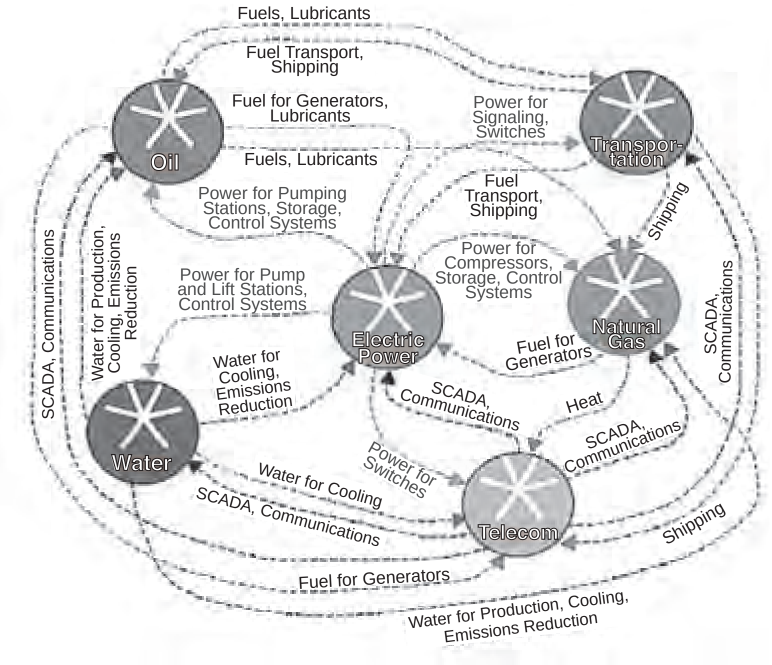
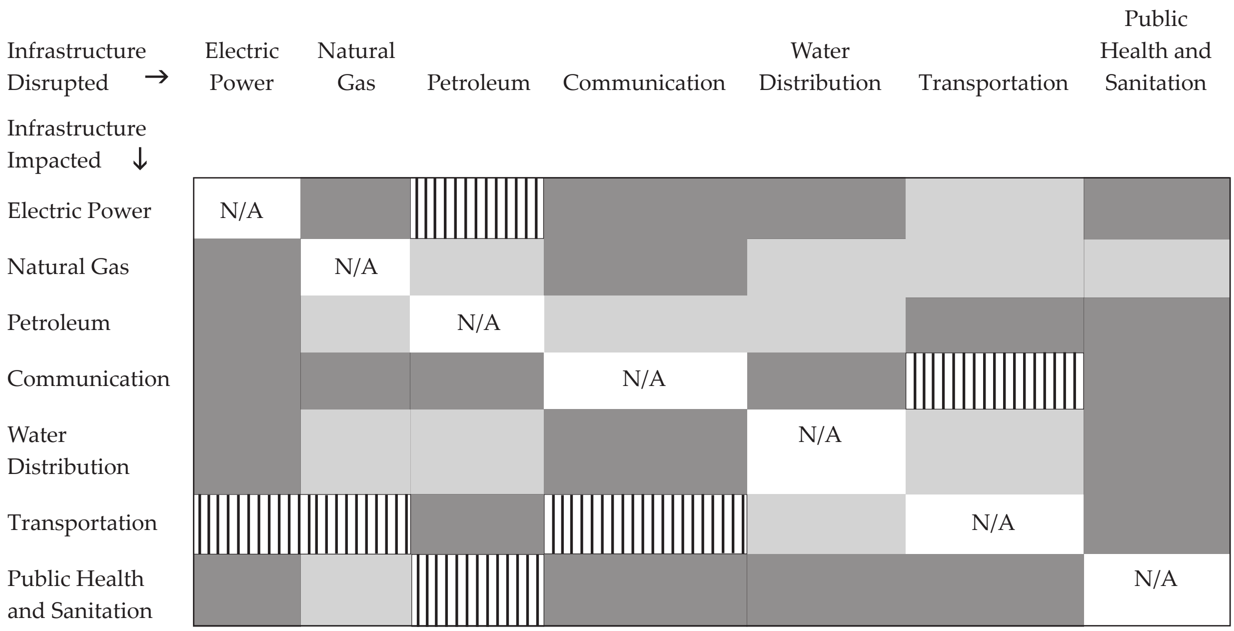


Figure 7 Modeling interdependent urban sectors as each is impacted by climate drivers

interdependency models number in the hundreds. Being able to trace these interdependencies makes it possible to answer questions in particular instances; for example, suppose that a severe weather event or other kind of disruptions causes electric power supplies to be interrupted. One effect would be that traffic lights would go dark. As a result, traffic congestion would increase, then highway vehicle emissions would increase, then respiratory distress in the area would increase, then demands for public health care services would increase, etc. (Figure 7). Figure 8 summarizes current knowledge about the importance of these interdependencies in both directions.



Infrastructure Disrupted → Infrastructure Impacted ↓	Electric Power	Natural Gas	Petroleum	Communication	Water Distribution	Transportation	Public Health and Sanitation
Electric Power	N/A	■	▥	■	■	░	■
Natural Gas	■	N/A	░	■	░	░	░
Petroleum	■	░	N/A	░	░	■	■
Communication	■	■	■	N/A	■	▥	■
Water Distribution	■	░	░	■	N/A	░	■
Transportation	▥	▥	■	▥	░	N/A	■
Public Health and Sanitation	■	░	▥	■	■	■	N/A

░ *Weak* interdependency-cascading disruptions through more than intermediary events, i.e., transportation is interdependent upon water distribution only to the extent that water utility workers require transportation routes to reach workplaces.

▥ *Medium* interdependency-cascading disruptions through foreseeable but loosely coupled relationships, i.e., transportation is loosely coupled to communications for control and dispatch, but can still be operated in degraded mode without communications and centralized routing

■ *Strong* interdependency-cascading disruptions have engineered basis such as power systems are dependent upon fuel supplies or public health facilities dependent upon power to electronic systems

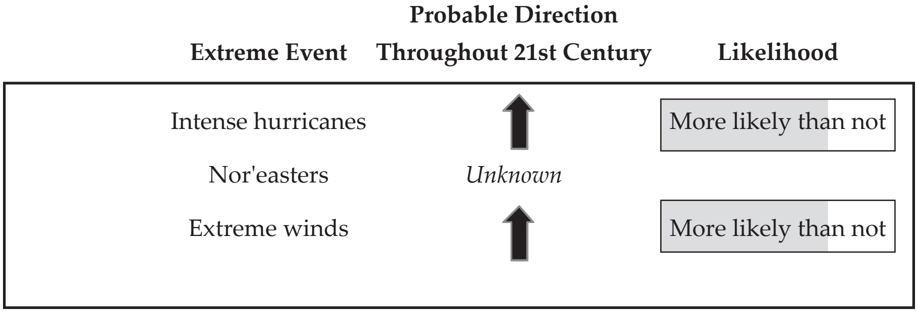
COASTAL FLOODS AND STORMS

	Baseline	**2020s**	**2050s**	**2080s**
1-in-10 yr flood to reoccur, on average	~once every 10 years	~once every 8 (8 to 10) 10 years	~once every 3 (3 to 6) 8 years	~once every 1 (1 to 3) 3 years
Flood heights (in ft) associated with 1-in-10 yr flood	6.3	6.5 (6.5 to 6.8) 6.8	6.8 (7.0 to 7.3) 7.5	7.1 (7.4 to 8.2) 8.5
1-in-100 yr flood to reoccur, on average	~once every 100 years	~once every 60 (65 to 80) 85 years	~once every 30 (35 to 55) 75 years	~once every 15 (15 to 35) 45 years
Flood heights (in ft) associated with 1-in-100 yr flood	8.6	8.7 (8.8 to 9.0) 9.1	9.0 (9.2 to 9.6) 9.7	9.4 (9.6 to 10.5) 10.7
1-in-500 yr flood to reoccur, on average	~once every 500 years	~once every 370 (380 to 450) 470 years	~once every 240 (250 to 330) 380 years	~once every 100 (120 to 250) 300 years
Flood heights (in ft) associated with 1-in-500 yr flood	10.7	10.9 (10.9 to 11.2) 11.2	11.2 (11.4 to 11.7) 11.9	11.5 (11.8 to 12.6) 12.9

Note: Does not include the rapid ice-melt scenario. Numbers inside parentheses indicate central range (67% of model-based distribution); numbers outside are full range.

Figure 8 Strengths of interdependencies between infrastructures impacted by events and other infrastructures that are disrupted as a result

Note: > 50% is used when the likelihood can be estimated with reasonable good precision, and 33 to 66% is used when there is not high confidence in the likelihood estimate.



These definitions of likelihood are used by the IPCC (2007) to describe potential outcomes.

>99%	Virtually certain	>66%	Likely
>95%	Extremely likely	>50%	More likely than not
>90%	Very likely	33 to 66%	About as likely as not

Figure 8 Continued.

Although these modeling tools were initially developed to answer questions about possible infrastructure implications of terrorist actions, they have been widely used to provide decision support during weather and other emergencies. As disruptions such as Hurricane Irene and the San Diego blackout emerge, infrastructure interdependency models are used to help anticipate and deal with cascading infrastructure effects. A co-benefit has been that interdependencies predicted by the models can, in each case, be compared with observed interdependencies; and the models can be refined to close the gap between predictions and real-world effects. Rarely have there been such rich opportunities to connect model development with observations, and a result has been significant improvement in the accuracy of the model depictions of interdependencies over the past half-dozen years.

One approach for representing interactions between systems and the population, developed to answer national security questions, is illustrated by Figure 9. For example, there will be multiple factors influencing the risks to electric power supply within a region. There will be changes in demand for electric power, including peaks, averages and variability in demand, due to:

- Changes in temperatures and their impact on demand (residential heating, cooling, industrial and commercial)
- Changing economic conditions
- Population relocation

Moreover, changes in electric power transmission are possible if:

- Transmission capacities are reduced due to high temperatures and/or
- New transmission capacity utilization patterns emerge due to changes in demand

In order to evaluate all of these risks, it is necessary to estimate the probability of each change and the capacity of the existing infrastructure to adjust to the potential perturbations. For instance, changes in the distribution of population and economic activity will

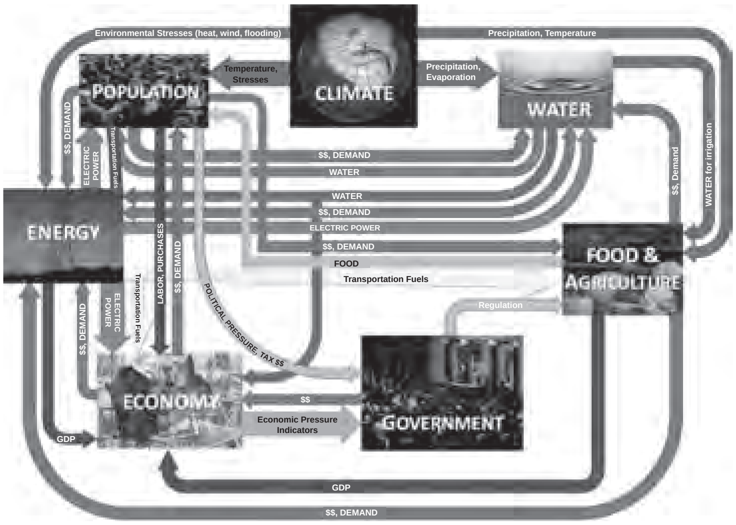


Figure 9 An illustration of interactions among systems related to climate change impacts

impact the distribution of demand for water, food, transportation fuels, utilization of transportation systems and other infrastructure services (e.g., communications, healthcare, banking and finance).

These interdependencies can be illustrated by focusing on two infrastructure sectors – transportation and energy – along with supplementary illustrations from other key sectors.

Transportation

Transportation systems are the lifelines of the nation's economy. All modes of transportation – road, rail, air, water– rely to a greater or lesser extent on infrastructure, vehicles and people to operate and manage them, energy for locomotion, and communications to ensure safe and smooth travel flow. Wherever people are, water supply and wastewater/drainage systems will be vital. Transportation services are located in the same geographic area as other services; and, as climate stressors affect one infrastructure, they are likely to affect transportation infrastructure and services as well.

Providing fuels and electricity is accomplished through the energy system which transports raw materials to refineries and power plants, and transports the final products via transmissions lines, pipelines or trucks. Communications, too, are a critical part of today's transportation network. Pilots in the air and sea, and train engineers must communicate with centralized support for safe and smooth operation. Road travel depends increasingly on intelligent transportation systems that employ advanced communications equipment in traffic management centers, automatic vehicle identification, synchronized signals, and electronic messaging signs. Subway and bus systems often employ computerized vehicle control, vehicle locator and voice communications in daily operations. Disruptions to any of these services will curtail transportation service even if transportation infrastructure is not affected.

While these interactions are in effect everywhere in the country, they are more critical in metropolitan areas where travel demand is much higher and greater population densities require an extensive transportation infrastructure. Urban transportation networks

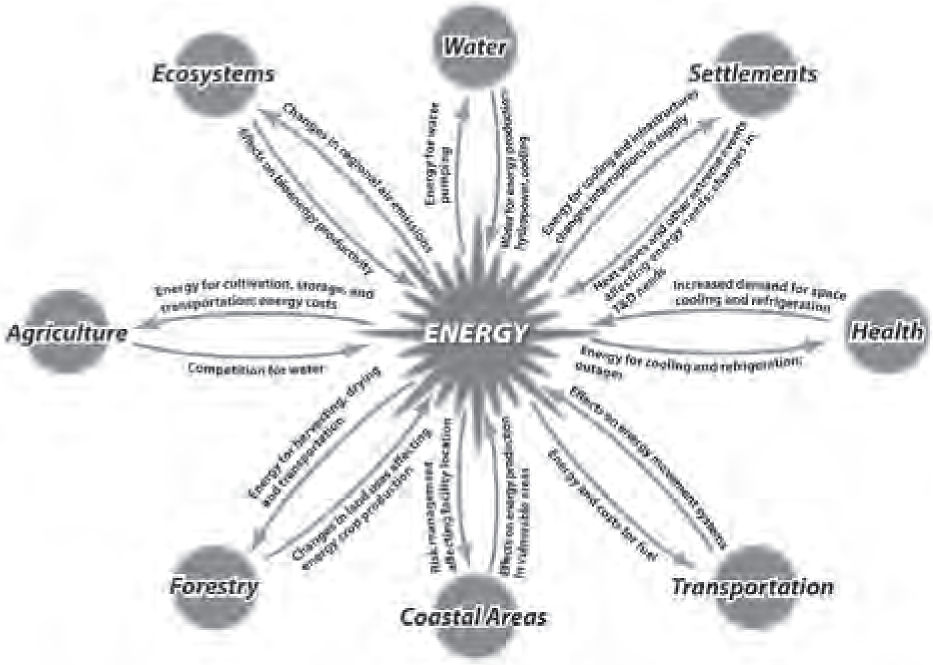


Figure 10 Interdependencies between energy and other sectors

frequently consist of airports, ports, heavy rail terminals and subways systems and are already under significant stress from aging infrastructure, congestion, and economic and environmental pressures. Congestion, not only on major roadways, but also on transit, at airports and at major ports of call, is common in urban locations, and demand for passenger and freight services continue to grow. "Just-in-time" delivery mechanisms make the reliability of the transportation infrastructure and operations critically time sensitive.

Energy

In recent years, a number of sessions at the annual Energy Modeling Forum in Snowmass, CO, have discussed cross-sectoral relationships between the energy sector and other infrastructures, including urban systems. For every sector of interest in climate change vulnerability, impact, and adaptation analysis, energy infrastructures and services are strongly linked in both directions: as a *source* of cross-sectoral impacts and as a *subject* of cross-sectoral impacts. Figure 10 illustrates these linkages with examples. For instance, take water: water infrastructures need energy for pumping, and energy infrastructures need water for hydropower and thermal power plant cooling; take transportation: vehicles need energy for motive power, and energy infrastructures need transportation to supply coal, oil, gas, and other essential supplies; take telecommunications: communication technologies need electricity to operate, and energy infrastructures need communication infrastructures to manage what they do (and that dependence is increasing: e.g., the Smart Grid concept). Hints of the importance of energy for other infrastructures can be seen in the level of investment in electric power backup systems, from battery storage to diesel generators, and in oil supply backup systems, from oil reserves maintained by industry to the national Strategic Petroleum Reserve.

Particularly important for the National Climate Assessment are interactions between energy and both water and land (see *NCA Technical Report on Water/Energy/Land Use*, 2012) and between energy and urban areas, transportation, wastewater/drainage, information, and health infrastructures. Experience with extreme weather events has shown vividly, for example, how the loss of electricity supplies due to storms and floods can disrupt communication and information services, which in turn complicates emergency responses related to health and safety. Meanwhile, energy infrastructures – both supply and demand – are increasingly reliant on communication and control systems that are jeopardized if information systems are disrupted.

Other sectors

Illustrative examples of cross-sectoral interdependencies for other categories of infrastructure include:

Water supply and wastewater/drainage management. Water and wastewater pumping and treatment are major energy users. Transportation and communication networks are needed to maintain and operate the infrastructures; and flood management infrastructures are often needed for protection. Both water and wastewater management are closely linked with health infrastructures and usually nested in building infrastructures, especially for end uses.

Health. Health assurance and health care infrastructures, from public health care systems to hospitals and nursing homes, are heavily reliant on energy, telecommunication, and transportation infrastructures; and their effectiveness depends heavily on wastewater and water infrastructures, as well as shelter as a buildings infrastructure service.

Telecommunications. Modern telecommunications depend utterly on energy sources, nearly always electricity infrastructures – online or stored. Transmission lines are a transportation infrastructure as well, and telecommunication infrastructures are firmly connected with other infrastructures as users of their services.

Buildings. Modern buildings depend on energy services for climate conditioning, office equipment, elevators and escalators, and communications. Their occupants rely on transportation infrastructures to connect homes with jobs and commercial needs. Their suitability for occupancy depends on water, wastewater, and health infrastructures – mutual dependencies in every case.

Others. Other examples could be added, including security/emergency preparedness and banking/finance as categories of infrastructure.

2) FACTORS AFFECTING VULNERABILITIES, RISKS, DECISIONS, AND RESILIENCE/ADAPTABILITY

Given uncertainties about not only future climate changes at a detailed scale but also such other infrastructure design parameters as changes in demand and changes in the policy environment, responses are most appropriately framed in terms of risk management rather than optimization based on precise predictions of the future.

Risk management is especially salient for many kinds of infrastructure investment and management, because the decisions tend to be large-scale in so many ways: large institutions making decisions about large structures involving large investments and long expected lifetimes. Risks that a structure may have to be decommissioned before the end of its designed lifetime can imply high costs, and risks that an infrastructure may have to be retrofitted during its lifetime to adapt to change conditions also can imply high costs. As a result, in times when external conditions appear likely to change over periods of decades, risk management is vitally important, involving such issues as estimates of the economic costs of disruptions and potentials for flexibility over a structure's lifetime – in contrast to rigidity and inflexibility.

Applying risk analysis to infrastructure projects

The Transportation Research Board (2008) states that new methods are necessary for addressing the impacts of climate change in transportation decision making on infrastructure and services. In particular, the report cites the need for probabilistic methods, like risk assessment, to be used in lieu of the more deterministic methods currently employed. Making the principles of risk assessment operational for transportation and other infrastructure managers is a critical next step in decision support.

The fundamental equation of risk analysis is: *risk equals the product of probability and consequence.* The idea is that if one can quantify the value of the investment at risk, this can be compared to the investment necessary to avoid that risk and sound economic decisions can be made. In very simplistic terms if the investment to avoid the risk is less than the value of the risk to the infrastructure itself then the investment is sound and should be made. If it is not, then it is better to accept the consequences and repair or rebuild as necessary.

Recent attempts to apply risk analysis to climate change adaptation have sometimes been unclear about the meaning and application of probability and consequence. Some have directly applied the probability that a climate stressor -- such as a heat wave -- will occur to indicate the probability of damage. However, this presupposes that the infrastructure will necessarily be damaged if the stressor occurs which is not always the case. Probability, in the case of infrastructure services, more appropriately refers to the probability of degraded service in the event of a climate stressor.

To be sure, the probability of degraded service depends on the probability of the stressor occurring in the first place. But these probabilities are related by the ability of the infrastructure to withstand the climate stresses, including both exposures to stress and vulnerabilities to stress. For example, a 100-year storm may occur, yet a robust power plant may withstand that storm and continue to provide full service without interruption. Hence the probability of reduced service in this example is zero, even though the probability of the climate stressor is 1 percent.

There are concerns in the identification of the consequences as well. Some analysts have only included the loss of the infrastructure itself, sometimes employing replacement costs and other times the depreciated value of the structure. Either approach ignores the true benefit to society of the infrastructure, i.e. the value of the service provided. While this may be a challenging variable to estimate, failure to do so greatly underestimates the true consequences. A more complete analysis of the consequences, then, would entail not only the costs associated with the clean-up, repair and/or replacement of affected infrastructure but also the economic loss of service as supply chains are disrupted, business operations are suspended, or cascading economic effects occur.

The concept of redundancy is similarly related. The consequences of service loss can be greatly ameliorated, and possibly even eliminated in some cases, if redundant services exist. The road network in many urban areas is a good example. While the loss of a critical, single road in a rural area may be catastrophic to travelers on it, loss of a similar road would have far less consequence in urban areas which typically have more than one way to get from an origin to a destination.

In practice, applying risk analysis to infrastructure services will require simplifying assumptions and approaches as many of the relevant variables cannot be estimated at this time, especially the probability distributions of future climates. They should, however, still be addressed conceptually to gain a more accurate and complete perspective to assist infrastructure decision makers in addressing climate effects.

A strategic approach to the cost and timing of adaptation measures

As more climate impact assessments are being carried out on individual pieces of infrastructure, many analysts are failing to realize that adaptation measures to reduce the impacts of climate change must be appropriate to the time frame of the anticipated impacts. Failure to recognize this will lead to very high costs and unrealistic adaptation decisions.

Near-term problems call for near-term solutions. Infrastructure that is currently vulnerable to storms, for example, may require immediate measures to address that vulnerability, which is magnified if the intensity or frequency is expected to increase. But if there is no immediate urgency and future climate effects are perhaps many decades away, pre-emptive high cost adaptation actions should be very carefully assessed before being undertaken, for two reasons.

First, many infrastructure adaptation measures are very expensive. These can entail changes to the operations and maintenance, materials, design, engineering, or location of the structures. For major pieces of infrastructure, like a bridge, design, engineering and location changes are counted in the millions to billions of dollars, and most infrastructure managers will be appropriately cautious about undertaking major investments without a clear and present need.

Second, our ability to project distant climate impacts is significantly reduced as reflected by the wide ranges for impacts. Infrastructure managers who might attempt to take pre-emptive actions will quickly face the difficult task of determining more precisely what the future impacts will be. With uncertain future sea levels by the end of the century, what design height should be employed for say, a bridge, recognizing that each additional increment carries a substantial price tag? On the one hand, the manager is faced with the potential of very high and possibly unnecessary costs, while on the other, the probability of infrastructure failure in the future. This task is made even more crucial by an economic outlook that is ever more financially constrained. These two factors have important considerations for climate assessments.

The cost of adaptation has been of increasing interest in the assessment community. Some have estimated costs applying the full burden to adaptation, and if this were true, the worldwide costs would be astronomical. A more strategic approach is to tie infrastructure adaptation to asset management cycles. Asset management recognizes the projected life span of infrastructure, maintenance needs and rehabilitation schedules. By tying adaptation measures to asset management schedules, most of its cost would be tied to the normal rehabilitation or maintenance schedule of the asset. Costs to adapt are therefore more appropriately limited to an incremental cost of the rehabilitation and are thus minimized. This will lead to more realistic estimates of the true adaptation costs. It also allows time for scientific climate assessments to improve and ranges to narrow which better targets the adaptation measure to the climate impact.

Some adaptation options may focus on land use rather than engineering solutions. This approach may be employed where retreat from a highly vulnerable area is deemed to be the most sensible alternative. If history is any guide, such options will be controversial and difficult to implement. Where development already exists in vulnerable areas, people and communities are typically loath to move. Barrier islands have seen significant development despite risks of flooding and storm damage, and many communities already engage in major activities like beach replenishment to protect their property and livelihoods. Disinvestment strategies, new land use restrictions, and development prohibitions are likely to face serious political opposition and as a result require significantly long lead times to be put in place. These strategies must be started early if serious climate effects on these communities are to be avoided.

As a final note, the relative imprecision of our ability to estimate distant climate effects makes monitoring of the natural environment and of impacts on infrastructure critical. Since the climate record is fraught with periods of inconsistent change, vigilance is necessary to identify the need for adaptive action and tie it to asset management schedules to safeguard vulnerable infrastructure.

3) INSIGHTS FROM CRITICAL INFRASTRUCTURE RESEARCH

Published research on critical infrastructures and their interrelationships, although limited, offers a number of insights about implications of climate change for infrastructure disruptions.

Relationships between climate change and infrastructure disruptions

Impacts from disrupted infrastructures occur almost annually from extreme weather events (NSF 2009). In 2011, for instance, Hurricane Irene, the September San Diego Blackout, and the flooding in the Upper Midwest illustrated both the cascading of disruptions through infrastructures and cascades reaching far from the original damage zone in ways that are difficult to predict because of the complex connections of built infrastructures (Perenboom, Fisher, and Whitfield, 2001). Climate impacts are likely to increase flooding, wind damage and increased demand for services in areas currently unequipped to handle the new challenges (DEFRA, 2011). Extreme weather events such as hurricanes create direct and cascading impacts within the key infrastructure sectors (DEFRA) 2011 such as:

- Energy (electric power, natural gas)(Rosato, Bologna, and Tiriticco, 2008)
- Water/wastewater (including sewage and sanitation)

- Water distribution
- Telecommunications (wireline, wireless, internet) (Hajsaid, et al., 2010)
- Public health (hospitals, urgent care, nursing homes) (Wheeler, 2011)
- Transportation (ports. road, rail, air including pipelines)

Climate impacts that present specific, identifiable risks to these six sectors of energy and other infrastructures include increases in precipitation, changes in wind (both damaging and as an emerging source of electricity), increased frequency of storms, and higher temperatures (Webster, et al., 2005; DEFRA, 2011).

As indicated above, each of these sectors is interdependent with the others because disruptions within one networked infrastructure will cascade into other infrastructures which may in turn cause further disruptions in a third infrastructure (Brown, Beyler, and Barton 2004). This coupling can provide both a source of resilience and a source of additional vulnerabilities beyond those discovered by examining each infrastructure independently (Peerenboom, Fisher, and Whitfield, 2001).

During this assessment, examples were found of potential impacts of climate change on the six engineered infrastructures and their linkages in addition to evidence that the trend for these linkages is increasing. For example, if weather and climate extremes associated with climate change exceed the designed resistance of a structure, or if resistance has degraded through time, then increased vulnerabilities result. As urban infrastructures evolve to higher degrees of interconnected complexity, the likelihood of large-scale cascading outages are likely to increase as risks to infrastructures increase (President's Commission on Critical Infrastructure Protection, 1997). This outcome in turn leads to higher levels of vulnerability and consequence within urban infrastructures (Brown, et al., 2004). This effect is due in part to temporal and spatial interdependencies that are inadvertently created in an attempt to service changing populations using constrained resources (Warner, et al., 2009).

For instance, reliance upon and integration of Smart Grid technologies and digital control systems places public health, communications, and transportation sectors at increased risk from loss of electric power and in turn power availability increasingly depends on undisrupted communication networks (Energy Sector Control Systems Working Group, 2011), while information technologies are critically important for infrastructure service restoration and recovery. Traffic control is more reliant on communication technology that is dependent on power availability that in turn relies on undisrupted fuel deliveries (DEFRA, 2011). Power outages can cascade through direct damage to the power grid as well as disruptions to control communications, fuel sources, and workers unable to get to work stations (Brown, et al., 2004). Public health and wastewater management tolerate only a couple of hours of power disruption before direct sewage spills are released into public waterways (Chillymanjaro, 2011). Refineries in blackout areas cannot fulfill deliveries to pipelines with impacts to transportation hubs throughout the served region. Fuel deliveries to hospital generators must be restored within 1-2 days to maintain hospital and other lifeline utilities. Loss of power to water distribution systems reduces pipeline pressure allowing infiltration of contaminated sources (Chillymanjaro, 2011). Each networked infrastructure in turn is highly dependent on computerized

Supervisory Control and Data Acquisition Systems (SCADA) that depend on an undisrupted data and information networks (Energy Sector Control Systems Working Group, 2011; Water Sector Coordinating Council Cyber Security Working Group, 2008).

As illustrated by the examples of the 2011 San Diego Blackout, the 2003 Northeast Blackout, (US Canada Power System Outage Task Force, 2004), and Hurricane Irene (Wheeler, et al., 2011), the greatest losses may be distant from the infrastructure where damages started. For example, Hurricane Katrina disrupted oil terminal operations in South Louisiana, not because of direct damage to port facilities, but because workers could not reach work locations through surface transportation routes and could not be housed locally because of disruption to potable water, housing, and food shipments (Myers, 2008).

As illustrated by a Miami case study (section IV D below), interdependent infrastructure cascades occur when failures of components within one infrastructure trigger failures in other, interconnected infrastructures (Brown, et al., 2004). These cascading failures can be either caused or aggravated by regional convergence (which refers to collective business decisions concentrating important infrastructure in small geographic areas or corridors) (DEFRA, 2011). Regional convergence is likely to place more infrastructure assets at or near climate-sensitive environmental features that are particularly sensitive to water availability, water quality, and direct damage from floods, wind and precipitation (Titus and Richman, 2001), suggesting that some separation might be a risk management strategy for the future. The case studies within this assessment showed examples of the close coupling of the direct damages within the power infrastructure cascading to degrade water quality and availability and the resulting difficulties that communities experience in recovering from these events. Power outages lasting more than 12 hours usually result in raw sewage spills degrading coastline water resources and cause loss of water pressure resulting in water supply contamination. These infrastructures placed in environmentally sensitive areas also experience constraints adopting adaptation strategies that require new infrastructure construction or reconfiguration (Titus and Richman, 2001).

As mentioned above, in the 2001 Baltimore Howard Street Tunnel Fire tunnel, a particular, focused disruptive event, not only re-routed truck traffic around Chesapeake Bay but destroyed co-located fiber optic communication cables, causing wide ranging slow-downs and congestion within data and information networks nation-wide. In the movement of key infrastructure to Southwest Florida in the event of sea level rise, regional convergence focuses on points where many important systems link, with significant consequences for other areas of the country in the event of an extreme weather event (Curtis and Schneider, 2011; Federal Railroad Administration, 2005).

Particular infrastructure vulnerabilities

Experience with extreme weather events in the US shows that infrastructures are particularly vulnerable to such events if they are located in areas exposed to such events; they are located at or near especially climate-sensitive environmental features such as coastlines, rivers, storm tracks, and vegetation in arid areas; and/or they are already stressed by age and by demand levels that exceed what they were designed to handle.

A number of federal initiatives have called for new investments in the US portfolio of public infrastructures, recognizing that much of our infrastructure is aged and unable to handle the new capacity demands of increased population and climate initiated stressors (Curtis and Schneider, 2011). Many adaptation strategies examined by interdependency modeling call for additional demand or loads to be handled by alternative paths which are poorly sized or maintained in order to accept the emergency demands placed upon the system. This was a contributing factor to the San Diego blackout where demand for alternative power flows into Southern California were unavailable because of capacity limitations during extreme heat (Keegan, et al., 2011).

4) CHARACTERISTICS OF RESILIENT CONNECTED INFRASTRUCTURES AND URBAN SYSTEMS

Related to such risk management is the concept of climate-resilient pathways (SREX, 2012, IPCC Working Group II, Fifth Assessment Report, Chapter 20, forthcoming). Resilience has emerged into public discourse in the past decade from research literatures on ecosystem stress and response and on emergency preparedness as a positive counterpoint to vulnerability: where vulnerability communicates threat, resilience communicates an ability to respond to threats (a theme in several professional communities for decades: e.g., NAE, 1988).

Resilience is defined as the capacity to anticipate, prepare for, respond to, and recover from significant disruptions (Wilbanks and Kates, 2010); and related literatures associate resilience with such system characteristics as flexibility and redundancy, both physically and institutionally, which in turn are associated with such business concerns as continuity of operations.

While resilience is frequently considered in the context of a sudden occurrence, such as an earthquake or a terrorist event, its consideration in the context of potential climate change impacts on infrastructure is equally salient. It is important to take actions to prevent or limit the negative effects of climate change, but it is equally important to make plans to enhance the resilience of the Nation's infrastructure to climate change and its potential negative impacts. For instance, decision-makers can consider the following factors when assessing climate change risks to infrastructure systems– including physical, environmental, economic and social – and how to configure infrastructure systems so as to improve resiliency.

- *Climate change effects on weather-related phenomena:* how will the frequency and intensity of flooding, tornadoes, droughts, hurricanes, extreme temperature events, and other weather-related phenomena change?
- *Weather-related phenomena impacts on infrastructure systems:* how will the changes in weather-related phenomena impact the function of infrastructures? For example, drought frequency increases may strain water and agriculture systems, greater intensity hurricanes may physically destroy infrastructure systems, and sea level increases may even render some systems inoperable and unable to be repaired.
- *Regional changes in supply and demand for infrastructure systems services:* while climate change may directly impact demand for infrastructure services (e.g., higher extreme temperatures may increase demand for electric power), secondary impacts due to population migration and other phenomena should be

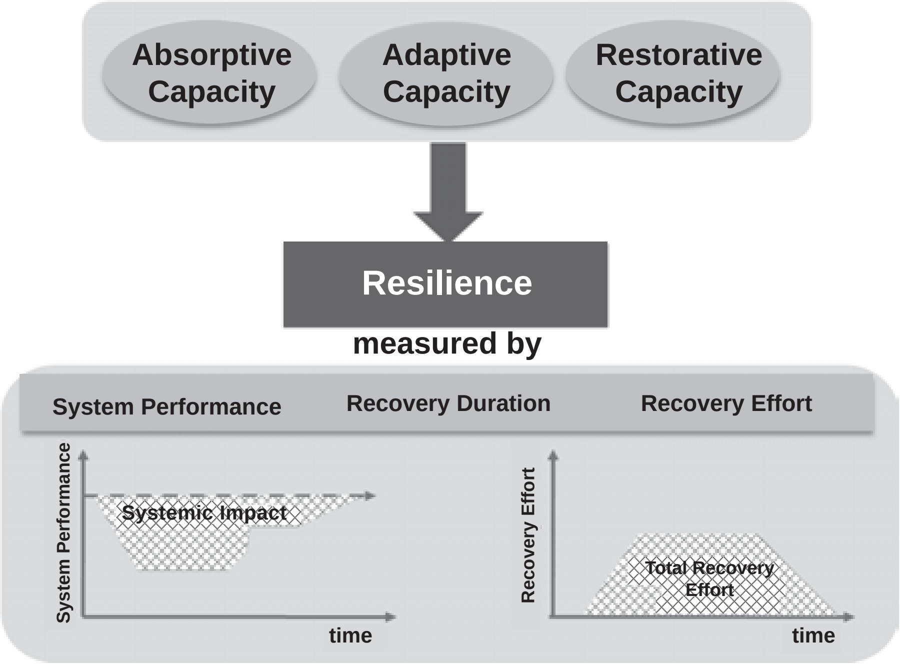


Figure 11 Conceptual illustration of a resilience assessment framework

considered. Supply may also be affected directly (e.g., increased drought could lead to less water availability) or indirectly (e.g., population migration may limit the available work force).

- *Intervention options to enhance infrastructure system resilience:* a comprehensive analysis is needed to determine the entire suite of resilience enhancement options and how to address the challenges facing each infrastructure system. In many cases, it is expected that significant intervention may be necessary to adapt infrastructures to improve their resilience. The possibility of population migration poses a significant challenge as most infrastructure systems are relatively immobile. Decision-makers will need to consider construction of new infrastructure systems or evaluate how to adapt existing ones so that infrastructure services can be provided to new population centers.
- *Time and resource requirements:* each infrastructure resilience enhancement option will require time and resources (e.g. financial, material and human) to effectively implement them. A lack of necessary resources and allocation of them prior to and following a regional or national disaster is frequently a significant challenge faced by emergency planners and responders. Understanding these requirements and related constraints will be essential to initiating planning and response activities aimed at adapting existing infrastructure systems.
- *Prioritization:* planning efforts to enhance infrastructure resilience should prioritize infrastructure adaptation activities so that they can be effectively and

efficiently implemented. Prioritization should consider the expected impact that adaptations may have towards increasing the resilience of infrastructures, resource availability, and time required for implementation.

- An improved understanding of the climate impacts on infrastructure and subsequent changes in supply and demand of infrastructure services, as well as resource constraints, will help provide a higher-level understanding of planning strategies and policy options. As one step in this direction, a prototype resilience assessment approach has been developed (Vugrin et al., 2010; Vugrin and Camphouse, 2011, Figure 11).

One study based on this approach analyzed the resilience of the national petrochemical sector to different hurricane scenarios (Vugrin et al., 2011). Researchers integrated the resilience assessment framework with an agent-based model of the national petrochemical sector to analyze how sector adaptations to hurricane events mitigated impacts and to identify less/more resilient supply chains. This analysis demonstrated that the petrochemical sector was less resilient to a Hurricane Ike- scenario that makes landfall near Houston than a Hurricane Gustav-type scenario that makes landfall near New Orleans. Not only was chemical production more severely compromised in the former scenario, but the cost of adaptations (rerouting chemical shipments; finding materials and supplies from new, more distant suppliers) were also three times larger. In another study, researchers investigated the identification of optimal recovery strategies for freight rail carriers in a hypothetical flooding scenario (Vugrin et al., 2010b). In this scenario four key railroad bridges, located along the northern Mississippi River and which are bottlenecks in the rail network, are assumed to be washed out due to flooding. The study demonstrated that east-west freight rail traffic would be severely degraded in this scenario when bridge repairs are being performed.

D. Assessment Findings

Regarding implications of climate change for infrastructures in the United States, we find that:

- Extreme weather events associated with climate change will increase disruptions of infrastructure services in some locations

  High consensus, moderate evidence

  See Section III A, III C 3, IV D

- A series of less extreme weather events associated with climate change, occurring in rapid succession, or less extreme but severe weather events associated with other disruptive events may be similarly disruptive

  High consensus, moderate evidence

  See Section III A, IV D

- Disruptions of services in one infrastructure will almost always result in disruptions in one or more other infrastructures, especially in urban systems, triggering serious cross-sectoral cascading infrastructure system failures in some locations, at least for short periods of time

High consensus, strong evidence

See Section III A, III C 3, IV D

- These risks are greater for infrastructures that are:
- Located in areas exposed to extreme weather events
- Located at or near particularly climate-sensitive environmental features, such as coastlines, rivers, storm tracks, and vegetation in arid areas
- Already stressed by age and/or by demand levels that exceed what they were designed to deliver

High consensus, strong evidence

See Section III A, III C 2

- These risks are significantly greater if climate change is substantial rather than moderate

High consensus, strong evidence;
also see NCA climate change scenarios
and IPCC SREX 2011

See Section III C 3, IV D

Chapter 4

Urban Systems As Place-Based Foci For Infrastructure Interactions

A. Why The Urban Systems Lens

In considering the implications of climate change for interactions among various kinds of built infrastructure and environments, urban areas are often of special interest, for at least four reasons (SAP 4.6). First, urban areas are nodes where all of the kinds of infrastructures come together in a particular place and are integrated in support of the functions of the urban system; as we know from recent experience with major weather events in the US, this close dynamic interconnection increases potentials for cascading impacts from disruptions. Second, urban areas are where the demands for infrastructure services are concentrated: where infrastructure disruptions have the greatest impacts on comfort, convenience, mobility, and labor productivity for the largest number of people. Third, for reasons having to do with why they developed in those locations, many US urban areas are in areas especially vulnerable to impacts from climate-related extreme weather events, such as coastal areas or river valleys subject to flooding and severe storms. Fourth, urban areas are important more broadly for decision-making about climate change responses; they are where the votes are, the financial centers are, the media centers are, and often vicinities where both university and industrial centers of innovation are located. Urban areas matter profoundly in assessing cross-sectoral interactions among infrastructures (see the NCA Technical Input Report on U.S. Cities and Climate Change).

In addition, working at the scale of urban areas brings many of the more generic assessment issues for infrastructures into focus. For example, cities across the US represent a wide diversity of climate-related threats and circumstances and a wide diversity of distributed/decentralized initiatives in responding to stresses and threats to their economic and social sustainability (see Section II). Consider, for example, New York vs. Miami vs. Chicago vs. Denver vs. Seattle vs. Los Angeles: enormously different contexts, mixes of activities, types and ages of infrastructures, and histories of climate and weather-related disruptions. This diversity complicates any effort to identify generic issues and appropriate responses, but at the same time it offers a wide range of opportunities for learning from experience and for encouraging and benefiting from bottom-up innovations.

B. Overviewing Urban Infrastructure Sectors And Services

Climate change will significantly impact the operation of urban systems defined within specific sectors and services. In most cases the impacts will be negative, but there also will be opportunities resulting from climate change such as reduced wintertime heating demands. This statement briefly reviews some of the sectors and services impacts of climate change, drawing especially on the experience of New York City. The focus is on energy, water and wastewater, transportation, public health, and urban land use and planning (also see II B regarding Boston).

In regard to critical urban infrastructure, degradation of building and infrastructure materials is projected to occur, especially affecting the energy and transportation sectors (Rosenzweig et al., 2011; Wilby, 2007). The gap between water supply and demand will likely increase as drought-affected areas expand, particularly for cities located in the lower latitudes, and as floods intensify (see as example as detailed case study of the Tijuana River watershed: Das et al., 2010). While precipitation is expected to increase in some areas of the U.S., water availability is projected to eventually decrease in many regions, including cities whose water is supplied primarily by meltwater from mountain snow and glaciers (Major et al., 2011). In many coastal cities, critical infrastructure is within areas that are more likely to be flooded with increasing sea level rise and storm surge (SFBCDC, 2011; Cela et al., 2010). Below, some of these significant impacts across several sectors and services are briefly detailed.

1) ENERGY

As climate change emerged as an issue of global concern, some cities prioritized mitigation efforts to reduce energy consumption and their carbon output. Emphasis is now being placed on adaptation and climate resilience as well as mitigation (Hammer et al., 2011). Effects of climate change on the energy sector operations will be felt on both supply and demand. Power plants are frequently located along bodies of water and are therefore susceptible to both coastal and inland flooding. Increased variability in water quantity and timing due to the projected changes in intensity and frequency of precipitation will have impacts on hydropower. The likely increase in heat waves implies more peak load demands, stresses on the energy distribution systems and more frequent brownout and blackouts. These will have negative impacts on local health and local economies. For any given city, analyses are needed to determine the overall impact of climate change on energy demand as it may increase or decrease depending on the balance of seasonal effects, i.e., reduction in energy demand in cooler seasons and increased demand in warmer seasons. In these season shifts, it is generally found that increased cooling demands are greater than the GHG emission reduction created from lower heating demands (Hammer et al., 2011).

For the energy sector, adaptation and mitigation strategies often overlap, and it is critical to put emphasis on adaptation as well as mitigation to help reduce the inevitable impacts of climate change on the energy sector. Specific strategy examples which blend both adaptation and mitigation within the energy sector include the application of demand management programs to cut peak load; updating of power plants and networks to increase resilience to flooding/storm/temperature risks, and diversification of fuel-mix for city power to increase share of renewables. In these cities, scaling up access to modern energy services to reduce poverty, promote economic development, and improve social institutions often takes precedence over climate-related concerns. However, if adoption of these mitigation measures brings greater reliance on renewable sources of energy (including biomass-based cooking and heating fuels), these cities may become even more vulnerable to climate change, since many sources of renewable energy are subject to changing climate regimes.

2) WATER AND WASTEWATER

Cities consistently grapple with maintaining sufficient supplies of fresh drinking water and managing excess water from flooding as well as handling waste water and sewerage flow (Major et al., 2011). Urban water and wastewater systems can come under great stress as a result of climate change. Both the quantity and quality of the water supply will be significantly affected by the projected increases in both floods and droughts (Aerts, et al., 2009; Case, 2008; Kirshen, et al., 2008), as climate change shortens the return frequencies of extreme weather events. Within cities, impervious surfaces and increased precipitation intensity can overwhelm current drainage systems. As climate continues to change, both formal and informal urban water supply services will be highly vulnerable to drought, extreme precipitation, and sea level rise. Moreover, air temperature increases will affect temperatures of receiving waters. Long-term planning for the impacts of climate change on the formal and informal water supply and wastewater treatment sectors in cities is required, with plans monitored, reassessed, and revised every 5–10 years as climate science progresses and data improve (Major et al., 2011).

Several significant adaptation and mitigation strategies – often with co-benefits - are available for the water and wastewater sector which make these systems more resilient in the face of increased supply and function stress (Kirshen et al., 2008; Nelson et al., 2009). In regard to immediate adaptation strategies, programs for effective leak detection and repair and the implementation of stronger water conservation/demand management actions – beginning with low-flow toilets, shower heads, and other fixtures – should be undertaken in formal and, to the extent relevant, informal water supply systems (Rosenzweig et al., 2007). As higher temperatures bring higher evaporative demand, water reuse also can play a key role in enhancing water-use efficiency, especially for landscape irrigation in urban open spaces (Major et al., 2011).

3) TRANSPORTATION

Transport-related climate risks that a city faces are contingent on its unique and complex mix of transportation options (Wilby, 2007). The location of transportation systems either at ground level, underground or as elevated roads and railways changes the impacts of different climate variables, particularly to flooding (Prasad et. al., 2009). Tunnels, vent shafts, and ramps are clearly at risk. Flooding necessitates the use of large and numerous pumps throughout these systems, as well as removal of debris and the repair or replacement of key infrastructure, such as motors, relays, resistors, and transformers. Besides sea-level rise and storm surge vulnerability, steel rail and overhead electrical wire associated with transportation systems are particularly vulnerable to excessive heat. Overheating can deform transit equipment, for example, causing steel rail lines to buckle, throwing them out of alignment, which potentially can cause train derailments (Mehrotra et al., 2011). Heat can also reduce the expected life of train wheels and automobile tires. Roadways made of concrete can buckle or “explode” and roads of asphalt can soften and deteriorate more rapidly.

Whether a city's transportation system moves mainly people or whether it tends to transport large volumes of goods also affects the risks associated with climate change. Climate impacts on power and telecommunication systems can create additional risks in the transportation network. Furthermore, transportation systems can play a key role in climate change mitigation, such as the adoption of energy-efficient taxis, and enhancement of public transportation systems with accompanying reduction in individual vehicle miles traveled.

4) PUBLIC HEALTH

Cities are subject to demanding health risks from climate change since larger and higher density population amplifies the potential for negative outcomes (Barata et al., 2011; Barreca, 2010; English et al., 2009). Climate change is likely to exacerbate existing health risks in cities such as poor air quality (Jacob and Winner 2009) and to create new ones. Increases in the number of poor and elderly populations in cities also compound the threats of heat and vector-related illnesses (O'Neill, 2009; Gosling et al., 2009; Balbus et al., 2009; Bartlett et al., 2009; Luber and McGeelin, 2008). Cities with stressed existing water services are at a greater risk of drought (Reid and Kovats, 2009). Heat waves add further stresses, especially for the poor and disadvantaged. Other significant health related issues can arise with sea level rise and increased flooding in coastal zones (McGranahan et. al., 2007).

Since the infrastructure for health protection is already overburdened in many country cities, climate change adaptation strategies should focus on the most vulnerable urban residents (O'Neill et al., 2010). Adaptation and mitigation strategies associated with public health issues in cities are integrated with strategies for other sectors and services (Frumkin et. al., 2008; WHO, 2009). Such strategies need to promote "co-benefits" such that they ameliorate the existing and usually unequally-distributed urban health hazards, as well as helping to reduce vulnerability to climate change impacts (Barata et. al., 2011; Bell et. al., 2007). For example, efforts to reduce urban heat islands by passive approaches such as tree planting, green roofs, and permeable pavements will promote positive health outcomes as well as energy savings associated with reduced air conditioning use (Stone et al., 2010; Hamin and Gurran, 2009; Bell et. al., 2007). Other public health adaptation strategies include: improve water and energy service, regulate settlement growth in flood plains, and expand health surveillance and early warning systems utilizing both technology and social networks.

5) URBAN LAND USE AND PLANNING

Urban land use can modify climate change vulnerability through awareness of natural setting, design of urban form and the built environment, and active reduction of the extent of the urban heat island effect (Blanco et. al., 2011; Ntelekos et al., 2010; Blanco and Alberti, 2009). Cities can enhance their adaptive capacity to climate change through their urban land management, which includes the legal and political systems, planning departments, zoning regulations, infrastructure and urban services, land markets, and fiscal arrangement. The effectiveness of urban planning and management of climate change response is highly dependent on coordination, since many metropolitan areas are politically fragmented. Smaller and mid-sized cities often have additional burdens of lacking extensive human and capital resources (Leichenko et al., 2010). In other situations, development pressures to build on lands highly vulnerable to climate change, such as along coastal zones, is still strong (Titus et al., 2009). A variety of reasons have been defined as to why specific cities act progressive to address climate change risk and adaptation opportunities (Brody et al., 2009). One important factor is whether or not other near-by cities are engaged in climate action (Brody et al., 2009) – the local capacity to translate climate science into public policy (Krause, 2011; Corburn, 2009).

Several adaptation and mitigation strategies have been identified which reduce risk exposure and vulnerability or promote energy use reduction, and in some cases both (Buckeley, 2010; McEvoy et al., 2006). Some of the strategies include relatively small scale adjustments to existing codes and regulations such as changing building codes and land regulations to reduce damage from climate change hazards e.g., elevating buildings in flood-prone areas, reducing energy use for heating and cooling, and increasing urban trees and vegetation to reduce the heat island effect (Condon et al., 2009). Other potential strategies involve more transformative shifts many of which have been presented within the hazard mitigation literature (Solecki et al., 2011; SREX, 2011). These include reducing sprawl by increasing population and building densities, mixing land uses to reduce automobile traffic, and increasing use of public transit, and restricting land use in areas subject to climate change impacts such as sea level rise and riverine flooding (Hamin and Gurran, 2009). Overall, the success of these efforts can be negatively affected by the level of fiscal stress that communities experience from long-term economic decline or from the loss of revenue experienced by the financial crisis of 2008 (Leichenko et al., 2010).

C. Vulnerabilities Associated With Infrastructure Interdependencies In Urban Systems

One of the chief functions of urban infrastructure services is to attempt to isolate human settlements from climate influences. Examples include air conditioning in hot weather, heating in cool weather, water from taps and electrical energy from outlets inside our buildings, roads that are functional in most types of weather, and toilets that flush wastes from inside our buildings. To provide these services, infrastructure must be designed to meet climate standards, such as 10 year precipitation conditions, low stream flows, and high and low temperatures. Therefore, as the climate changes, the services provided by infrastructure will change. Much infrastructure, particularly for water management, is also dependent upon ecosystem services. Wastewater management relies upon in-stream organisms to degrade wastes; flood management utilizes wetlands to mitigate impacts and stress; and other urban vegetation improves urban drainage. Therefore as ecosystems respond to climate change, infrastructure will also be impacted by that response. Infrastructure demands are also dependent upon climate. As temperatures increase, more air conditioning and energy are needed. Water demand also increases under higher temperatures. Thus urban infrastructure is impacted by a myriad of climate influences.

The various types of urban infrastructure also form an interacting web such that the potential exists for disruption of one type of service if another is disrupted. Because of the hydrologic cycle, the various types of infrastructure most closely tied together are related to water and wastewater management. For example, if storm water can be managed through increasing infiltration through the surface, then drainage, water quality, and water supply can be improved.

There are also ties of water infrastructure to other types of infrastructure. Of these, the most widely researched is the energy-water nexus. For example, if water demands decrease, energy demands will also decrease because there will be less water to supply and wastewater to treat. Another well-known interaction is the impacts of impervious road networks on local drainage and water quality. Floods and intense precipitation events can disrupt most infrastructure systems.

Non-water infrastructure systems also interact. Communication networks rely upon energy to relay information, some of which is used to manage the energy sources. Transportation networks require energy and also transport some energy sources.

These interactions present management challenges but also opportunities for adaptation because if impacts on one type of infrastructure can be managed, then other infrastructure systems may benefit if the adaptation is well planned. Unfortunately, management structures for infrastructure do not reflect the interaction of some types of infrastructure and these opportunities for adaptation may be lost.

Infrastructure and its users can involve both increasing and decreasing vulnerabilities due to climate change, but increasing vulnerabilities are of concern then they involve flooding associated with rising sea levels and intense precipitation as well as persistent heat from rising temperatures, and there are other outcomes also such as wind damage. Infrastructure design, operation and use have to adapt to these conditions by combining characteristics of infrastructure with underlying population characteristics that contribute to vulnerability. The following patterns and trends are contributing to the vulnerability of infrastructure and its users.

Related to a number of different driving forces according to the sector, the concentration of infrastructure in the US often tends to be increasing in many areas. For example, about half of the nation's oil refineries are located in only 4 states, about half of the electric power plants are located in only 11 states (Zimmerman, 2006, pp. 531-532), and a large percentage of roadway travel and transit trips occur in and around only a few metropolitan areas. Within urban areas, transfer points and intersections reflect even greater concentrations of transportation infrastructure and activity (INRIX, Inc., 2011) and in and around urban areas distribution systems for electric power and water are similarly concentrated where relatively few transmission lines connect resources to urban areas. Where such concentrations are co-located with areas of climate change impact vulnerabilities, infrastructure vulnerabilities are affected as well.

Meanwhile, people are concentrated and are continuing to concentrate in areas where coastal and inland flooding is a threat (Zimmerman, 2012); for example, according to Wilson and Fischetti, (2010, p. 3), between 1960 and 2008 population increased by 84% in coastal counties compared to a population increase of 70% nationwide. Moreover, population density in coastal counties is twice the density in non-coastal counties, and density in coastal counties increased faster than in non-coastal counties between 1960 and 2008 (101% vs. 62% when Alaska is included) (Wilson and Fischetti 2010, p. 11). Regardless of coastal location, sprawl is still rampant with smaller areas growing at a faster rate than population in the suburbs in and around metropolitan areas (U.S. Census Bureau, March 2011). These suburban areas are also potentially vulnerable to the outcomes of climate change, since they may have very few alternatives should conventional infrastructures become impaired.

Vulnerable populations need to be identified, and strategies to address their infrastructure needs must be developed not only for conventional infrastructure but also innovative infrastructure that will help to adapt to and reduce the impacts of climate change (see section IV below).

D. Infrastructure Interdependencies And Cascading Impacts: A Case Study

This section illustrates, through a case study in South Florida commissioned for this NCA technical report, how impacts and vulnerability to extreme weather events would change as built infrastructures evolve in response to climate and non-climate drivers. The selected weather event is a hypothetical category 5 hurricane landfall near Miami. We examine the impacts derived from infrastructure models in 2010 and compare those impacts to those forecasted in 2030 from a hurricane of similar intensity and landfall point. The difference in the observed impacts are derived from population movements from forecasted sea level rise in the Miami area and population migration patterns that might be disrupted in the process. Built infrastructures will evolve within a different pattern based on people and economic activity being found in different locations than they were found previously. Changes in the impacted areas will increase the vulnerability of some infrastructure sectors and decrease the vulnerability in others that may evolve to more resilient configurations.

1) THE STUDY AREA – CURRENT IMPACTS AND FUTURE EVENTS

Extreme weather events associated with climate change affect communities disproportionally that have high population density, aging infrastructures, outdated building codes, insufficient reactive power, lack of coordination among system protection agents, ineffective communication, and untimely warning systems (US Canada Task Force, 2004).

Extreme events such as a hypothetical category 5 hurricane landfalling near Miami and causing widespread and persistent outages in energy, waste water and water distribution, telecommunications, public health, and transportation have been projected as plausible (NISAC, 2011) possibly with increasing frequency. Correlations have been established between rising sea levels, and more frequent and intense storms in the US (Meehl et al., 2007; Travis, 2010). Hurricane Andrew, for example, which reached landfall in southern Florida in August 1992 as a Category 5 hurricane (Miami Hurricane Scenario Analysis Report October, 2011), was projected to produce a storm surge exceeding 12 feet of flooding in some areas, which would cause about 1.1 million people to experience more than 1 foot of storm surge. This effect approximates an extreme sea level rise event such as described within the case study that, if realized, could inundate large areas of the southeastern Florida coastline resulting in infrastructure damage with increasing frequency, initiating population movements. Economic damage, unstable

Table 5. Illustrative depiction of interdependencies among infrastructures in the Miami case depending on infrastructure design features and the location and timing of sector disruptions

	Electric Power	**Natural Gas**	**Petroleum**	**Water Communications**	**Distribution**	**Transportation**	**Public Health & Sanitation**
Electric Power	N/A	Strong	Medium	Strong	Strong	Weak	Strong
Natural Gas	Strong	N/A	Low	Strong	Weak	Weak	Weak
Petroleum	Strong	Weak	N/A	Medium	Weak	Strong	Strong
Communication	Strong	Strong	Strong	N/A	Strong	Medium	Strong
Water Distribution	Strong	Weak	Weak	Strong	N/A	Weak	Strong
Transportation	Medium	Medium	Strong	Medium	Weak	N/A	Strong
Public Health & Sanitation	Strong	Weak	Medium	Strong	Strong	Strong	N/A

coastlines, and population shifts during and after extreme weather events are forecast to increase continuously in the coming decades (Zhang et al., 2000). As climate conditions change, populations shift, and requirements for power increase; infrastructure is likely to evolve to accommodate demand, and simultaneously to prevent risk to human welfare such as described within this case study.

Extreme weather events such as hurricanes create direct and cascading impacts within key infrastructure sectors such as those listed on page 32 (Table 5). These sectors are interdependent within the described case study in that disruptions within one networked infrastructure will cascade into other infrastructures which may in turn cause further disruptions in a third infrastructure, adding up to far more vulnerabilities than would be discovered by examining each infrastructure independently. This coupling can provide both a source of resilience and a source of additional stress. Infrastructures will evolve and their interdependencies will change in reaction to climate drivers as the networks expand into new population areas and as portions of the networks are abandoned as people leave environmentally and economically degraded locations. Event drivers and asset specific vulnerabilities include changes in temperature, precipitation, population, frequency of extreme storm events and sea level rise. Population migration

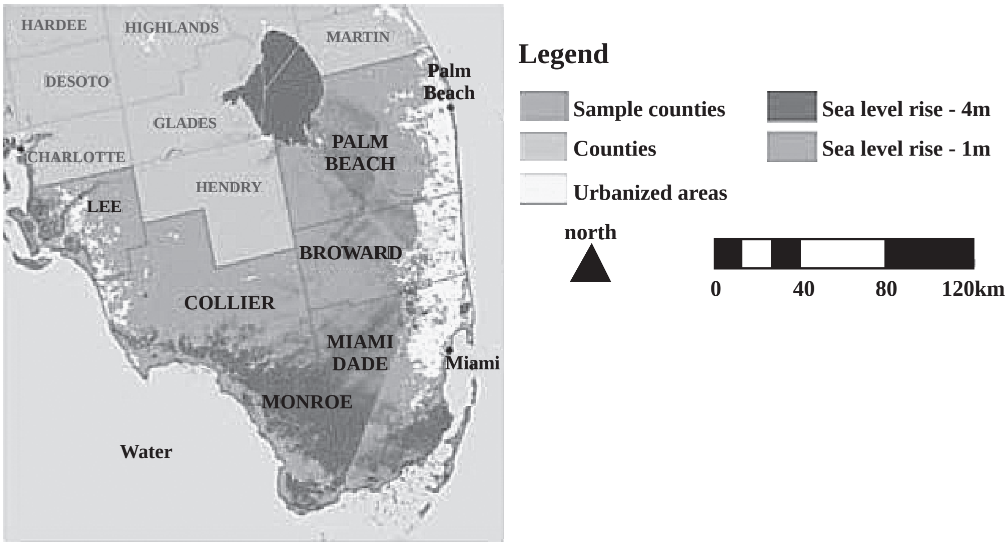


Figure 12 Curtis and Schneider, 2011, map the vulnerable parts in the study area to 1 meter and 4 meter sea level rise

in response to both sea level rise and increased frequency of extreme events is likely to occur or, more likely, migrating persons that would normally choose destinations in impacted areas will select alternative destinations. These displaced populations create new demand for built infrastructure that in turn generates new economic activity that attracts new workers and associated households to the new locations. This movement then becomes a motivating driver for regional convergence that concentrates vulnerable nodes in constrained geographic locations.

In this case study we consider sea level rise-driven migration between now and 2030 in South Florida following the methodology of Curtis and Schneider, 2011. The second form of sea-level rise is potential flooding associated with major storms or hurricane events. This type of inundation is likely to be more extreme and to affect a greater area than the case above and may be temporary or permanent in its impact. In Figure 12 above, Curtis and Schneider (2011) map the vulnerable areas in the study area to 1 meter and 4 meter sea level rise. The six-county Florida case study encompasses an area with significant risk to human populations. Miami-Dade has rates of net in-migration during the last five years greater than 17% compared to the national average of 11%). The majority of the 6 million people in the region live in the greater Miami metropolitan area, Fort Lauderdale, or Palm Beach. Places with fewer resources may be less equipped to respond effectively compared to places with greater resources. The resulting forecasts are based on trends for the projection horizon given status quo population change, assuming that the current rates of natural increase and migration will continue for all counties through 2030. In this simulation, population impacts extend to both nearby and distant counties through out-migration streams.

The population implications, however, are not restricted to inundated counties because counties directly impacted by sea-level rise are connected to other places through

Table 6. Movement of population and associated power demand under 1 meter sea level risk scenario

County	Population in 2030 (customers)	Percent of power demand (GW)	Population in 2030 (customers)	Percent of power demand (GW)	Population without migration	Change from straight line assessment (million people)
Palm Beach	2,051,141 (932,336)	20.5 (2.3)	1,320,134 (600,060)	18.3 (1.5)	1,549,400	+0.5
Broward	2,600,197 (1,529,527)	33.6 (3.8)	1,748,066 (1,028,274)	31.4 (2.5)	1,903,000	+0.7
Miami-Dade	1,220,317 (610,158)	13.4 (1.5)	2,496,435 (1,248,218)	38.2 (3.1)	2,854,000	1.6
Monroe	 (30,885)	83,390 (0.8)	0.7 (29,468)	79,566 (0.07)	0.9	75,500 min.
Collier	684,491 (342,245)	7.5 (0.9)	315,839 (157,919)	4.8 (0.4)	728,900	min.
Lee	3,325,802 (1,108,600)	24.4 (2.7)	618,754 (206,251)	6.3 (0.5)	948,900	+2.4
Total	9.965,338 (4,553,747)	100 (11.3)	6,578,794 (3,270,190)	100 (8.1)	8,059,700	+2.0

migration streams. Inundation not only dislocates human populations, but restructures existing migration networks. Such restructuring increases immigration to places that currently receive minimal immigration from impacted counties, forms links to entirely new destinations, and eliminates some migration streams. People impacted by sea-level rise will be forced to relocate to new areas and potential immigrants to impacted counties will have to move to alternative destinations. Some of the most popular receiving and sending counties will also experience a loss of inhabitable land due to sea-level rise; among them counties for out-migrants that would be coming from inundated areas. Migrant streams connecting two inundated counties will no longer be viable, thus compounding the impact of climate change-related inundation (Figure 13). Using the 2030 population estimates in Curtis and Schneider, 2011, we estimated impacts on the built infrastructure based on projected population increases through business as usual with migration, and the associated gigawatts of annual average power consumption (Table 6), although we recognize that peak consumption is often a more significant issue than average consumption. Although it is unlikely that infrastructure and public services would support such a large population increase into Lee County, we may see a change in immigration networks that would select unanticipated destination counties. Orange and Hillsborough counties might absorb more Miami-Dade out-migrants, or connections to new destinations might develop. Similarly, Miami-Dade might see shifts in in-migrants

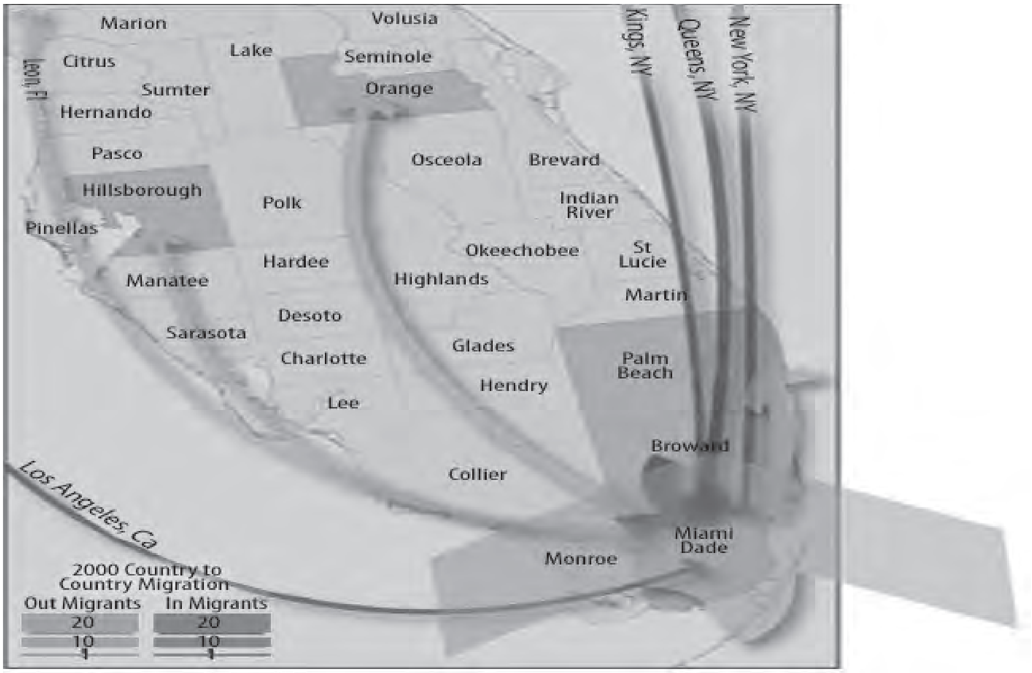


Figure 13 Historic migration trends into the Miami area (dark) could be reversed in the event of disruptive extreme weather events in Miami (light)

from New York state and Los Angeles to alternative destinations, perhaps outside of the state of Florida. The potential reach of impacts can inform efforts to coordinate local area responses to include areas geographically distant from those directly impacted by environmental shocks, but indirectly affected through social relationships, as shown by migration streams such as those hypothesized by Curtis and Schneider, 2011.

Using these changes we can forecast the trends of vulnerability to the hypothetical hurricane event before and after the anticipated sea level rise, taking into account the regional convergence created by land use and other driving forces in South Florida. Box 2 considers possible approaches for estimating economic costs of such interdependent infrastructures and their impact on risk assessments.

During the hurricane event, wind and rain impairs adjacent distribution power lines, resulting in power outages. Increased precipitation could also affect many substations and generating plants in the Miami area, along with assets inland. If these facilities are flooded, individual component sustain damage. A three-foot or greater inundation of a typical substation renders a substation out of service

Before sea-level -rise, Miami-Dade and Broward counties on the east side and Collier and Monroe counties on the west side of southern Florida and the Keys will experience near complete power outages. About 4.6 million people live in the area where electric power damage is expected to be 100 percent. Approximately 90 percent of outaged customers would have power restored in less than 26 days and 80 percent in less than 22 days, depending substantially on storm surge effects. After sea-level rise, substations will be built to accommodate greater populations on the west coast. The power outages

BOX 2

Economic Approaches to Population Migration and Infrastructure Risk Assessment

Much of the risk associated with infrastructure vulnerabilities is linked to populations who are seeking different economic opportunities and with portions of existing networks that are abandoned in favor of newly constructed infrastructure networks. Some of these drivers are the ate to other areas. The "unaffected" population and industries in the areas may generate increased demand for transportation to provide the goods no longer locally produced. A description of this risk associated with climate-induced drought conditions between 2010 and 2050 is found in Backus, 2010. The analysis simulates the U.S. economy across individual states and 70 industry categories that encompass all economic activity.

The analysis shows that some states are more affected than others. The Southwest experiences drought conditions in almost all cases. Companies and laborers migrate from more distressed states to relatively less affected states, such as California. Although an analysis of California in isolation would show negative impacts from climate change, the net economic impacts are positive. Similarly, areas like New Mexico and Arizona are relatively resilient to drought due to their already arid environment. The impacts there are less than what might be expected given the larger changes in water availability. On the other hand, areas of the Southeast already have the demand and supply for water at comparable values with minimal capacity to accommodate significant changes in supply. Relatively modest climate impacts have correspondingly larger economic impacts. The result could be migration from the Southeast to the Northeast, where a similar water balance exists, but the climate has less impact on water supply.

The total risk across all the states, over the 40 years, was estimated at a little over $1 trillion, with a job loss of approximately 7 million labor-years. Although the information is shown at a state level, it is the businesses within each state that largely experience the impacts. Impacts on the population are largely through the industry impacts. While this total risk through 2050 is a small fraction of the economy, the analysis illustrates how an integrated risk assessment that includes population migration and the changing demand for infrastructure services can inform decisions about climate adaptation and accommodating climate impacts. It also highlights how the impact from uncertain climate conditions will only add to this value, and that the much more significant changes in climate beyond 2050 represent a much larger risk.

in Miami-Dade will likely result in longer restoration times as resources are diverted to less-damaged circuits serving greater numbers of customers to the west. Miami-Dade customers will likely endure outages that extend closer to 26 days than to 22 days. Power outages impair hospital operations through essential systems, such as life support equipment, computerized medical records, and laboratory operations. In addition, pharmaceutical products and food will require ice shipments to replace loss of refrigeration. Most hospitals have backup generators; these generators require re-fueling dependent on inundated surface routes. Eastern roadways will suffer temporary flooding of over four feet of water.

In the 2030 scenario, refueling routes are likely to depend on new and better maintained routes refueling from the west with more critical bottlenecks coming into the urban areas from Lee and Collier County.

Power outages degrade communication with ambulance dispatchers, delaying emergency treatment. At cellular towers, a power outage longer than four hours drains backup batteries. Services would continue to deteriorate after four to eight hours and cellular towers and small wire centers will fail. Without portable generators or mobile base stations, cellular services degrade after eight hours without power. Larger wire centers continue to function for two to three days on the fuel reserves present onsite. Currently, communication restoration use satellite phone service until regular service can be restored.

In the 2030 scenario, communications would be restored first in the western counties and more slowly restored in the Miami-Dade area further slowing restoration in the most damaged areas within the east coast counties and taxing the availability of emergency phones and radios in the eastern damage zone.

Wired telecommunication outages are projected to be caused by subsurface inundation and to be aggravated by power systems failures, flooding or wind damage to pole-mounted telecommunications systems. In the 2010 scenario, fifteen wireline centers, which serve 413,000 households, are expected to be out of service. Two additional mobile switching centers in the Miami area are in the surge zone, along with 12 wire centers that provide competitive exchange service.. Beyond the surge zone are stationed an additional 51 wireline centers serving approximately 1.3 million households in the high electric damage area. In the 2010 scenario, a similar number of households located further west would likely lose service, but would be restored more rapidly since they would be located in a less intense damage area.

Water and wastewater treatment systems failures pose the most significant threats to public health. Prolonged outages to the power and data communication infrastructures increase water supply treatment requirements and increase flood losses from contaminated floodwater. Restoring disrupted facilities will involve major cleanup, repair of small motors and transformers, and clean up and repair of major electrical equipment. It is also possible that these wastewater treatment plants will be overloaded during flooding. If this occurs, wastewater may have to be diverted around the facility, bypassing the treatment facility protocols and resulting in untreated discharge. Analysis of potable treatment facilities identified 36 water treatment facilities in the high electric damage area, indicating a higher likelihood of power disruption to these facilities. Analysis of wastewater treatment facilities identified 14 wastewater treatment facilities with a higher likelihood of power disruption to these facilities. One of the facilities in any damage zone was identified as being a large treatment facility, processing more than 200 million gallons/day (MGD). In the 2030 scenario, discharges from this facility would likely be released to the more economically sensitive Gulf of Mexico than the Atlantic Coast, which would result in significantly increased economic risks.

2) RISK IMPLICATIONS

As illustrated in the brief case study illustrated here, as sea level rise and other climate impacts cause both infrastructures to adapt to new environmental conditions, and people to change locations in response to both environmental and economic drivers; new points of resilience and new vulnerabilities are created in different locations with obscure unanticipated effects. Because infrastructure systems are complex systems of systems, study is suggested about the unanticipated couplings and interactions caused by new mitigation and adaptation strategies

E. Emerging Leadership In Adaptation/Resilience Enhancement

Finally, urban areas matter profoundly in the fact that a number of cities are becoming the nation's leaders in exploring adaptive strategies for infrastructure systems threatened by environmental and other stresses (see section VI regarding risk management strategies below).

F. Assessment Findings

Regarding implications of climate change for urban systems in the United States, we find that:

- Urban systems are vulnerable to extreme weather events that will become more intense, frequent, and/or longer-lasting with climate change

  High consensus, strong evidence

  See Section IV A, C, D

- Urban systems are vulnerable to climate change impacts on regional infrastructures on which they depend

  High consensus, strong evidence

  See Section IV A, C, D

- Urban systems and services will be affected by disruptions in relatively distant locations due to linkages through national infrastructure networks and the national economy

  High consensus, strong evidence

  See Section III C 3

- Cascading system failures related to infrastructure interdependencies will increase threats to health and local economies in urban areas, especially in locations vulnerable to extreme weather events

  High consensus, moderate evidence

  See Sections III C 3, 4
  Section IV C, D

- Such effects will be especially problematic for parts of the population that are more vulnerable because of limited coping capacities

  High consensus, strong evidence

  See Section III C 2 and IV C

Chapter 5

Implications for Future Risk Management Strategies

A. Overview

Although risks to infrastructures and urban systems from climate change are significant, especially if climate change is substantial rather than moderate, risk management strategies offer impressive prospects to reduce those risks and thereby reduce the likelihood of disruptive impacts in the future.

Most of the attention to risk management for infrastructures has been infrastructure-specific, such as (TRB, 2008, SAP 4.5, 2005), although the need for a more integrative systems approach is widely recognized (see Section VI below).

The major exception to date has been initiatives by some cities to promote integrated "green infrastructure" strategies, in some cases pursuing synergies between cli-mate change adaptation and climate change mitigation (Box 2). These innovative programs offer examples of efforts to convert infrastructure systems from inflexible constraints on adaptation to leaders in making urban systems (and, in principle, other infrastructure systems) more adaptable overall. Two leading examples are Philadelphia and New York City:

1) PHILADELPHIA

In 2006, the Philadelphia Water Department began a program to develop a green stormwater infrastructure, intended to convert more than one-third of the city's impervious land cover to "Greened Acres:" green facilities, green streets, green open spaces, green homes, etc., along with stream corridor restoration and preservation. This *Green City, Clean Waters* program is being implemented over the next 25 years without the expenditure of billions of dollars on new pipes, tunnels, and treatment systems, in part due to leveraged funding from the development community as a part of every new development project. In the process, it has catalyzed the development of a Model Neighborhoods program to encourage broad-based community participation in greening the city of Philadelphia.

2) NEW YORK CITY

As a part of its comprehensive, participative PlaNYC effort, New York City has developed an extensive program to increase the resilience of its built and natural environments and to protect its critical infrastructures, in part to respond to concerns about climate change (see case study below). Among its many components are plans to protect the city's coastal areas, to reduce the urban heat island effect, and to improve emergency management. Plans include "Greener, Greater Communities," increasing green spaces, improving the sustainability of waterways and wetlands, increasing the efficiency of water supply systems and increasing water conservation, implementing a Greener Buildings Plan, increasing the use of solar power, and developing a smarter and cleaner electric utility grid, with a commitment to invest $1.5 billion in implement the Green Infrastructure Plan.

3) OTHER CASES

Portland's multi-agency planning and budgeting processes offer one possible model in which key goals are identified and then expressed in the budgets and priorities of each agency. Tucson, which recently linked its land-use planning to water planning, offers another example.

Milwaukee, for example, has spearheaded creation of a nonprofit trust that includes multiple cities along shared watersheds to jointly plan and implement stormwater management strategies. A water agency in Portland that needed to meet water temperature standards in obtaining a combination of 5 wastewater and stormwater permits clustered these permits together and, rather than investing $60 million in refrigeration systems, paid farmers to plant vegetation and trees along 37 miles of adjacent stream banks outside the city to meet its temperature requirements

Seattle has an extensive green stormwater infrastructure (GSI) program, which enables flexible responses and strategies in response to such challenges as climate change.

Just South of Tucson, the Sonoita Valley Planning Partnership provides a multi-stakeholder governing board to set goals and implement shared strategies across federal, state trust, and nonprofit lands.

Some stormwater utilities have pegged their stormwater fees to amount of impermeable surface rather than to road frontage or square footage, as a better reflection of runoff into stormwater systems.

These cases and others suggest several lessons in moving toward more adaptable infrastructures and urban systems:

- Potentials for green infrastructures, based on conceptions of infrastructure as a dynamic, changing, focus of innovation, are often underestimated, at least where current regulatory/engineering practice rules permit innovations
- Attention to standards, codes, certification programs, and other administrative structures that set rules for infrastructure design and construction can be a way to reduce barriers and open up opportunities. Guidelines for building design and building rehabilitation can be revisited to consider how projected climate changes can be accommodated: e.g., sizing HVAC systems and culverts
- Risk-resilient infrastructures often involve thinking about optimization in new ways. Being able to respond to changes in climate-related stresses and possible climate-related surprises calls for increasing the value attributed to such characteristics as flexibility and redundancy which in stable short-term optimization modeling may be considered wasteful.
- Green infrastructures can often be pursued through partnerships between the public sector, the private sector, and communities in ways that reduce their net

cost to taxpayers. Note, for example, a 2010 by the World Economic Forum, *Positive Infrastructure: A Framework for Revitalizing the Global Economy* (2010) and a statement by the Insurance Institute for Business & Home Safety in 2011: "The Mutual Benefits of Business Continuity and Community Resilience."

- Where classes of infrastructure are toward the end of their lifetimes, or performing poorly under growing demand, so that changes are going to be required, there are often windows of opportunity to do the new things in ways that are adaptable rather than inflexible and even maladapted to future climate changes.
- Leadership and effective governance are virtually always essential to the development and execution of effective green infrastructure strategies (also see NCA technical impact report on US Cities and Climate Change

One underlying theme is that risk management strategies often involve both structural approaches (focused on physical structures themselves) and non-structural approaches (focused on how physical structures are operated, including rules and guidelines, operating protocols, and innovative management).

Meanwhile, new tools are emerging. For example, the Institute for Sustainable Infrastructure has created Envisionm a system for rating the sustainability and resilience of infrastructure to climate change which directs attention to such issues as changes in environmental extremes during an infrastructures lifetime and its location in exposed areas.

Issues in realizing potentials identified by the workshop discussion for this report include:

- Prospects for bundling climate change responses with other sustainability issues, e.g.: multi-hazard resilience, infrastructure asset management planning, business continuity, ecosystem protection
- Assistance with risk/vulnerability assessments to enhance resilience
- Opportunities for citizen service that may be met in less capital-intensive ways
- Adapting strategies to differences in local hydrologic regimes
- Approaches for spurring innovation
- Addressing issues regarding funding, e.g.:
    - Different capital dynamics by infrastructure type
    - Recalibrating pricing structures
    - Finding smart approaches that are less expensive
- Relationships between climate change adaptation and climate change mitigation offer opportunities for synergies (Box 3).

One part of the equation is the method and means by which a community is designed and built has a major impact on its contribution to climate change and on its ability to prepare for and adapt to changes in the climate.

- Compact development that uses land efficiently uses fewer resources to build and operate and enables people to get around easily with less driving or without

BOX 3

Relating Adaptation And Mitigation

Built infrastructures are among the most salient of all cases where climate change responses touch on both adaptation and mitigation, because the infrastructures usually have direct connections with both reducing vulnerabilities to climate change and with emissions of greenhouse gases that are a cause of climate change. Especially prominent examples include energy, transportation, industry, and building infrastructures.

In these cases, there are opportunities to explore synergies between adaptation and mitigation in considering infrastructure designs, operations, and overall strategies – as contrasted with adverse effects of one focus on the other. It is very useful, when actions related to mitigation are being considered, to ask: what are the effects on adaptation? And the converse.

In many cases, because the answers are not always perfectly clear, it is useful to consider incorporating monitoring and evaluation elements in an infrastructure development strategy in order to learn from experience about effects and how to enhance positive outcomes. Such an approach, related to iterative learning, benefits from infrastructure strategies that are innovative in that they are flexible, able to adjust to new information about emerging climate change impacts and experience about payoffs from alternative responses.

In discussions of these kinds of issues, a major gap in the availability of information about both options and current activities is an inability to track what is happening in the private sector, where many strategies and actions are related to perceptions of competitive advantage in the marketplace. It would be valuable to stimulate discussions with private sector institutions and the associations that represent them to find ways to assure that the continuing national climate change impact and response assessment process is informed, at least in a general way, about this extremely important part of the bigger national picture.

driving at all. Communities that avoid building new infrastructure for far-flung, disconnected developments can use their limited funding instead to keep existing infrastructure in good repair. In addition, shorter water pipes mean less drinking water lost to leaks, which will become even more important as water supplies become strained.

- Communities with a mix of land uses and multiple transportation options, including public transit and streets that are safe for walking and biking, can help residents drive less, which reduces GHG emissions. Street networks laid out in a grid pattern reduce congestion by giving drivers alternate routes, which reduces time spent idling. Co-benefits include health benefits from reduced air pollution and from increased physical activity.
- Energy- and water-efficient buildings also reduce GHG emissions, but they also are important for adapting to the changing climate. In a heat wave, fewer people might die if it were more affordable to cool their homes. Homes with water-efficient fixtures help reduce pressure on water supplies in a drought.

- With the projected increase in precipitation events in much of the country, green infrastructure could be important as a way to help manage the increased storm water flows without having to build expensive new "gray" infrastructure. In addition, green infrastructure like street trees and green roofs can mitigate the heat island effect, which can help reduce the cooling load for buildings. Other co-benefits include aesthetic improvements, which can make walking and biking more appealing and add green space to compact neighborhoods.
- These types of solutions are being used in communities around the country, from major urban centers like New York City to small rural towns like Howard, South Dakota. They can be adapted for cities, suburbs, and rural areas alike. People want to live in these types of communities; market research suggests that anywhere from one-third to three-quarters of homebuyers want to live in walkable neighborhoods with amenities close by. (Logan, et al., 2011). Demographic changes are driving some of this increased demand; for example, one market research firm found that 77 percent of Millennials want to live in an urban area (Kannan, 2010). However, the supply of homes in these areas comes nowhere close to meeting the demand.

Fallout from the economic crisis, however, could make it difficult for communities to revamp their land use regulations not only to respond to market demand for more compact and efficient development, but also to prepare for projected climate change. As budgets at all levels of government are cut, many municipalities are in crisis mode and unable to fund more than absolute basic levels of services. Reviewing and revising zoning codes, redrawing land use maps, investing in stronger and safer infrastructure, and other measures that could help a community better adapt to projected changes can be difficult to get done in a town that can barely fund its police and firefighters. Given the political difficulties in some places around anything related to climate change, the long timeframe of the projected changes, the relative uncertainty about the exact extent of changes, and the natural tendency of most elected officials to focus on challenges likely to arise during their term of office, changing land use decisions to respond specifically to projected climate change is difficult at best. Add to these issues the funding problems, and action seems even less likely unless it brings short-term benefits and is low-cost and no- or low-regrets.

B. Two Case Studies – Boston and New York

1) CITY OF BOSTON ADAPTATION PLANNING

The city of Boston has an active history of engagement in climate change management dating from 2001. Located at the confluence of several coastal rivers in the northeastern US, it faces many of the infrastructure adaptation challenges common to US cities. Some of the challenges it faces were initially described in the US EPA funded Climate's Long-term Impacts on Metro Boston (CLIMB) project (1999 to 2004) and the Union of Concerned Scientists' 2007 report Confronting Climate Change in the U.S. Northeast: Science, Impacts, and Solutions. City staff have further documented impacts. Spurred by these efforts and particularly realizing that the various infrastructure sectors impact each other (e.g., Kirshen et al., 2008), the city has embarked on a long-term, continuous plan both to mitigate greenhouse gases (GHG) and to adapt to climate change. The initial strategies are documented in the recently released the report, A Climate of Progress, City of Boston Climate Action (City of Boston, 2011).

This plan is focused on the adaptation planning, to which Boston is giving the same priority as mitigation The city's adaptation efforts are centered upon managing the impacts from sea-level rise, increased frequency and intensity of heat waves, and increased intensity of storms. The planning is designed to address the health, economic, and social consequences of these impacts and not to further stress existing social and economic inequalities – in fact, the goal is to reduce these whenever possible. Other adaptation actions include triennial plan review to maintain flexibility, considering climate change in all planning and reviews to identify no regrets, low cost, and wait and see strategies, and carrying out case studies. Planning is coordinated by a working group of eight city agencies under the leadership of the Office of Environmental and Energy Services. While coordinating with others, each major agency is attempting to go as far in adaptation planning as they can on their own. There is also cooperation with the many NGOs in the region and other levels of government. These efforts will form the foundation for the formation of a new task force in a few years to freshly examine long-term and low-probability, potentially catastrophic risks of climate change. Some of the actions the City is taking are summarized in Table 7.

With these strategies, the city is starting a continuous adaptation planning process. Presently it is a decentralized approach among the city's agencies driven by several broad mandates with central coordination when needed. The recently started BWSC master planning process will provide the first test of how successful this approach can be because the plan's time frame includes the start of significant climate change stressors, stakeholders range from individual households (e.g., basement flooding) to the federal government (e.g., Boston Harbor pollution) and the long-term adaptive water infrastructure strategies will impact many sectors other than just sewage and storm water (Appendix A).

2) CLIMATE CHANGE ADAPTATION IN NEW YORK CITY

The latest environmental challenge for New York City that requires long term strategic planning is climate change. It is projected to have wide impacts on the city's critical infrastructure through higher temperatures, more intense flooding events, and sea level rise. Because of its early recognition of the risks posed by climate change and its current commitment to mitigation of greenhouse gas (GHG) emissions as well as to adaptation, New York City has become a national and international leader in responding to climate change (Rosenzweig and Solecki, 2010).

Current climate change adaptation efforts in New York City build on previous assessments and studies. Within the metropolitan region, leading scientists, agency representatives, and nongovernmental organization members have been studying issues related to climate extremes and climate change for more than a decade. In 2004, a climate change adaptation initiative was launched by the NYC Department of Environmental Protection. The major product of the NYC DEP Task Force was the Climate Change Assessment and Action Plan for the agency (NYCDEP 2008). Since many climate change

Table 7. City of Boston adaptation actions

Agency	Adaptation Actions
Boston Conservation Commission (protects and preserves open space, permits development near wetlands)	Requires applicants to consider SLR over the design life of the project.
Boston Redevelopment Authority (carries out planning and economic development activities, permits large projects)	BRA is asking developers of new projects to consider effects of climate change and, in the case of the large-scale 6.3 million square-foot project in South Boston, is requiring that all the components of the plan comply with present and future state and city SLR strategies. BRA is also encouraging the development of green roofs which store potential runoff as well as provide mitigation benefits. Pervious pavement and rain gardens are also encouraged.
Boston Water and Sewer Commission (owns and operates city infrastructure for water supply, drainage, and sewage).	Boston is part of a regional water supply system which, unless there are major changes in system demand, is not very vulnerable to climate change. BWSC, however, is including adaptation to climate change in its recently initiated update of its sewer and drainage master plan.
Emergency Preparedness	Climate change is being included in the current planning efforts for emergency operations and natural hazards mitigation.
Parks and Recreation Department	Grow Boston Greener is an initiative with the goal of planting 100,000 new trees in Boston by 2020. Tree selection considers changes in rainfall and heat patterns.
Public Works Department	PWD is also evaluating impacts such as increased heat and freeze-thaw cycles on road durability.
Boston Harbor Islands	The City of Boston is part of the federal-state-local management team. The Harbor Islands are presently monitoring wetland conditions and prioritizing management of threatened coastal resources.

adaptations identified through this process help to increase the robustness of current systems managed by the agency, the NYCDEP Task Force had immediate benefits by improving responses to present-day climate variability, such as managing episodes of intense precipitation in the upstate reservoirs. This work became the benchmark and exemplar of work soon to be carried by other New York City agencies.

Although no single weather-related event can be attributed to climate change, New York City has experienced climate extremes in its recent history that have brought attention to the potential risks posed by climate change to the city's critical infrastructure. Recent extreme climate-related events include Hurricane Irene in August of 2011 which caused the City for the first time to implement its storm surge evacuation plan and associated risk reduction planning activities on a broad scale (e.g., shutting down the public transit system). While the storm surge flooding was not much as expected, the City agencies were able to test their emergency planning protocols. Other recent weather extremes include the summers of 2010 and 2011 that were exceedingly hot and stormy. The summer of 2011 was particularly intense – July was one of the hottest months on record for New York City; while August was one of the wettest. These events and others which resulted in large social and economic costs provide valuable insights into the impacts that climate change could have in the future. They also highlight the need, even without climate change, to improve the city's resilience to environmental stressors, of which climate extremes are one of the most important. In many cases, linking adaptation efforts to the climate risks faced by the city today is an effective adaptation strategy. New York's Mayor Michael Bloomberg created the Office of Long-Term Planning and Sustainability in 2006, with the goal of developing a comprehensive plan to create a greener, more sustainable city. Mitigating climate change were central goals of the City's comprehensive sustainability plan, PlaNYC 2030, released in 2007. The PlaNYC work was expanded to include climate change adaptation in response to the importance of doing both climate change mitigation and adaptation simultaneously to protect the citizens and infrastructure of the City. An immediate goal of PlaNYC was the creation of an interagency Climate Change Adaptation Task Force to protect the city's vital infrastructure in the face of a changing climate. The charge of the Task Force created in 2008 was to identify climate change risks and opportunities for the city's critical infrastructure and to develop coordinated adaptation strategies to address these risks. The Task Force[3] consisted of approximately 40 city, state, and federal agencies, regional public authorities, and private companies that operate, maintain, or regulate critical infrastructure in the region related to energy , transportation, water and waste, natural resources, and communications. To support the Task Force, the City convened a group of climate change and impact scientists, and legal, insurance, and risk management experts as the New York City Panel on Climate Change (NPCC) to advise the City on climate change science, potential impacts, and adaptation pathways specific to the city's critical infrastructure.

The NPCC consists of climate change and impacts scientists, and legal, insurance, and risk management experts and serves as the technical advisory body. It was designed to function in an objective manner similar to the role that the Intergovernmental Panel on Climate Change (IPCC) plays on an international stage for nation-states. The work of the NPCC is to ensure that the city's adaptation efforts are based on sound science and a thorough understanding of climate change, its potential impacts, and adaptation. To assist the City, the NPCC has analyzed climate change hazards, studied impacts on the critical infrastructure of New York City, and developed a risk management framework for adaptation planning, which, in turn, contributed to the development of the City's climate change adaptation planning framework.

A critical component of the NPCC's work was to define *Climate Protection Levels* to address the issue of climate change impacts on the effectiveness of current regulations and design standards related to sea level rise and storm surge, heat waves, and inland flooding. Most important for the City is that in order to maintain a similar level of current risk it will be necessary to adjust the current building codes. This is another way in which climate change becomes integrated into the urbanization process by influencing a set of climate risk-related construction guidelines – e.g. how to build for increased frequency and intensity of precipitation and flooding events, heat waves, and extreme wind events.

The Adaptation Assessment Guidebook (AAG), another product of the NPCC describes a detailed process designed to help stakeholders create an inventory of their at-risk infrastructure and to develop adaptation strategies to address those risks. The Adaptation Assessment Guidebook (AAG) includes three tools developed to aid the stakeholders in their adaptation planning process including an infrastructure questionnaires, risk matrix, and prioritization Framework. The adaptation process was defined as a dynamic cycle of analysis and action followed by evaluation, further analysis, and refinement (i.e., learn, then act, then learn some more). The steps outlined in the AAG are intended to become integral parts of ongoing risk management, maintenance and operation, and capital planning processes of the agencies and organizations that manage and operate critical infrastructure.

The adaptation approach developed by the NPCC fosters a Flexible Adaptation Pathways approach - originally developed by the London TE2100 - that can evolve over time as understanding of climate change improves and that concurrently reflect local, national, and global economic and social conditions. Flexible Adaptation Pathways is a concept that encourages building climate change adaptation strategies that can be adjusted and modified over time to reflect the dynamic and ongoing climate change understanding (see Figure 14 and 15 and Tables 8 and 9).

The NPCC consists of climate change and impacts scientists, and legal, insurance, and risk management experts and serves as the technical advisory body and was designed to function in an objective manner similar to the role that the Intergovernmental Panel on Climate Change (IPCC) plays on an international stage for nation-states. The work of the NPCC is to ensure that the city's adaptation efforts are based on sound science and a thorough understanding of climate change, its potential impacts, and adaptation, along with interactions with climate change mitigation. To assist the City, the NPCC has analyzed climate change hazards, studied impacts on the critical infrastructure of New York City, and developed a risk management framework for adaptation planning, which, in turn, contributed to the development of the city's climate change adaptation planning framework.

C. Adaptive Infrastructure in Other Countries

Many other countries, faced with climate change and other sustainable development concerns similar to those of the US, are proceeding with adaptive strategies for infrastructures and urban systems. Without suggesting that social contexts are unimportant, some of their experiences will serve as sources of information for the US about options

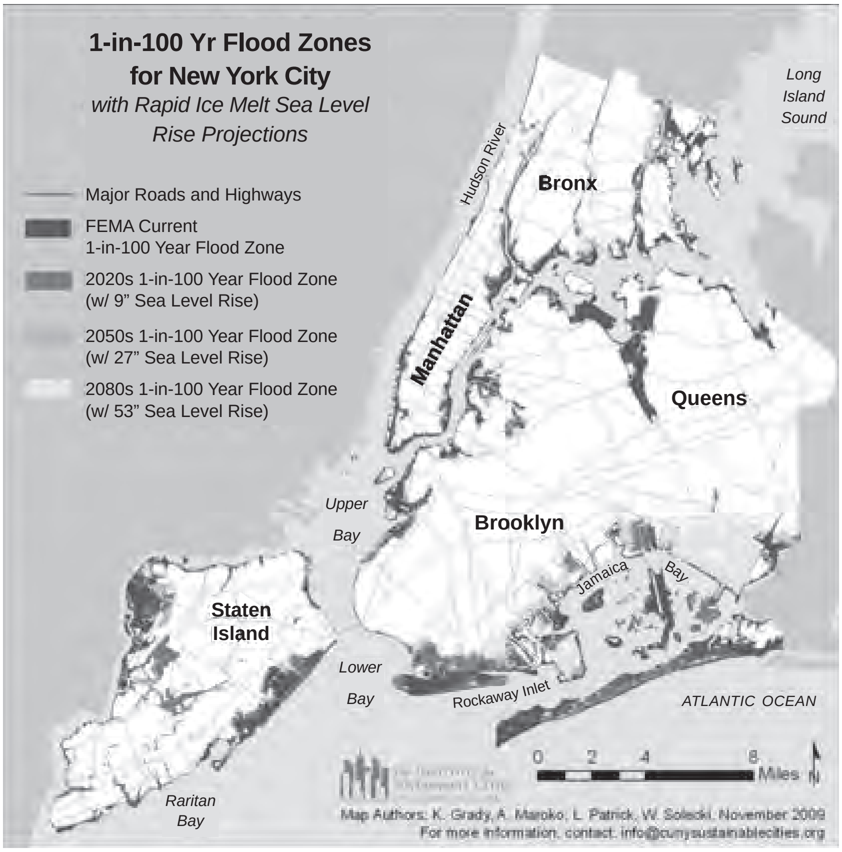
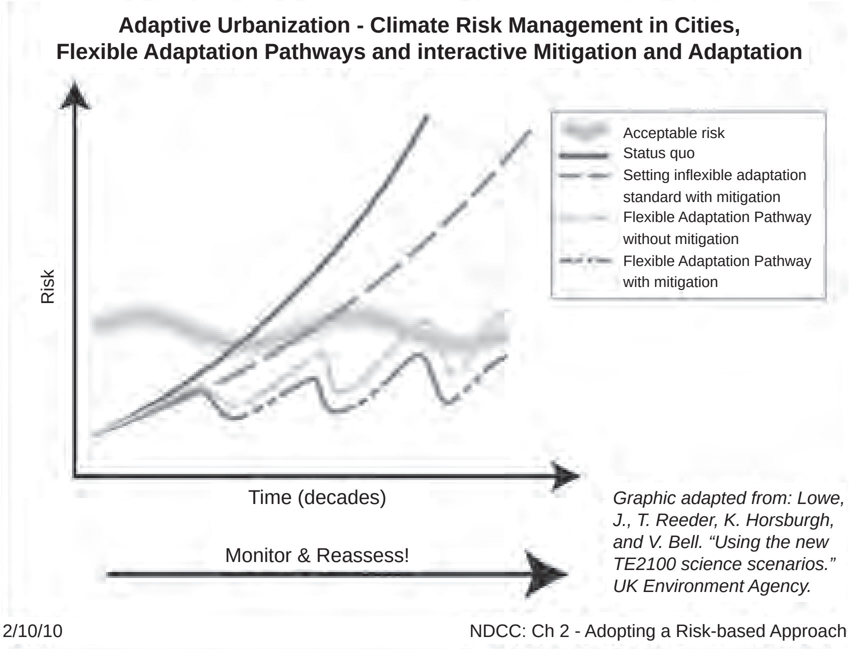


Figure 14 Flooding risks to the New York City area associated with substantial climate change. Note that a "1" in 100 Year Flood Zone" refers to a mean recurrence interval for that magnitude of flooding. It is not a prediction that such an event will occur only once in 100 years.



Graphic adapted from: Lowe, J., T. Reeder, K. Horsburgh, and V. Bell. "Using the new TE2100 science scenarios." UK Environment Agency.

Figure 15 Adaptive urbanization – climate risk management in cities, flexible adaptation pathways, and interactive mitigation and adaptation

Table 8. Climate hazards and coastal flooding events

	Baseline	2020s	2050s	2080s
1- in 10-yr flood to reoccur, on average	~ once every 10 years	~ once every 9 (8-10) years	~ once every 3 (3-6) 8 years	~ once every 1 (1-33)years
Flood heights (in ft) associated with 1- in-10 yr flood	6.3	6.5 (6.5 -6.8) 6.8	6.8 (7.0 -7.3) 7.5	7.1 (7.4-8.2) 8.5
1- in 100 yr flood to reoccur, on average	~ once every 100 years	~ once every 60 (65-80) 85 years)	~ once every 30 (35-55) 75 years	~ once every 15 (15-35) 45 years
Flood heights (in ft) associated with 1-in-100 yr flood	8.6	8.7 (8.8 -9.0) 9.1	9.0 (9.2-9.6) 9.7	9.4 (9.6-10.5) 10.7
1- in 500-yr flood to reoccur, on average	~ once every 500 years	~ once every 370 (380-450) 470 years	~ once every 240 (250-330) 380 years	~ once every 100 (120-250 (300 years
Flood heights (in ft) associated with 1-in 500 yr flood	10.7	10.9 (10.9-11.2) 11.2	11.2 (11.4 to 11.7) 11.9	11.5 (11.8-12.6) 12.9

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*NOTE: Does not include the rapid ice-melt scenario. Numbers inside parentheses indicate central range (67% of model-based distribution); numbers outside are full range.

Table 9. Qualitative changes in extreme events

NOTE:
>50% is used when the likelihood can be estimated with reasonably good precision, and 33 to 66% is used when there is not high confidence in the likelihood estimate.

Extreme Event	Probable Direction Throughout 21st Century	Likelihood
Intense hurricanes	↑	**More likely than not**
Nor'easters	***Unknown***	
Extreme winds	↑	**More likely than not**

These definitions of likelihood are used by the IPCC (2007) to describe potential outcomes:

> 99%	Virtually certain
>95%	Extremely likely
>90%	Very likely
>66%	Likely
>50%	More likely than not
33 to 66%	About as likely as not

and their costs and benefits, potentials, and limitations. The following are examples of adaptations to coastal flooding vulnerabilities.

1) UK / LONDON ADAPTATION PLANNING

In the late 1970's, London built the Thames Barrier in response to significant losses of life during a 1953 storm in the North Sea. This is a wall of towers that support rotating gates, which are closed when storm surges are predicted. It uses an energy-efficient design (rotating wheels that lift the barrier gates), and has been very successful. The system is being expanded with the East London Green Grid, a park system designed to provide flood storage along all the tributaries to the Thames in East London and southeast London. These parks have also been located to improve local communities' access to nearby recreational areas, introducing a social justice component into the primary stormwater detention strategy. London plans to expand this new network system into an "All London Green Grid" in the future, creating corridor systems for wildlife and plant dispersal throughout the greater London area at the same time they provide stormwater management and recreation for people. A citywide flood management plan is being written (DRAIN London) as a component of a very thorough urban adaptation plan, which is the most inclusive of its kind in the world. This climate change adaptation planning document is required by law for Greater London. In addition, the national Environment agency in the UK has been planning "adaptive pathways" for the Thames Estuary area that basically (1) identifies possible adaptation strategies, (2) organizes them into sequences of actions ("pathways"), and (3) lays them out next to a range of sea level rise scenarios to reveal which pathways would be sufficient to protect London against any given sea level rise scenario. The plan does, however, incorporate the idea that money should be allocated and spent only when the environmental change occurs – i.e., sea level actually reaches critical new levels, indicating imminent danger. The flaw in this strategy is that national borrowing capacity may not be available at reasonable rates at that future time. In contrast, Dutch adaptation planning works on the assumption that investments should be made while interest rates are low and funds are available, well in advance of the actual environmental change that is expected.

Like the British, the Dutch have also added movable barriers to their coastal defenses. The Rotterdam Maeslantkering was constructed using two 800-foot long fans of space-frame metal tubing to support a curving steel face wall, which rotate into place on large ball joints. The steel fans are raised hydraulically, by flooding their storage compartments, then rotated out into the water and lowered once they are in position in the channel. A miniature version of this design has been incorporated into the newly-built New Orleans storm surge barrier, designed by a team of Dutch companies, and has been proposed as part of a protection scheme for New York City as well.

The Dutch have partnered with the World Wildlife Fund to move their dikes back from the river channels in several key areas where additional flood storage is needed. This national effort, known as the Room for the Rivers Program, has required farmers to adjust to a lower standard of flood risk protection outside the new dike locations. It has also created opportunities to experiment with vegetation management, and the reintroduction of older cattle species that can browse riparian areas and prevent woody plants from becoming dominant inside the floodways (which is seen as producing an undesirable reduction in conveyance capacity outside the dikes).

Finally, Dutch engineering and construction companies are experimenting with houses on stilts in permanently-flooded polders, as well as floating houses and even entire urban blocks in the old harbor areas of Rotterdam. A pilot floating conference center was completed in December of 2010, and plans are underway to expand this to develop floating mixed-use blocks. These are intended for areas where a combination of the coastal storm surge barrier (Maeslantkering) and upstream flood barriers keep floodwaters free of debris and wave action, allowing structures to float up and down as the river waters rise without risking structural damage. Rotterdam recently issued its second citywide Water Plan, resolving to become a "climate proof" city that is ready for new industrial and commercial investments as a result of its enhanced stability in the face of extreme weather. IBM has recently invested in a Global Center of Excellence in water management located in Amsterdam, where they will showcase their ability to support water management with sophisticated sensors, gaming, and 3D internet resources to improve flood prediction and increase the effectiveness of protective responses

2) GERMANY

Hamburg is the home of Germany's largest container port, the second largest in Europe. Located more than 80 miles inland from the North Sea, Hamburg has had to dredge the Elbe River significantly to allow large container ships to enter the urban port and connect to rail lines and river barges. The river is diked along most of its length, raising the elevation of tides and storm surges. The extensive dredging activity has also increased the speed and size of annual storm surges (and daily tides) that flood the city's waterfront. Hamburg's urban core is on a high bluff, outside of the flooding area, but a new urban residential district has been built in the old warehouse area of the port, outside the city's dike defenses. The strategy was to build an urban district that is resilient to flooding, and accepts these floods rather than blocking them out. Multi-story buildings were constructed with waterproof parking garages on the first floor, along with retail or entertainment uses. Residential uses begin on the second stories of these buildings. A secondary circulation system was built to allow people to get around by bike and on foot during flooding. People are able to interact safely with floodwaters in public space. Parks were built to float on the floods, using decks that are attached to pilings as park surfaces. Other parks were built on land, with hardened surfaces to accept the battering of waves. Hamburg is also beginning to experiment with moving dikes back from the Elbe River to create more flood storage space, primarily upstream of the city and its port.

3) JAPAN

The city of Tokyo built a series of long, wide dikes along the Arakawa and Yodo rivers in the 1990's that implemented the concept of a "superdike," i.e., a dike that is so wide that it cannot fail catastrophically. These superdikes were constructed during a recession as an economic stimulus. The advantage of the superdike is that, with widths of 900 feet and more, buildings, roads and parks can be built on top. The Japanese approach was to extend property boundaries upwards through the new dikes so that the original landowners could develop or sell their properties for higher values, with water views instead of views of earthen dikes.

Tokyo has also begun to use stadium parking lots and other large public spaces near rivers as temporary floodwater storage areas (de Graaf and Hoolmeijer, 2008).

D. Assessment Findings

Regarding implications of climate change for infrastructure and urban system risk management strategies in the United States, we find that:

- Risks of disruptive impacts of climate change for infrastructures and urban systems can be substantially reduced by developing and implementing appropriate adaptation strategies

  High consensus, moderate evidence

  See Sections III A, C, D
  IV A, C

- Many of the elements of such strategies can be identified based on existing knowledge

  High consensus, moderate evidence

  See Section IV A, B

- In most cases, climate-resilient pathways for infrastructure and urban systems will require greater flexibility than has been the general practice, along with selective redundancy where particular interdependencies threaten cascading system failures in the event of disruptions

  High consensus, moderate evidence

  See Section V A, B

- Revising engineering standards for buildings and other infrastructures to accommodate projected climate changes is a promising strategy

  High consensus, moderate evidence

  See Section V A

- In some cases, especially if climate change is substantial, climate-resilient pathways will require transformational changes, beyond incremental changes.

  High consensus, moderate evidence

  See IPCC SREX

Chapter 6

Knowledge, Uncertainties, And Research Gaps

A. The Landscape Of Needs

Because the communities of expertise, decision-making, and policymaking about risk management for infrastructures have traditionally been focused on single categories, such as water or transportation, the existing knowledge base about cross-sectoral interactions and interdependencies is limited, at least in research studies published in the open literatures. As indicated above, recent simulation and analysis initiatives related to national security concerns have provided powerful evidence that cross-sectoral analysis is both possible and illuminating; but the research needs for the topic of this technical input paper are profound, if questions about climate change implications are to be answered in the longer run. In fact, a high priority should be given to verifying and validating the report's assessment findings, especially where the current evidence is not strong.

General needs for mature knowledge, rooted in effective tools and available evidence, include vulnerabilities of infrastructures and urban systems to weather phenomena associated with climate change; analyses of alternative actions: e.g., maintain and harden as is; replace, revise, move; or invest in increasing flexibility – focused especially on near-term choices (e.g., the next ten years).

More specifically, to assess climate change implications for infrastructures and urban systems, knowledge and analytical capacities are needed for:

- Climate change projections, with a focus on:
  - Uncertainty analysis of climate phenomena
  - Analysis at regional scale
  - Models of specific infrastructures
  - Capturing sectoral infrastructure dynamics: e.g., lifetimes, depreciation rates
  - Including issues of financing, management, and service delivery
- Models representing potential cross-sectoral effects of climate parameters, especially beyond historical experience, e.g.: issues for tool integration, interdependency consequence analysis, urban system analysis science – recognizing that model interactions are likely to be iterative
- Models of the infrastructure impacts of (non-climate) economic/policy change

- Climate change as a driver for both sectoral and cross-sectoral consequences, in a multi-driver context
- Infrastructure strategies as mitigation issues and opportunities
- Understanding cross-cutting science issues that underpin assessments, e.g.,
    - Climate science and services
        - Treatments of variance, extremes, and uncertainties: e.g., probabilistic methods, uncertainty quantification
        - Data, especially climate data needed to inform critical infrastructure issues, including proprietary issues
        - Non-linearities and tipping points/thresholds as well as performance degradation leading up to abrupt changes
        - Scale dependencies (e.g., isolated vs. widespread), slow versus fast impacts
        - User interactions: visualization/communication, stakeholder participation
- Risk management science: risk-based scaling/framing/scoping capabilities, especially given uncertainties that surround large investments for long-term structures
- Multiple stresses and drivers
- Projecting economic and social changes, including changing demand patterns, population distribution, and financial conditions
- Distributional effects of urban and infrastructure strategies and actions (related to . . . (other study) as well)
- Learning from emerging responses

In some cases, it is possible to leverage existing capabilities, as the NISAC modeling tools demonstrate; and the experience in utilizing Los Alamos tools to evaluate emergency responder options for the Wallow Fire in AZ shows that such capabilities can be used not only to inform strategic thinking but also to provide actionable results for real-time decisions. Box 4 offers a specific example of a capacity development need.

B. Assessment Findings

Regarding implications of climate change for infrastructure and urban system research needs in the United States, we find that:

- Improving knowledge about interdependencies among infrastructures exposed to climate change risks and vulnerabilities will support strategies and actions to reduce vulnerabilities

  High consensus, moderate evidence

  See Section IV A

- The challenge is to recognize that, although uncertainties about climate change and payoffs from specific response strategies are considerable, many actions

BOX 4

An Example of Capability Development: Linking Modeling Capacities

In order to better understand the impact of climate change on infrastructure systems around the world, there is a need to make an infrastructure component compatible with the spatial and temporal resolution of existing Integrated Assessment Models (IAMs). However, the majority of the existing infrastructure simulation modeling capability is focused on detailed U.S. concerns. Further, the level of geographical and facility detail exceeds that useful for many climate change assessments. National Climate Assessment efforts suggest a need to include infrastructure dynamics within IAMs to quantify risk, determine impacts, and evaluate adaptation options. The development of infrastructure simulation modules for IAM use could start with U.S. (regional or state) resolved simulations. Once created and tested, the jointly-developed infrastructure modules could be parameterized to have the same global coverage as many IAMs. Based on detailed models or other studies, such parameterizations could recognize critical local vulnerabilities of the regions without having to fully simulate at the detailed spatial resolution. Further, a generalization of the parameterization process would enable any regional aggregation, as required for coupling to and use in other IAMs. This regionalization could identify any destabilizing international trade dynamics from climate change and the promulgation of consequences across international boundaries.

Perhaps most importantly, such a combined set of aggregate and high-resolution models would facilitate sensitivity analyses that highlight where additional research can reduce uncertainty, or have the greatest impact on enabling risk mitigation. Such analyses can also prioritize the importance of data for monitoring and evaluation. Data collection is expensive. Models can determine those limited critical components that most contribute to the understanding of risk and the consequence of decisions. The thoughtful use of *models can greatly enhance* visualization, communication, and stakeholder participation/understanding of risks and decision options. (For an example, see http://climateinteractive.org/). A vast amount of experience in 1) integrated assessment modeling, 2) infrastructure risk simulation, and 3) using computer models to inform stakeholders is available to extend the National Climate Assessment beyond mitigation to include adaption, resiliency, and societal responses in the context of uncertainty and risk management.

make sense now, such as developing monitoring systems to support assessments of emerging threats to infrastructures and urban systems

High consensus, moderate evidence

See Sections V and VI above

- A high priority should be given to verifying and validating the report's assessment findings, especially where the current evidence is not strong

High consensus, moderate evidence

See Section IV A

Chapter 7

Developing a Self-sustained Continuing Capacity for Monitoring, Evaluation, and Informing Decisions

For the communities of experts on climate change and infrastructures and urban systems, along with decision-makers and other stakeholders whose support is important to keep the assessment process self-sustaining, the challenge is to combine attention to both science issues (the what) and institutional issues (the how). Roles will need to be played by a variety of kinds of institutions beyond the federal government alone – foundations, the private sector, non-governmental organizations, and universities – all of which have unique things to offer but limitations in performing some aspects of the continuing process. Universities may be especially important as institutions with long-term commitments to learning and communicating that learning, increasingly looking toward issue-oriented cross-disciplinary programs in response to both student and stakeholder interest. But a key will probably be implementation of the US Global Change Research Program's Strategic Plan, with its support for decision support science and supporting assessments. In addition, the nation's engineering societies – such as the American Society of Civil Engineers – will be an invaluable resource for knowledge development and application in assessing and responding to challenges for adaptive built infrastructures.

A. Science Issues

The science issues include:

- strengthening linkages between climate science and domain science, especially regarding scenarios
- enhancing scientific capacities for analyzing cross-sectoral interactions and interdependencies at both regional and urban scales
- increasing the capacity to acquire emerging knowledge from experience as well as formal published research, including experience from efforts to make infrastructures and urban systems more climate-resilient

B. Institutional Challenges

- Institutional roles and partnerships, given that infrastructures and urban systems involve extensive and intensive interactions among a wide variety of kinds of expertise, vested interests, and service-rooted concerns: national government agencies and programs; regional, state, and local governments; large and small private sector institutions of an enormous variety of types: e.g., construction firms, consulting firms, financial institutions, insurers, materials producers, and commercial firms; non-governmental organizations related to such interests as community well-being and the environment; and the world of knowledge and learning, from research to education, formal and informal.

- Deploying for monitoring, evaluation, learning, and approaching adaptive risk management iteratively, given that (a) current knowledge and experience provides a better understanding of how to mobilize the top-down elements of such an approach than how to mobilize the bottom-up elements and (b) no current structures exist for such monitoring, especially of experience being gained in the private sector.

C. Assessment Findings

Regarding a continuing assessment process for climate change and infrastructure and urban systems in the United States, we find that:

- A self-sustaining long-term assessment process needs a commitment to improving the science base, working toward a vision of where things should be in the longer term

  High consensus, moderate evidence

  See Section VII above

- Capacities for long-term assessments of vulnerabilities, risks, and impacts of climate change on infrastructures and urban systems will benefit from effective partnerships among a wide range of experts and stakeholders, providing value to all partners

  High consensus, moderate evidence

  See Section V and VII above

Appendix A

Adaptive Water Infrastructure Planning

Approaches to adaptive infrastructure planning can be illustrated by the case of water infrastructure.

Holistic Water Management

Holistic management of storm water, flood waters, water supply, and wastewater management is a theme that continues to be explored for climate change adaptation (Novotny and Brown, 2007, Zoltay et al., 2010, Gleick, 2010, Daigger, 2009). For example rainwater harvesting not only contributes to management of storm water but can also be used for water supply. Storm water infiltrated into the ground also recharges groundwater, which improves water supply and baseflows in rivers. More open floodplains decrease flood damages as well as provide groundwater recharge, recreation, and the elimination of some nonpoint source pollutants. Wetlands provide for ecological benefits as well as filtering of water pollutants and flood mitigation. Wamsley (2010) found through both data and modeling analysis that 4 to 60 km of wetlands in the coastal region of Louisiana can decrease surge elevation by one meter depending upon landscape and storm characteristics. Reclaimed wastewater partially eliminates wastewater and also provides water supply. Morsch and Bartlette (2011) report that some states have presently have policies to encourage these strategies as part of their adaptation plans. It is now the policy of California to integrate for water supply management the following water sources: groundwater, surface water, recycled municipal water, flood flows, urban runoff, imported water, and desalination. Demand management can also be mandated by the state. Pennsylvania has policies to encourage the use of green infrastructure and ecosystem-based approaches to manage storm water and flooding. Maryland is recommending changes in building codes and retaining and expanding wetlands and beaches to protect against coastal flooding as well as combining estimates of coastal erosion, sea level rise, and storm surge to define critical areas to manage. The state is also planning how to minimize impacts on coastal resource-based economies.

Improved Planning Tools and Approaches

Spurred on by climate change and the complexities of other challenges they are facing, many water management organizations are encouraging the use of new approaches and tools for planning. For example, Mearns et al. (2010) for the Water Utility Climate Alliance (WUCA) reviewed methods that may be useful for water utilities responding to climate change impacts including Classic Decision Analysis, Traditional Scenario Planning, Robust Decision Making, Real Options, and Portfolio Planning. US EPA (2010) have reviewed actual adaptation planning practices of eight water utilities including top down and bottom up approaches, sources of climate information, and use of models. WERF (2009) have discussed the impacts of climate change on the various components of wastewater and storm water utilities and then a bottom–up based method for risk management. The NRC (2010) presented a climate change adaptation strategy based upon improved communication and risk management – presenting many processes to accomplish this. Brekke et al. (2011) also present processes for water management adaptation. The US EPA Water Security Division has developed the planning tool Climate Resilience Evaluation & Awareness Tool (CREAT) to help water supply and wastewater understand climate change related threats and adaptation options (http://water.epa.gov/infrastructure/watersecurity/climate/creat.cfm, accessed November 25, 2011). Many of the adaptation planning processes recommend the use of monitoring to determine when to take adaptive management actions. A major challenge of this is the determination of whether a climate change has actually occurred or not. A novel method which integrates risk-based decision theory and hypothesis testing of trends to determine the economic consequences of taking action versus not taking action is presented by Rosner et al. (2011).

Adaptation

Approaches for urban water adaptation are similar to those of other sectors. They should be robust (actions implemented over time and space that function acceptably well under all future uncertainties and risks), flexible, and adjustable; include no-regret (valuable even without climate change) and co-benefit (valuable to multiple sectors) actions, integrating with sustainability planning to respond to other pressures on the region, GHG mitigation, and a portfolio of approaches for multiple levels of safety; be evaluated with multiple social, economic and environmental criteria; respect equity and adaptive capacity needs; responsive to climate surprises; and be resilient and employ adaptive management as needed. In addition, because adaptation is often implemented at the local level, local stakeholders must be integrated into the planning process (Kousky et al., 2009, Stakhiv, 2010, Brekke et al., 2011, Lempert and Groves, 2009, Ray et al ., 2011, NRC, 2010, Yohe, 2009).

There are two types of plans in an adaptation strategy. The first is “Here and Now” actions for new projects or for presently threatened areas. They should be designed for climate change adaptation. The incremental costs are relatively low compared to capital costs under the present climate (citation). “Prepare and Monitor” actions are where implementation does not take place now because uncertainties are too high and/or present threats are low– but options are preserved and actions taken when a trigger point or threshold also determined as part of the adaptation planning process is reached based upon a monitoring system. (Thames Estuary, 2009, Brekke et al, 2009, Ray et al., 2011). For the built environment, there are three general categories of responses or adaptation to the impacts of climate change. These include protecting against the impacts by structural means; accommodating the impact; and retreating from the impacts.

The recommendations of the US Interagency Climate Change Adaptation Task Force (2011) are particularly appropriate for the management of urban water infrastructure under climate change. These include:

- Establish a Planning Process to Adapt Water Resources Management to a Changing Climate
- Improve Water Resources and Climate Change Information for Decision-Making
- Strengthen Assessment of Vulnerability of Water Resources to Climate Change
- Expand Water Use Efficiency
- Support Integrated Water Resource Management
- Support training and Outreach to Build Response Capability
- Below are presented adaptation approaches for the management challenges of urban drainage, water supply, and river flooding.

Drainage

Researchers are stressing using flexible, decentralized approaches to adapt to the increased drainage flooding and associated water quality impacts under climate change (Auld et al (2010), WERF 2009). This is in contrast to large-scale solutions such as sewer separation, which might be effective and robust, but also overly expensive and inflexible, although they continue to be effective in reducing the amount of combined wastewater that must be treated. One of the most flexible and decentralized approaches is Low Impact Development (LID), in which even without climate change, there is currently much interest and some such as Heaney and Sansalone (2009) view as one of the best approaches for the future management of urban drainage. Thus this approach is no-regrets policy. LID is ". . . an approach to land development (or re-development) that works with nature to manage storm water as close to its source as possible. LID employs principles such as preserving and recreating natural landscape features, minimizing effective imperviousness to create functional and appealing site drainage that treat storm water as a resource rather than a waste product." (U.S. Environmental Protection Agency, http://www.epa.gov/owow/NPS/lid, accessed July 5, 2011). LID techniques essentially let the water stay where it falls either through storage or infiltration and are seen as particularly promising to better manage runoff by keeping the water out of the built drainage network and not letting the flows concentrate and cause damage (Roseen et al, 2011). LID techniques include decentralized approaches such as green and blue roofs, porous pavement, preservation of buffers, bioretention (i.e., infiltration), distributed storage, and rain gardens. Conventional approaches are generally designed for singe large events such as 10 or 100-year events and may not have the water quality benefits of LID. LID techniques also have the additional benefits of providing more open, green space in communities, aiding GHG mitigation, and have social and environmental benefits.

Some drawbacks of LID include potential construction and maintenance costs, presently unknown long-term performance, possible attraction of waterborne diseases, and ability to manage only the first inch or few inches of a storm. Management of the first inch or so may be adequate for water quality but will not stop large scale local flooding.

Effective management of storm water may require mixing green and gray (conventional) approaches (Roseen, et al., 2011). Gray manages large flooding events and LID provides for water quality treatment and reduction of overall costs as fewer catchbasins, curbing, conduits and other gray features are needed. LID is particularly effective in meeting new water quality goals for storm water management, which traditional methods are not. LID can be economical if life cycle and total benefits are included. Economic benefits are due to cost savings in land space for large ponds, below ground conduits, curbs, catch basin and other gray features. Extra benefits exist such as promotion of natural cooling and higher property values. The storm drainage cost for shopping center in the northeast was able to reduce costs by 26% or approximately $1 million using LID instead of conventional approaches. A combined approach by Portland OR reduced costs of combined sewer overload (CSO) management costs by from $144 M to $ 81 million. LID enabled Chicago to divert 70 millions gallons in year from its CSO system resulting in energy savings as well as green space benefits. New York City Department of Environmental Protection expects to reduce its CSO costs from $6.8 billion using a gray-only strategy to $5.3 billion using a mixed LID-gray strategy. Philadelphia Water Department (2011) is also using a combined approach to better manage CSOs. In addition, the combined strategy will result in other benefits related to sustainability including reduced Urban Heat Island effect, better air quality, higher property values.

For present and future drainage systems, Heaney and Sansalone (2010) recommend load management by removing pollutants from overland surfaces such as by street cleaning. They also advocate for the use of real-time monitoring and control to improve the management of urban drainage and sewage systems. As stated previously, the flexibility of LID makes it attractive for adaptation; it can be added as needed to manage precipitation changes over time – perhaps augmenting conventional approaches. The mixing with conventional approaches may be needed as LID can only manage a few inches of runoff. As WERF (2009) states, " It is conceivable that, under the right conditions, the long term answer may lie in green infrastructure strategies designed to reduce runoff and prevent it from entering combined sewers or leaky sewers. As more and more green infrastructure is added to such a program year after year, it may be capable of keeping up with the gradually increasing rainfall intensity phenomenon over the course of time", page 62. LID is also attractive for adaptation because of its co-benefits and no-regrets aspects. Roseen et al. (2011) present several examples where significant cost savings in adaptation may be possible using LID to help capture increases instead of relying solely upon expansion of gray networks. Pyke et al. (2011) also present an example. There still seems to be gap between practice and theory because, for example, Philadelphia Water Department (2011) does not consider impacts of climate change on urban drainage and only cite GHG mitigation as the climate change management bene-fit of LID. However, Cohn (Alan Cohn, NYC DEP, personal communication, November 23, 2011) reports that New York City may consider how climate change impacts storm water drainage quantities.

Water Supply

Besides the limited option of developing new sources, adaptation approaches include demand management, new advanced technologies such as water reuse and drip irrigation, and use of new types of sources such as brackish water and rainwater harvesting

(Gleick, 2010, Brekke et al., 2009). Yields of existing systems can also be increased by adjusting operation rules (e.g., in the Pacific Northwest, Vano et al., 2010) and by the use of seasonal and short-term climate and weather forecasting. Daigger (2008, 2009) presents a view of the future urban water supply system that would be very useful for adaptation. He advocates for closed-loop urban water systems to meet urban sustainability goals that not only result in less water being removed from the natural system, but also result in energy and nutrient recovery. Recycled water, reclaimed wastewater, and rainwater harvesting can be used irrigation needs with potable needs met from outside the area or local sources. Energy use is decreased by the decentralized nature of these types of sources and recovery of heat and organic matter from wastewater. Nutrients are also recovered from wastewater. Improved water management is also obtained by separating waste streams into gray water, black water (feces) and yellow water (urine). The concept is that graywater would used locally while the other wastewater streams are would be treated in centralized facilities, although assuring the separation of graywater systems and potable water systems in the home remains problematic. Source separation also reduces wastewater treatment capacities and energy used (due to high-energy requirements, desalination should not be viewed as a sustainable water source). Such a system also provides benefits in terms of a reduced urban heat island effect, use of less energy, and improved aesthetics. These systems combined with demand management from tools such as low-flow toilets can reduce urban indoor use in the USA from over 400 liters per capital per day (l/c/d) to 120 l/c/d to 150 l/c/d. He states these advanced systems will be economic when comparing all the costs and benefits. Zoltay et al (2010) illustrated these concepts in a case study in the Northeastern USA. Use of reclaimed or recycled water also removes some of the variability in water supply sources. Such a system must monitor possible public health problems and build up of pollutants in the closed loop systems.

River Flooding

Galloway (2009) reports upon guidelines developed by the Association of State Floodplain Managers (ASFPM) and recommends these be used to guide floodplain management over the next decades to respond to climate change as well as other river flood stressors. These include ”Make room for rivers, oceans, and adjacent lands; ◎Reverse perverse incentives in government programs that make it more profitable to act unwisely than to recognize the need for long term safety and sustainability; Restore and enhance the natural, beneficial functions of riverine and coastal areas; Generate a renaissance in water resources governance and development of the policies and organization that will support this renaissance; Identify risks and resources and communicate at public and individual levels; Assume personal and public responsibility for their actions in the floodplain.”(page 2333) . He also supports the recent switch to risk-based flood management by the US Army Corps of Engineers. Opperman et al. (2009) support similar concepts. Flood management will also be improved by better weather and seasonal climate forecasting of precipitation and associated runoff.

References

Aerts, J., et al., 2009. *Connecting Delta Cities: Coastal Cities, Flood Risk Management, and Adaptation to Climate Change,* Free University of Amsterdam Press, Amsterdam.

Aerts, J., et al., 2011. *Climate Adaptation and Flood Risk in Coastal Cities.* London: Earthscan.

Amato, A., et al., 2005. Regional energy demand responses to climate change: Methodology and application to the Commonwealth of Massachusetts, *Climatic Change,* 71:175-201.

American Society of Civil Engineers, 2009. *2009 Report Card for America's Infrastructure.* http://www.asce.org/reportcard

Backus, G., et al., 2010. Assessing the Near-Term Risk of Climate Uncertainty: Interdependencies among the U.S. States, *SAND Report,* April. https://cfwebprod.sandia.gov/cfdocs/CCIM/docs/Climate_Risk_Assessment.pdf

Balbus, J. M., and C. Malina. 2009. Identifying vulnerable subpopulations for climate change health effects in the United States, *Journal of Occupational & Environmental Medicine* 51(1): 33–37.

Barata, M., et al, 2011. Climate change and human health in cities, in C. Rosenzweig, W. D. Solecki, S. A. Hammer, and S. Mehrotra (eds), *First Assessment Report on Climate Change and Cities (ARC3),* Cambridge University Press, New York.

Barreca, A. I., 2010. Climate change, humidity, and mortality in the United States, *Journal of Environmental Economics and Management* 63: 1.

Bartlett , S., et al., 2009. *Social aspects of climate change in urban areas in low- and middle- income nations.* World Bank Fifth Urban Research Symposium – Cities and Climate Change: Responding to an Urgent Agenda. http://www.dbsa.org/Vulindlela/Presentations/Session1_Dodman_old.pdf.

Bell, M. L, et al., 2007. Climate change, ambient ozone, and health in 50 U.S. cities, *Climatic Change* 82: 61–76.

Bierwagen, B. G., et al., 2010. National housing and impervious surface scenarios for integrated climate impact assessments, *PNAS,* DOI 10.1073/pnas.1002096107.

Blanco, H.. and M. Alberti, 2009. Building capacity to adapt to climate change through planning, in H. Blanco and M. Alberti (eds), Hot, Congested, Crowded, and Diverse: Emerging Research Agendas in Planning, Progress in Planning, 71: 153–205.

Blanco, H., et al., 2011. The role of urban land in climate change, in C. Rosenzweig, W.D. Solecki, S.A. Hammer, and S. Mehrotra (eds), *First Assessment Report on Climate Change and Cities (ARC3),* Cambridge University Press, New York.

Brekke, L. D., et al., 2009. *Climate Change and Water Resources Management—A Federal Perspective,* U.S. Geological Survey Circular 1331, 65 pp. http://www.pubs.usgs.gov/circ/1331/Circ1331.pdf

Brekke, L., D., 2011. *Addressing Climate Change in Long-Term Water Resources Planning and Management, User Needs for Improving Tools and Information,* U.S. Army Corps of Engineers Civil Works Technical Series CWTS-10-02, January. http://pubs.usgs.gov/circ/1331/Circ1331.pdf

Brody, S. D., S. Zahran, and G. H., Vedlitz, 2009. A spatial analysis of local climate change policy in the United States: Risk, stress, and opportunity. *Urban Studies* 46(2): 413–427.

Brown, T., W. Beyele, and D. Barton, 2004. Assessing Infrastructure Interdependencies: The Challenge of Risk Analysis for Complex Adaptive Systems, *Int. J. Critical Infrastructures* 1(1).

Bulkeley, H., 2010. Cities and the Governing of Climate change, *Annual Review of Environment & Resources* 35(1) 229–253.

California Energy Commission. 2009. *Potential Impacts of Climate Change on California's Energy Infrastructure and Identification of Adaptation Measures,* CEC-150-2009-001, January. www.energy.ca.gov/2009publications/CEC-150-2009-001/CEC-150-2009-001.pdf.

Case, T. , 2008. Climate Change and Infrastructure Issues, AWWA Research Foundation, Drinking Water Research, *Climate Change Special Issue* 18: 15–17.

Cela, M., J. Hulsey, and J. G. Titus, 2010. South Florida, in James G. Titus, Daniel L. Trescott, and Daniel E. Hudgens (eds), *The Likelihood of Shore Protection along the Atlantic Coast of the United States, Volume 2: New England and the Southeast,* Report to the U.S. Environmental Protection Agency, Washington, DC. www.risingsea.net/ERL/shore-protection-and-retreat-sea-level-rise-South-Florida.pdf.

Chang, H., et al., . 2010. Potential Impacts of Climate Change on Flood-Induced Travel Disruptions: A Case Study of Portland, Oregon, USA, *Annals of the Association of American Geographers,* 100(4): 1–14.

Chillymanjaro. 2011. San Diego power outage caused 2 million gallons of raw sewage spilled into Los Penasquitos Lagoon and Sweetwater River, *Pollution,* September 9, 2011. http://thewatchers.adorraeli.com/category/earth-changes/pollution-earth-changes

City of Boston. 2011. *A Climate of Progress,* City of Boston Climate Action Plan Update. http://www.cityofboston.gov/climate/bostonsplan/

Committee on Climate Change and U.S. Transportation, National Research Council. 2008. *Potential Impacts of Climate Change on U.S. Transportation,* Special Report 290, Transportation Research Board, March.

Condon, P. M., D. Cavens, and N. Miller, 2009. *Urban Planning Tools for Climate Change Mitigation,* Policy Focus Report, Lincoln Institute of Land Policy, Cambridge, MA. http://www.lincolninst.edu/pubs/1573_Urban-Planning-Tools

Corburn, J., 2009. Cities, Climate Change and Urban Heat Island Mitigation: Localising Global Environmental Science, *Urban Studies* 46(2): 413–427.

Curtis, K. J. and A. Schneider, 2011. Understanding the demographic implications of climate change: estimates of localized population predictions under future scenarios of sea-level rise, *Population and Environment,* DOI 10.1007/s11111-011-0136-2.

Daigger, G. 2008. New Approaches and Technologies for Wastewater Management, *The Bridge* 38(3), National Academy of Engineering.

Daigger, G. 2009. *Urban Water and Wastewater Management in 2050,* Proceedings ASCE World Environmental and Water Resources Congress, Kansas City, MO, May 17–21. Available in pdf format by searching Google by author and title.

Das, T., M. D. Dettinger, and D. R. Cayan, 2010. Potential impacts of global climate change on Tijuana River Watershed hydrology – An initial analysis, UCSD Sustainability Solutions Institute, University of California–San Diego, http://tenaya.ucsd.edu/~dettinge/global.html

DEFRA Report. 2011. Climate Resilient Infrastructure: Preparing for a Changing Climate, Synthesis of the independent studies commissioned by the Government's Infrastructure & Adaptation Project, http://www.defra.gov.uk/publications/2011/05/09/climate-resilient-infrastructure/

DeGraaf, R., and F. Hoolmeijer, *Urban Water in Japan, London: Taylor and Francis,* http://www.lib.muohio.edu/multifacet/record/mu3ugb3928264

Energy Sector Control Systems Working Group. 2011. Roadmap to Achieve Energy Delivery Systems Cybersecurity, September, English P. B., et al., 2009. Environmental Health Indicators of Climate Change for the United States: Findings from the State Environmental Health Indicator Collaborative, Environmental Health Perspectives 117(11): 1673–1681.

Federal Emergency Management Agency (FEMA), 1997. *Multihazard Identification and Risk Analysis,* Washington, DC.

Federal Railroad Administration. 2005. Washington, D.C. (2005–11), pp. 2–18 in "Report to Congress: Baltimore's Railroad Network, Challenges and Alternatives, http://www.fra.dot.gov/rpd/passenger/1605.shtml

Freas, K., 2010. Confronting Climate Change: An Early Analysis of Water and Wastewater Adaptation Costs Through 2050, pp. 1940–1966 in *Proceedings of the Water Environment Federation, WEFTEC 2010: Session 31 through Session 40.* Available in pdf format by Googling author and title

Freight Transportation Economic Assessment Report, 2008. "Storm-related Closures of I-5 and I-90,, Winter 2007-2008," Washington State Department of Transportation, Freight Systems Division, WA-RD 708.1.

Frumkin, H. et al., 2008. Climate change: the public health response, *American Journal of Public Health* 98: 435–445.

Galloway, G., 2009. Flood Risk Management Circa 2050, *ASCE Proceedings World Environmental and Water Resources Congress,* Kansas City, MO, May 17–21, http://cedb.asce.org/cgi/WWW display.cgi?171643

GCRP, 2009. *Global Climate Change Impacts in the United States,* US Global Change Research Program, Washington, DC.

Gleick, P. 2010. Roadmap for Sustainable Water Resources in Southwestern North America, *Proceedings of the National Academy of Sciences* 21300–21305, December 14.

Gosling, S.N., G. N. McGregor, and J. A. Lowe, 2009. Climate change and heat-related mortality in six cities, Part 2: climate model evaluation and projected impacts from changes in the mean and variability of temperature with climate change, *International Journal of Biometeorology* 53(1): 31–51, DOI: 10.1007/s00484-008-0189-9.

Grayman, W., 2009. Environmental and Developmental Risks and Stressors Impacting a 2050 Vision, *ASCE Proceedings World Environmental and Water Resources Congress,* Kansas City, MO, May 17–21. http://ascelibrary.org/proceedings/resource/2/ascecp/342/41036/232_1?isAuthorized=no

Hadjsaid M., et al., 2010. Interdependencies of coupled heterogeneous infrastructures: the case of ICT and Energy, in IDRC Davos 2010, 3rd International Disaster and Risk Conference, Davos, Switzerland, http://hal.archives-ouvertes.fr/hal-00611581/

Hallegatte, S., et al.. 2011. Assessing climate change impacts, sea level rise and storm surge risk in port cities: a case study on Copenhagen, *Climatic Change* 104(1): 113–137.

Hamin, E. M. and N. Gurran , 2009. Urban form and climate change: Balancing adaptation and mitigation in the U.S. and Australia, *Habitat International* 33(3): 238–245.

Hammer, S. A., et al., 2011. Climate change and urban energy systems, in C. Rosenzweig, W. D. Solecki, S. A. Hammer and S. Mehrotra (eds), *First Assessment Report on Climate Change and Cities (ARC3),* Cambridge University Press, New York, uccrn.org/wp-content/uploads/2011/06/ARC3-Chapter-4.pdf

Haveman, J. D., and H. J. Shatz, 2006. *Protecting the Nation's Seaports: Balancing Security and Cost.* Public Policy Institute of California, http://www.ppic.org/content/pubs/report/R606JHR.pdf

Hayhoe,, K., et al., 2010. *An Integrated Framework for Quantifying and Valuing Climate Change Impacts on Urban Energy and Infrastructure: A Chicago Case Study,* International Association for Great Lakes Research, July, http://www.sciencedirect.com/science/article/pii/S0380133010000547

Heaney, J. J. , 2009. Urban Stormwater Management in 2050, *ASCE Proceedings World Environmental and Water Resources Congress,* Kansas City, MO, May 17–21.

INRIX, Inc. 2011. *INRIX National Traffic Scorecard 2010 Annual Report,* http://scorecard.inrix.com/scorecard.

Interagency Climate Change Adaptation Task Force, Draft National Action Plan: Priorities for Managing Freshwater Resources in a Changing Climate, June 2, 2011.

IPCC. 2007. Summary for Policymakers, Contribution of Working Group I to S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M.Tignor and H.L. Miller (eds), *Climate Change 2007: The Physical Science Basis,* Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge and New York, http://www.ipcc.ch/pdf/assessment-report/ar4/wg1/ar4-wg1-spm.pdf

Jacob, D. J. and D. A. Winner, 2009. Effect of climate change on air quality, *Atmospheric Environment* 43(1): 51–63.

Kannan, S. "The Growing Market for Smart Growth: Consumer Demand and Demographic Drivers." Presentation, Feb. 2010. Slide 8. http://www.rclco.com/pdf/Market_for_Smart_Growth.pdf

Keegan, K., 2011. Four Big Unanswered Blackout Questions, posted Fri, Sep 9, 8:20 pm, and updated Fri, Oct 14, 5:10 pm, http://www.voiceofsandiego.org/data-drive/article_dc4aabe6-db5b-11e0-97ba-001cc4c03286.html

Kirshen P., K.. Knee, and M. Ruth, 2008. Climate change and coastal flooding in Metro Boston: Impacts and adaptation strategies, *Climatic Change* 90: 453–473.

Kirshen, P., M. Ruth, and W. Anderson, 2008. Interdependencies of Urban Climate Change Impacts and Adaptation Strategies: A Case Study of Metropolitan Boston USA, *Climatic Change* 86: 105–122.

Koetse, M. J., and P. Rietveld, 2009. The impact of climate change and weather on transport: An overview of empirical findings, *Transportation Research Part D: Transport and Environment,* 14(3).

Kousky, C., et al., 2009. *Responding to Threats of Climate Change Mega-Catastrophes,* RFF DP 09-45, Resources for the Future Faculty Research Working Paper Series.

Krause, R. M., 2011. Policy innovation, intergovernmental relations, and the adoption of climate protection initiatives by U.S. cities, *Journal of Urban Affairs* 33(1): 45–60.

Leichenko, R., K. O'Brien, and W. Solecki, 2010. Climate Change and the Global Financial Crisis: A Case of Double Exposure, *Annals of the Association of American Geographers* 100(4): 963–972.

Lempert, R. J., and D. G. Groves, 2010. Identifying and Evaluating Robust Adaptive Policy Responses to Climate Change for Water Management Agencies in the American West, *Technological Forecasting and Social Change* 77: 960–974.

Logan, G.,, S. Siejka, and S. Kannan, 2009. The Market for Smart Growth." EPA. 2009. http://www.epa.gov/smartgrowth/pdf/logan.pdf and National Association of Realtors. *2011 Community Preference Survey.* 2011. http://www.realtor.org/government_affairs/smart_growth/survey

Lovins, A. and H, Lovins, 1982. *Brittle Power: Energy Strategy for National Security,* Brick House Publishing Company.

Luber, G., and M. McGeehin, 2008. Climate change and extreme heat events, *American Journal of Preventive Medicine* 35(5): 429–435.

Major, D.C., et al., 2011. Water and wastewater, in C. Rosenzweig, W. D. Solecki, S. A. Hammer and S. Mehrotra (eds), *First Assessment Report on Climate Change and Cities (ARC3),* Cambridge University Press, New York.

Massachusetts, State of, 2011. *Climate Change Adaptation Report,* Executive Office of Energy and Environmental Affairs and the Adaptation Advisory Committee, State of Massachusetts, September. http://www.mass.gov/eea/air-water-climate-change/climate-change/climate-change-adaptation-report.html

McEvoy, D., S. Lindley and J. Handley, 2006. Adaptation and mitigation in urban areas: synergies and conflicts, *Proceedings of the Institution of Civil Engineers* 159(4): 185–191.

McGranahan, G., D. Balk, and B. Anderson, 2007. The rising tide: Assessing the risks of climate change and human settlements in low elevation coastal zones, *Environment and Urbanization* 19: 17–37.

Meehl, G. A., et al., 2007. Global climate projections, in *Climate Change 2007: The Physical Science Basis,* Cambridge University Press, Cambridge.

Mehrotra, S., et al., 2011. Climate change and urban transportation systems, in C. Rosenzweig, W.D. Solecki, S.A. Hammer and S. Mehrotra (eds), *First Assessment Report on Climate Change and Cities (ARC3),* Cambridge University Press, New York.

Morsch, A. and R. Bartlett, 2011. *State Strategies to Plan for and Adapt to Climate Change,* Policy Brief, Nicholas Institute, Duke University, October, http://nicholasinstitute.duke.edu/climate/adaptation/state-strategies-to-plan-for-and-adapt-to-climate-change

Myers, C. A., T. Slack, and J. Singelmann, 2008. Social vulnerability and migration in the wake of disaster: The case of Hurricanes Katrina and Rita, *Population and Environment* 29: 271–291.

National Academy of Engineering (NAE), 1988. *Cities and Their Vital Systems: Infrastructure Past, Present, and Future.* National Academy of Engineering.

National Research Council (NRC), 1999. *The Impacts of Natural Disasters: A Framework for Loss Estimation,* Washington, DC: NAS Press.

National Research Council (NRC), 2010. *Adapting to the Impacts of Climate Change, America's Climate Choices: Panel on Adapting to the Impacts of Climate Change.*

National Science Foundation. 2009. *NSF solving the puzzle: Researching the impacts of climate change around the world.*

Nelson, K .C., et al., 2009. Forecasting the combined effects of urbanization and climate change of stream ecosystems: from impacts to management options, *Journal of Applied Ecology* 46(1): 154–163.

Newman, M. E. J., 2010. *Networks: An Introduction,* Oxford University Press, New York

New York City Department of Environmental Protection, 2011. *Guidelines for the Design and Construction of Stormwater Management Systems, Developed in Consultation with the New York City Department of Buildings.*

Nicholls, R. J., et al., 2008. *Ranking Port Cities with High Exposure and Vulnerability to Climate Extremes: Exposure Estimates,* OECD Environment Working Papers, No. 1, November. http://www.aia.org/aiaucmp/groups/aia/documents/pdf/aias076737.pdf

Novotny, V., and P. Brown P., 2007. Cities of the Future: Towards Integrated Sustainable Water and Landscape, proceedings of an international workshop held July 12–14, 2006, in Wingspread Conference Center, Racine, WI, IWA Publishing, London, www.coe.neu.edu/environment/events/cotf.pdf

Ntelekos, A. A., et al., 2010. Urbanization, climate change and flood policy in the United States, *Climatic Change* 103: 597–616.

NYCDEP (New York City Department of Environmental Protection), 2008. *Assessment and Action Plan: A Report Based on the Ongoing Work of the DEP Climate Change Task Force,* New York City Department of Environmental Protection Climate Change Program, New York. http://www.nyc.gov/html/dep/.../news/climate_change_report_05-08.shtml

O'Neill, M. S., et al., 2010. US local action on heat and health: are we prepared for climate change? *International Journal of Public Health* 55(2): 105–112.

O'Neill, M. S., and K. Ebi. 2009. Temperature extremes and health: impacts of climate variability and change in the United States, *Journal of Occupational & Environmental Medicine* 51(1): 13–25.

O'Rourke, K., A. Rahman, and A. Taylor, 2007. "Trade, Knowledge, and theh Industrial Revolution," Institute for International Integration Studies Discussion Paper Series, IISDP 219.

Opperman , J., et al., 2009. Sustainable floodplains through large-scale reconnection to rivers, *Science* 326: 11.

Peerenboom, J. P., R. E. Fisher, and R. Whitfield, 2001. Recovering from Disruptions of Interdependent Critical Infrastructures, presented at the CRIS/DRM/IIIT/NSF Workshop, Alexandria, VA, September 10–11, 2001. http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=4076595&userType=inst

Pejovic, T., et al., 1997. Factors Affecting the Frequency and Severity of Airport Weather Delays and the President's Commission on Critical Infrastructure Protection, *Critical Foundations: Protecting America's Infrastructures,* October, http://www.fas.org/sgp/library/pccip.pdf.

Pejovic, T., et al., 2009. Factors Affecting the Frequency and Severity of Airport Weather Delays and Implications of Climate Change for Future Delays, *Transportation Research Record: Journal of the Transportation Research Board* 2139: 97–106.

Philadelphia Water Department. 2011. *Green City Clean Waters, The City of Philadelphia's Program for Combined Sewer Overflow Control,* amended June 1. http://www.phillywatersheds.org/what_were_doing/documents_and_data/cso_long_term_control_plan

Prasad, N., F. Ranghieri, and F. Shah (eds), 2009. *Climate Resilient Cities,* World Bank, Washington, DC.

President's Commission on Critical Infrastructure Protection, 1997. *Critical Foundations: Protecting America's Infrastructures,* October, http://www.fas.org/sgp/library/pccip.pdf.

Pyke, C, et al., 2011. Assessment of Low Impact Development for Managing Stormwater with Changing Precipitation due To Climate Change, *Landscape and Urban Planning* 103(2), Nov 30.

Ray, P., P. Kirshen, and D. Watkins, 2011. Stochastic Programming for Integrated Climate Change Adaptation of the Water Supply System of Amman, Jordan, *Journal of Water Resources Planning and Management* (in press).

Reid, H., and S. Kovats, 2009. Special issue on health and climate change of TIEMPO, *Bulletin on Climate and Development,* Vol. 71.

Rinaldi, S., J. P. Peerenboom , and T. K. Kelly, 2001. Identifying, Understanding and Analyzing Critical Infrastructure Interdependencies, *IEEE Control Systems Magazine,* December.

Rosato, V., et al., 2008. Modeling interdependent infrastructures using interacting dynamical models, *International Journal of Critical Infrastructures,* 63.

Roseen, R, et al., 2011. *Forging the Link Linking the Economic Benefits of Low Impact Development and Community Decisions,* The UNH Stormwater Center, University of New Hampshire, July. https://cariregistration.unl.edu/wconnect/ace/Custom/PCSW/flyer.pdf

Rosenberg, E. A., et al., 2009. Precipitation Extremes and the Impacts of Climate Change on Stormwater Infrastructure in Washington State, in *The Washington Climate Change Impacts Assessment,* DOI 10.1007/s10584-010-9847-0. Available in pdf format by Googling author and title.

Rosenzweig, C., D. C. Major, and K. Demong, 2007. Managing climate change risks in New York City's water system: Assessment and adaptation planning, *Mitigation and Adaptation Strategies for Global Change* 12(8): 1391–1409.

Rosenzweig, C., and W. Solecki, (eds), 2010. Climate Change Adaptation in New York City: Building a Risk Management Response—Report of New York City Panel on Climate Change, *Annals of New York Academy of Sciences* 1196: 1–354.

Rosenzweig, C., W. D. Solecki and A. Degaetano, (eds). 2011. Responding to Climate Change in New York State: The ClimAID Integrated Assessment for Effective Climate Change Adaptation Final Report, Annals of the New York Academy of Science 1244: 2–649.

Rosenzweig, C., et al., (eds), 2011. *First Assessment of Research on Climate Change in Cities,* Cambridge University Press.

Rosner, A., R. Vogel, and P. R., Kirshen, 2011. Climate Change Adaptation Decisions Using Risk-Informed Trend Analysis, poster presented at NOAA's 36th Climate Diagnostics and Prediction Workshop, Fort Worth, TX, Oct 3–6. http://m.coreapps.com/agu2011/abstract/a505d5411b790df6de823079f9fcd6af

SAP 4.5 (CCSP), 2007. *Effects of Climate Change on Energy Production and Use in the United States,* a Report by the U.S. Climate Change Science Program and the subcommittee on Global Change Research [Thomas J. Wilbanks, et al., eds)], Department of Energy, Office of Biological & Environmental Research, Washington, DC., 160 pp.

SAP 4.6 (CCSP), 2008. Effects of Global Change on Human Settlements, T. Wilbanks et al., in *Analyses of the Effects of Global Change on Human Health and Welfare and Human Systems,* U.S. Environmental Protection Agency, September.

SAP 4.7. (CCSP), 2008. *Impacts of Climate Variability and Change on Transportation Systems and Infrastructure – Gulf Coast Study.* U.S. Department of Transportation and U.S. Geological Survey.

SFBCDC (San Francisco Bay Conservation and Development Commission). 2011. Living with a Rising Bay: Vulnerability and Adaptation in San Francisco Bay and on Its Shoreline, http://ww.bcdc.ca.gov

Solecki, W., K. O'Brien, and R. Leichenko, 2011. Disaster risk reduction and climate change adaptation strategies: convergence and synergies, *Current Opinion in Environmental Sustainability* 3: 135–141.

SREX, IPCC. 2012. Summary for Policymakers, pp. 1–19 in C.B. Field, V. Barros, et al., (eds), *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation,* A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge and New York.

Stakhiv, E., 2010. Practical Approaches to Water Management under Climate Change Uncertainty, *Workshop on Nonstationarity, Hydrologic Frequency Analysis, and Water Management,* R. Olsen, J. Kiang, and R. Waskom (eds), Colorado Water Institute Information Series No 109. http://onlinelibrary.wiley.com/doi/10.1111/j.1752-1688.2011.00589.x/full

Stone, B., J., J. Hess , and F. Howard, 2010. Urban Form and Extreme Heat Events: Are Sprawling Cities More Vulnerable to Climate Change Than Compact Cities? *Environmental Health Perspectives* 118(10): 1425–1428.

Thames Estuary 2100. 2009. *Managing Flood Risk though London and the Thames Estuary,* Consultation Document, Thames Estuary 2100 Environment Agency, London. http://www.preventionweb.net/english/professional/publications/v.php?id=20496

Titus, J. G., and C. Richman, 2001. Maps of lands vulnerable to sea level rise: Modeled elevations along the US Atlantic and Gulf coasts, *Climate Research* 18: 205–228.

Titus J. G. et al., 2009. State and local governments plan for development of most land vulnerable to rising sea level along the US Atlantic coast, *Environmental Research Letters* 4: 1–7.

Transportation Research Board, 2008. *Potential Impacts of Climate Change on U.S. Transportation,* TRB Special Report 290, National Research Council, Washington, DC.

Travis, W. R., 2010. Going to extremes: propositions on the social response to severe climate change, *Climatic Change* 98: 1–19.

United Nations Conference on Trade and Development, 2009. *Multi-Year Expert Meeting on Transport and Trade Facilitation: Maritime Transport and the Climate Change Challenge,* Summary of Proceedings, Feb 16–18, Geneva. http://www.unctad.info/en/Special-Unit-on-Commodities/Events-and-Meetings/Multi-Year-Expert-Meeting/

U.S. Army Corps of Engineers, 2009. Institute for Water Resources, *Flood Risk Management: Value to the Nation,* http://www.corpsresults.us

U.S. Census Bureau, 2011. *Population Distribution and Change: 2000 to 2010,* U.S. Census Bureau, Washington, DC, March. http://www.census.gov/prod/cen2010/briefs/c2010br-01.pdf

U.S. Environmental Protection Agency, 2010. Climate Change Vulnerability Assessments: A Review of Water Utility Practices, Office of Water, EPA 800-R-10-001, August.

U.S. Environmental Protection Agency, 2010. Green Infrastructure Case Studies, U.S. EPA, Washington, DC, August. Available in pdf format by Googling author and title.

U.S.-Canada Power System Outage Task Force. 2004. Final Report on the August 14, 2003 Blackout in the United States and Canada: Causes and Recommendations, April. http://www.nrcan.gc.ca/energy/sources/electricity/1378

Vano, J., et al., 2010. Climate change impacts on water management in the Puget Sound region, Washington State, USA, *Climatic Change* 102: 261–286.

Villasenor, J., 2011. *Securing an Infrastructure Too Complex to Understand,* Brookings Institution, Sep 23. http://www.brookings.edu/opinions/2011/0923_infrastructure_villasenor.aspx

Vugrin, E. D., 2010. Measurement and Optimization of Critical Infrastructure Resilience, presentation to the 4th Annual Meeting of the Security and Risk Management Association, Arlington, VA, Oct 5, 2010 (journal paper in preparation).

Vugrin, E. D., and R. C. Camphouse, 2011. Infrastructure resilience assessment through control design, *International Journal of Critical Infrastructures* 7(3): 243–260.

Vugrin, E. D., Warren D.E., Ehlen M.A. 2011. A resilience assessment framework for infrastructure and economic systems: Quantitative and qualitative resilience analysis of petrochemical supply chains to a hurricane, *Process Safety Progress* 30(3): 280–290.

Vugrin, E .D., et al., 2010. A Framework for Assessing the Resilience of Infrastructure and Economic Systems, in K. Gopalakrishnan and S. Peeta (eds), *Sustainable and Resilient Critical Infrastructure Systems: Simulation, Modeling, and Intelligent Engineering,* Springer-Verlag, 2010.

Wamsley, T., et al., 2010. The Potential of Wetlands in Reducing Storm Surge, *Ocean Engineering* 37: 59–68.

Warner, K., et al., 2009. *In Search of Shelter: Mapping the Effects of Climate Change on Displacement and Migration,* a joint effort of the United Nations University Institute for Environment and Human Security, CARE International, and the Center for International Earth Science Information Network at the Earth Institute of Columbia University. http://www.care.org/getinvolved/advocacy/pdfs/Migration_Report.pdf

Water Environment Research Foundation (WERF). 2009. Implications of Climate Change for Adaptation by Wastewater and Stormwater Agencies, CC2R08, prepared by Stratus Consulting Inc. and MWH Global Inc., December 2009. http://www.werf.org/a/k/Search/ResearchProfile.aspx?ReportID=CC2R08

Water Sector Coordinating Council Cyber Security Working Group. 2008. *Roadmap to Secure Control Systems in the Water Sector,* http://www.awwa.org/files/GovtPublicAffairs/PDF/WaterSecurityRoadmap031908.pdf

Webster, P . J., G. J. Holland, J. A. Curry , and J.-R. Chang, 2005. Changes in Tropical Cyclone Number, Duration, and Intensity in a Warming Environment, *Science,* New York. www.sciencemag.org/content/309/5742/1844.full.pdf.

Wheeler, T. B., and M. G. Hare, 2011. Hurricane Irene leaves sewage spills in wake, *The Baltimore Sun,* Sep 2. http://articles.baltimoresun.com/2011-09-02/news/bs-md-sewage-spill-20110902_1_sewage-spills-gallons-of-raw-sewage-david-fidler

WHO (World Health Organization), 2009. *Protecting Health from Climate Change: Connecting Science, Policy and People,* World Health Organization, Geneva. http://www.who.int/globalchange/publications/reports/9789241598880/en/index.html

Wilbanks, T., J. and R. W. Kates, 2010. Beyond Adapting to Climate Change: Embedding Adaptation in Responses to Multiple Threats and Stresses, *Annals of the Association of American Geographers* 100(4): 719–728.

Wilby, R. L., 2007. A review of climate change impacts on the built environment, *Built Environment* 33: 1.

Wilson, S. G., and T. R. Fischetti, 2010. *Coastal population trends in the U.S.: 1960–2008,* U.S. Bureau of the Census, Washington, DC. http://www.consesus.gov/prod/2010pubs/p25-1139.pdf.

World Economic Forum. 2010. *Positive Infrastructure: A Framework for Revitalizing the Global Economy,* Geneva. http://www.weforum.org/pdf/ip/ec/Positive-Infrastructure-Report.pdf.

Yohe, G., 2009. Toward an Integrated Framework Derived from a Risk-Management Approach to Climate Change: an Editorial Comment, *Climatic Change,* 95: 325-339.

Zhang, K. Q., B. C. Douglas, and S. P. Leatherman, 2000. Twentieth-century storm activity along the U.S. east coast, *Journal of Climate* 13: 1748–1761.

Zimmerman, R. , 2006. Critical Infrastructure and Interdependency, Chapter 35, pp. 523–545 in D.G. Kamien (ed), *The McGraw-Hill Homeland Security Handbook,* McGraw-Hill, New York.

Zimmerman, R., 2012. *Transport, the Environment and Security: Making the Connection,* Edward Elgar Publishing, London.

Zoltay, V., et al., 2010. Integrated watershed management modeling: A generic optimization model applied to the Ipswich River Basin, *Journal of Water Resources Planning and Management.*