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Interdependencies of urban climate change impacts and adaptation strategies: a case study of Metropolitan Boston USA

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Abstract An analysis of the interdependencies of the impacts of climate change and adaptation strategies upon infrastructure systems in the Metro Boston urban area in the northeastern USA found that taking anticipatory actions well before 2050 results in less total adaptation and impact costs to the region than taking no actions. Because of the interrelations among infrastructure systems, it is critical to take account of the impacts that adaptation actions have on each other and other systems. For the most part these cross-system effects are complementary in nature. But there are important exceptions, so an integrated approach to adaptation policy formulation is needed. Furthermore, adaptation efforts must be designed so as not to confound mitigation efforts.

1 Introduction

Only recently have researchers started to investigate potential impacts of climate change and adaptation strategies in urban areas (here we include suburban land use within our definition of urban) – the places of much economic and social activity. Moreover, most of these urban studies are sector or system specific, concentrating, for examples, on implications of climate change for water supply, coastal flooding or air quality. Urban areas rely upon a complex set of infrastructure systems to provide human, environmental and economic services. Examples

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include flood control, water supply, drainage, wastewater management, solid and hazardous waste management, energy, transportation, and constructed facilities for residential, commercial, and industrial activities. One of the features of urban areas is that the different infrastructure systems are physically close to each other and have the potential to positively interact with each other. For example, in urban areas, it is possible to economically use reclaimed wastewater for industrial cooling, use waste heat from power plants for district heating, install dual quality water supply systems, and manage storm runoff and improve low flows by recharging runoff. The interdependencies and physical proximities of systems in urban areas, however, can have negative consequences as well. For example, failures in wastewater treatment systems can increase requirements for water supply treatment, increase flood losses because of contaminated flood waters, and decrease availability of cooling water for power plants because of inadequate quality. These cumulative impacts can cause disruption of commercial, industrial, and domestic activities and have major ripple effects upon a region's economy (Ruth et al. in press). Here, in the context of the metro Boston region, we analyze the interdependencies of the impacts of climate change and adaptation strategies upon infrastructure systems in urban areas.

There have been several in depth assessments of the implications of climate change on multiple infrastructure systems in urban areas in the United States. These include Bloomfield et al. (1999) and Rosenzweig et al. (2000) for the New York Metropolitan Area, Koteen et al. (2001) for Los Angeles, Kirshen et al. (2004) for Metropolitan Boston and Hoo and Sumitani (2005) for the Seattle Department of Transportation. Outside of the United States, Holman et al. (2005a,b) conducted an integrated assessment that included some urban areas in the United Kingdom and Jollands et al. (2005, 2006) analyzed impacts of climate change on multiple systems in Hamilton and Wellington, New Zealand. Of the USA studies, only the Metropolitan Boston study (known as CLIMB – Climate's Long-term Impacts on Metro Boston) and the research by Rosenzweig et al. (2000) included assessments of cross-system issues with the Boston research focusing considerably more upon this aspect. One of the recommendations of the Seattle research was that an interdepartmental team be established to consider cross-system issues.

After a brief summary of the CLIMB project, impact and adaptation interdependencies are examined. The CLIMB research addressed many of the adaptation research needs identified by Yohe and Schlesinger (2002) including reviewing options, considering local conditions and uncertainty, and calculating the costs of adaptation. It also included many of the elements of adaptation studies identified by Baethgen et al. (2004). While these are primarily for the developing world, they are research needs for all adaptation studies: targeting local decision makers, investigating sources of stress along with climate change, including uncertainty, use of multidimensional case studies and quantitative modeling, and involvement of stakeholders.

2 The CLIMB project

Even though urban infrastructure systems are important and are designed according to socioeconomic and environmental conditions that are very sensitive to climate, as previously noted there have been few major integrated assessments of the impacts of climate change on metropolitan infrastructure systems and services. Since infrastructure systems last considerably longer than decades (some a century or more) and provide the footprint and direction for future development, it is important that decision-makers understand the short- and long-term consequences of climate change on infrastructure.

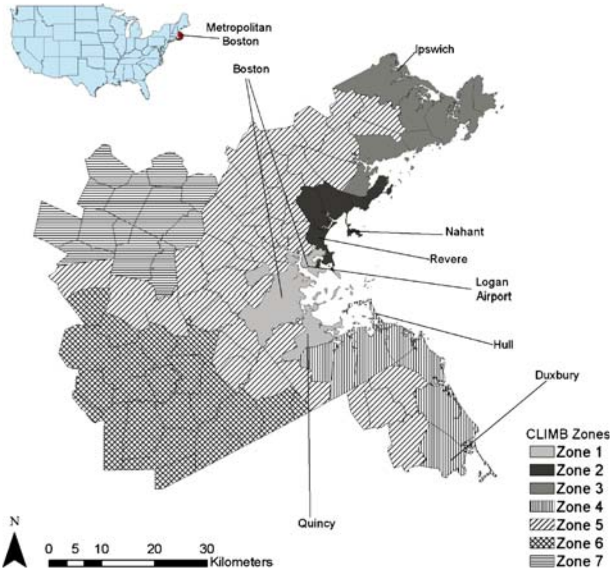

Fig. 1 Seven CLIMB Zones Zone 1 = South Coastal Urban, Zone 2 = North Coastal Urban, Zone 3 = North Coastal Suburban, Zone 4 = South Coastal Suburban, Zone 5 = Developed Suburbs, Zone 6 = Developing Suburbs South, Zone 7 = Developing Suburbs North

The CLIMB project was conducted from 1999 to 2004 by a multidisciplinary research team from Tufts University, University of Maryland, and Boston University with assistance from the Metropolitan Area Planning Council (Metropolitan Area Planning Council 1998) and a Stakeholder Advisory Committee composed of representatives of government and other interest groups and infrastructure and planning experts. The methodology and results are summarized in Ruth and Kirshen (2001) and Kirshen et al. (2006), and are available in full in Kirshen et al. (2004).

Metro Boston, which is located in the northeastern United States, is shown in Fig. 1 and includes the major cities of Boston and Cambridge and the other 99 municipalities within approximately 20 miles of Boston. The area is bordered on the east by Boston Harbor (the confluence of three major rivers) and on the south, west, and north approximately by the circumferential Route 495, covering an area of 3,683 km^2. Metro Boston's population is approximately 3.2 million and is expected to increase to 4.0 million by 2050. Land use varies from densely populated urban areas in the east, suburbs in the center, and undeveloped farmland and some urban "sprawl" on the fringes. It is the heart of the New England economy and provides its major airport, and seaport facilities. The region is currently experiencing pressure on most of its infrastructure systems and severe development pressure in the municipalities just outside of the core city areas. It is characterized by a climate with four distinct seasons with annual precipitation of 1,000 m relatively evenly distributed throughout the year; some as snow in the winter. The average monthly temperature is approximately 10°C.

3 Methodology

Potential changes in infrastructure performance play themselves out across space and time, owing to differences in infrastructure densities and use, differences in environmental conditions, and the long-term nature of climate change as well as the long-lived nature of the various infrastructure systems. To capture spatial variations in climate change impacts on Metro Boston, seven subregions or zones are distinguished (Fig. 1) such that:

- Coastal regions are treated separately from regions inland;
- Areas north of the city of Boston, which have different coastal properties and socioeconomic features, are delineated from southern parts of the MAPC region;
- Highly urbanized areas are dealt with separately from suburbs; and
- Rapidly growing suburbs are distinguished from already highly developed and densely populated ones.

In most cases, annual impacts from 2000 to 2100 were examined under one set of demographic projections, two climate change scenarios in addition to the present climate, and three possible adaptations responses to climate change. The demographic projections to 2050 were based upon the "medium scenario assumption" done for the region as part of the US national assessment of climate change (NPA Data Services Inc 1999) adjusted by the local projections of the MAPC (1998). The scenarios were based upon assumed trends in fertility, mortality, migration, labor force participation and productivity. After 2050, the CLIMB study assumed that there were no significant demographic changes in the region. We did not use another demographic projection because it would have added too much complexity to the results with three adaptation scenarios and two climate scenarios; we wanted to emphasize adaptation and climate sensitivities. The climate change scenarios were chosen to be the same that were used for the region for the US national assessment of climate change (New England Regional Assessment Group 2001). These were based upon the general circulation models (GCM) CGCM1 from the Canadian Climate Centre and HadCM2 from the Hadley Center. The greenhouse gas emission scenario assumed a 1% annual increase in equivalent CO2 and included the direct effects of sulphate aerosols in the atmosphere (IS92a scenario). Based upon their values of Transient Climate Response from Working Group I, Intergovernmental Panel on Climate Change (2001), CGCM1 is at the high end of the temperature change range, HadCM2 is mid range. Scenario data were obtained for the inland grid cell closest to our study area for 2030 and 2100 climate scenarios. We judged using the inland cell was appropriate for our research and that the downscaled results did not differ significantly from more coastal grid cells. A summary of scenarios for seasonal impacts in our study area is in Table 1. One scenario is humid and warm, the other more humid and less warm. Historical time series of past monthly climate conditions were then modified to represent future possible climate changes by increasing historical temperatures by the possible GCM

Table 1 Summary of climate change scenarios for Metro Boston – compared to 1961–1990

	2030 Seasonal temperature increase (C) (W S S F)	2095 Seasonal temperature increase (C) (W S S F)
GCM		
CGCM1	2.15, 0.81, 1.54, 0.78(1.32 annual)	5.40, 6.00, 4.29, 3.57 (4.8 annual)
HadCM2	1.21, 0.98, 1.41, 0.78 (1.10 annual)	3.32, 2.40, 3.08, 3.00 (2.95 annual)
	2030 Ratio precipitation change	2100 Ratio precipitation change
CGCM1	−0.05, 0.14,0.06, −0.03 (0.00 annual)	0.07, 0.17, −0.02, 0.02 (0.06 annual)
HadCM2	0.17, 0.10, 0.08, 0.07 (0.10 annual)	0.36, 0.01, 0.27, 0.28 (0.23 annual)

W S S F = winter, spring, summer, fall

temperature increases and changing precipitation and other climate parameters by the ratio of the parameter changes compared to present conditions in the GCMs. If the time step of an analysis for an infrastructure system was annual, annual differences were used.

After the US national assessment was started, new scenarios of climate change become available that were analyzed with more complete GCMs and the IPCC Special Report on Emission Scenarios (SRES). As explained in more detail below, the climate change scenarios that CLIMB used are approximately equivalent to mean results of multiple GCMs under the A2 scenario and some aspects of the B1 scenario. A2 scenario results in a moderately high global temperature increase (A1FI results in the highest temperature increase) and B1, the lowest increase (WGI, IPCC 2001). Therefore, the results from CLIMB are still relevant given the new scenarios.

For New England, the New England Regional Assessment Group (2001) reported an approximately 3–5°C temperature increase in the region (the six New England states plus upper New York state) in 2100 using the Hadley and Canadian models, respectively, and associated annual precipitation increases of 30 and 10%. Hayhoe et al. (in press) reported on climate change results based upon the output averages of nine of the latest coupled atmosphere-ocean general circulation models (AOGCMs) available from the IPCC database for the northeastern USA, which included the New England states, New York, Pennsylvania and New Jersey. The 3–5°C temperature increase is approximately equivalent for the 2100 temperature increases respectively for the B1 and A2 scenarios. The 2100 precipitation increase of 6% from the Canadian IS92a scenario is approximately the same as the A2 increase reported by Hayhoe et al. (in press). The 23% annual precipitation increase far exceeds the maximum increase value reported by Hayhoe et al. (in press) of 14% for the A1FI scenario. Therefore the IS92a scenario results from CGCM1 used in CLIMB are generally equivalent to mean results for A2 SRES scenarios. The Hadley temperature estimates used in CLIMB are similar to the B1 scenarios but not similar to the precipitation scenario results of Hayhoe et al. (in press).

The adaptation scenarios included:

- The "Ride it Out" (RIO) scenario in essence assumes that no adaptation to climate change occurs and that damages and benefits continue to occur with no attempts by society to minimize damages or maximize benefits.
- The "Green" scenario assumes conscious, sustainable responses to observed trends, as well as pro-active or anticipatory implementation of policies and technologies in efforts to counteract, and prepare for, adverse climate impacts. Some of the practices might be put in place before impacts are felt (for example, moving occupants out of flood plains), after impacts occur, or at the end of lifecycles of infrastructure systems.
- The "Build Your Way Out" (BYWO) scenario assumes that replacement of failed systems is undertaken and susceptible systems are protected by structural measures.

Generally we did not examine mixed, locally specific adaptation scenarios for each system. That is, for one adaptation scenario, we assumed that all infrastructure systems of one type would use the same adaptation approach. For example, we evaluated the consequences of the entire region adapting to river flooding by a structural approach, and then a nonstructural approach.

Regional systems analyzed included Energy Use, Sea Level Rise, River Flooding, Surface Vehicle Transportation, Water Supply, and Public Health (heat–stress mortality). Localized Case Studies were carried out for Water Quality, Tall Buildings, and Bridge Scour.

One somewhat unique feature of the CLIMB study was that dynamic modeling of the period 2000 to 2100 was used to analyze the performance of many of the critical infrastructure systems in Metro Boston. That is, interpolation was used to estimate annual climate and demographic changes in the CLIMB zones each year and then simulation models calculated the annual impacts in each infrastructure system under an assumed adaptation scenario. Impacts are sensitive to the timing of future climate events such as droughts or recurrent years of hot weather. For example, if a drought was to occur in 2020, it would have less impact than in 2050 when the population was greater. To remove these effects, bootstrapping (Vogel and Shallcross 1996) of the historical climate time series from 1960 to 2000 adjusted for climate change was used to determine 100 possible sequences of future climate events under each climate change scenario, analyses were done for each of the possible sequences, and then the results of each sequence averaged. The advantage of the dynamic analyses is that the impacts of the timing of adaptation actions can be explicitly determined.

Effects of the alternative assumptions about future climate, socioeconomic characteristics and technological potentials in the region were assessed with respect to various impacts to the region. As appropriate within each system, three broad categories of impacts were distinguished:

a) Loss of service: directly associated with a loss of service, such as number of lost days at work due to disruption of transportation services, loss of lives due to heat stress, decrease in reliability;
b) Repair/replacement: costs associated with restoring infrastructure systems and services to their pre-impact level;
c) Adaptation: cost of adjusting infrastructure systems and services to higher standards at which the experienced impact would have been avoided.

We did not discount any of the impacts. Implicitly, this assumes that property values and adaptation costs appreciated at the same rate and helps to avoid the ethical arguments surrounding the choice and magnitude of a discount rate.

A Stakeholder Advisory Group (SAG) made up of approximately 30 multi-level government officials, members of non-governmental organizations, and representatives from private industry was formed in the early stages of the project and used throughout the research to identify issues of regional concern, provide data sources, and, most importantly, ground-truth results. Interaction with the SAG took place several times each year through meetings of the entire group, public workshops, sectoral specific workshops, and individual contact.

4 Results

The conclusions of each infrastructure system are summarized below. Full results are in Kirshen et al. (2004) and in the papers referenced below.

As will be evident in the summaries below, the research conducted for each system had to be focused on particular aspects due to their relative importance and limitations in time, budgets, and data. The results of the research for each system, however, did provide guidance and insights into some of the other impacts on the system that we could not explore in detail. Some of these additional insights are included in the Section 5 of this paper.

Energy use The summer electricity demand increases for residential and commercial air conditioning due to climate change will cause negative impacts in the region. For example, by 2030 under both of our climate scenarios, per capita energy demand could more than double compared to the 1960–2000 average with climate change accounting for at least 20% of the increase. The remaining increase is due to the current trend in air conditioning proliferation due to a variety of demographic factors. Anticipatory adaptation could alter the region's energy demand response function to more effectively correspond with future climatic conditions via planned adjustments in the attributes of temperature-sensitive buildings and energy technologies (i.e. building thermal shells, air-conditioners, furnaces). Identifying potential impacts for the region now is important because the energy industry is extremely capital intensive and as a consequence the flexibility of policy induced changes in energy generation and demand trajectories over the short and medium run is limited. In the long run, as the capital stock naturally turns over, building codes may be changed to calibrate the thermal attributes of the building stock to expected future climates. However, such changes need to be implemented in the relatively near term or the building stock will become increasingly maladapted to climate. In the near term, polices such as urban shade tree planting and installation of high albedo roofs can begin to modify the thermal characteristics of the Massachusetts energy infrastructure in order to reduce space-conditioning energy use. More information is in Amato et al. (2005).

Coastal flooding and sea level rise Our findings on adaptation to increased storm surge impacts support those of others; it may be advantageous to use expensive structural protection in areas that are highly developed and take a less structural approach in less developed areas and/or environmentally sensitive areas. The option we considered for structural protection was expansion of existing seawalls and construction of new walls. Nonstructural approaches included retreat from the floodplain, limiting construction and reconstruction in floodplains. Our adaptation scenarios were based upon taking action well before 2050 or even earlier. Besides being more cost effective, the less structural approaches are no-regrets or co-benefit policies, are environmentally benign, and allow more flexibility to respond to future uncertain changes. While uncertainty in the expected rate of sea level rise and damages makes planning difficult, the results also show that no matter what the climate change scenario or the location, not taking action is the worst response. More information is available in Knee et al. (under review).

River flooding Our analysis of climate change impacts on river flooding indicate that the number of properties damaged and the overall cost of flood damage will both approximately double relative to what might be expected with no climate change in the future but with same demographic changes. The most severe incremental impacts will occur in the fast growing western suburbs. The likely economic magnitude of these damages is sufficiently high to justify large expenditures on adaptation strategies. The most extensive adaptation strategy – as incorporated in the "green" scenario of improved floodplain management – greatly reduces the incremental flood damage due to climate change. In fact, damages under the green strategy with climate change are substantially lower than might be expected in the absence of climate change but with no adaptation strategies.

Transportation This research examined impacts of increased flooding over the course of the twenty-first century on travel times and delays in the metro Boston road network. We found that there will be a major increase in delays and lost trips due to road flooding. For example, over the period 2000–2100, the aggregate traffic delay during flooding events measured in hours may increase by 80%. The economic impact of these delays and lost trips, however, will be relatively small because the increases are far less than the aggregate magnitude of the delays during nonflood events. It is unlikely that infrastructure improvements such as realignment of roadways in river valleys can be justified on a cost-benefit basis. Thus, increased weather induced delays are a nuisance that motorists will have to endure as the frequency of extreme rain events increases. More details are in Suarez et al. (2005).

Water supply In the eastern section of the region, most of the water is supplied by the regional system of the Massachusettts Water Resources Authority (MWRA) which utilizes two large reservoirs in central Massachusetts as sources. The remainder of the region is served by local groundwater and surface water systems with limited storage capacity. Under the climate change scenario with the least future precipitation and the adaptation actions considered in the report, only by the local systems joining the MWRA and using the regional system to supplement their supplies is it possible for them to meet demands under climate and demographic changes. Even with the higher demands on it under this scenario, the reliability of the regional MWRA systems remains manageable in the future under climate and demographic changes. Since presently the MWRA is not obligated to serve all locally supplied systems in event of temporary or permanent shortages, local systems should consider anticipating climate and demographic changes by using adaptation actions such as demand management coupled with actions not analyzed in this study such as increasing instream flows through better storm water management, increasing system storage capacity though reservoirs or aquifer use, and considering using such water supply sources as reclaimed wastewater and desalination. Implementation of these actions has historically taken long lead-times.

Public health Only impacts related to heat–stress mortality were analyzed. Using statistical analysis of historic heat-related mortality adjusted for monthly trends, daily maximum temperature, and other factors, we found that there will be slightly higher average heat–stress mortality until about 2010 under climate change compared to the base case. From 2010 onward, mortality declines more rapidly under climate change than without it and from approximately 2012 onward, the number of deaths actually declines as the number of heat events increases. One explanation behind this observed reversal lies in the effects that repeated events may have on a population's adaptive behavior – the more frequent the number of events, the more may the population be prepared to dealing with them. These findings, however, assume that current adaptation trends in the region continue such as increases in the use of air conditioning, and improvements in health care and the use of early warning systems for individuals most prone to changes in temperature. Besides maintaining these trends, additional adaptations to climate change may be needed. For example, the region has seen only few efforts to increase the use of shade trees to decrease albedo, increase moisture retention and thus contribute to local cooling. Similarly, little new construction uses materials or designs that reduce a building's albedo, its heating and cooling needs, and thus energy consumption and impacts on local air quality. Such engineering approaches to prepare the local building stock to a changing climate, together with appropriate zoning and transportation planning could go a long way in reducing, for example, urban heat island effects, which may be exacerbated by climate change. For these results to be achievable requires aggressive investments in all areas ranging from health care to space cooling to smart land use, as well as the local population adjusting their activities sensitive to outdoor temperatures. More details are presented in Ruth et al. (2006).

Water quality management A steady state, one dimensional water quality model was used to conduct a localized case study in a suburban area of the impacts of lower, warmer summer streamflows and more nonpoint source pollution (NPS) on stream dissolved oxygen. The river also receives discharges from several municipal wastewater treatment plants that remove most organic and nutrient material. It was found that the additional costs to adapt to climate change with or without population growth are significant because of the high costs of extra nonpoint source pollution management. These results point to the need to consider the integrated impacts of temperature, streamflow, precipitation, land use, population, and water and wastewater management in evaluating the potential impacts of climate change upon water quality.

Tall buildings The localized case study of a typical tall building in metro Boston found that if design wind velocities increased by 30% over the present Massachusetts Building Code, large wind induced sways potentially could cause human discomfort and costly architectural damage (Sanayei et al. 2003). Sways could also cause cracking and spalling of fire protection materials from the surface of steel structural members leading to reduced safety against fire protection. The structure may also experience increased cracking of non-structural architectural finishes, leading to increased maintenance costs. In sum, the serviceability of the building will be reduced.

Bridge scour The localized case study of Kirshen et al. (2002) found that with increased flood discharges in rivers, bridge foundation scour could become a problem. Instantaneous discharges were estimated from scenarios of possible increases in peak precipitation. One solution to increased scour is retrofitting existing bridge footings with riprap.

Generally, five themes emerge from these analyses. Either structural (BYWO scenario) or less structural (Green scenario) actions taken before full climate change impacts occur will result in less expected total infrastructure negative impacts to the region. The second is that under many scenarios, an effective adaptation action taken soon will result in less total future negative impacts in a system even if climate change does not occur. For example, this was found in the analyses of river and coastal flooding impacts and adaptation. The third theme is that climate change will significantly add to the negative impacts of demographic changes upon infrastructure services in the region. Another theme is the interactions upon each other of the climate change impacts of various infrastructure systems and their adaptation actions. The fifth theme is that adaptation of infrastructure to climate change must also consider integration with land use management, environmental and socio-economic impacts, and various institutions. These final two themes are the focus of this paper and present addition considerations in adaptation planning.

5 Interdependencies of impacts and adaptation actions

Impacts The emphasis of the CLIMB project was on the integration of climate and demographic changes upon infrastructure in Metro Boston and on examining these impacts with a common framework. Based upon the results of this research, it was possible to examine how impacts in one sector will impact another sector. While it was not possible in all cases to make quantitative estimates of the magnitude of interaction effects, we were able to identify a comprehensive set of such effects and indicate which are the most important. As noted earlier, the research conducted for each system had limitations due to time, budget, and data constraints. The results of the research for each system, however, did provide guidance and insights into some of the other impacts on the system that we could not explore in detail. Some of these additional insights are preceded in the following tables by “also” and are included in the interdependencies analysis.

Table 2 identifies the most important interaction effects. It is based on the Ride It Out (RIO) scenario, which means no major policy interventions are assumed. System-specific RIO impacts are summarized in the gray cells of the table. Reading the table horizontally shows the impacts of one system upon another. Reading the table vertically shows possible impacts upon

Table 2 Integration of infrastructure impacts

	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 (N/A)	N/A	Summer Also increased cooling water needs.	Summer Also more cooling water will impact water quality (heat and blowdown).
Health	N/A	Summer Slightly higher heat-related mortality until about 2010. Also increased emission-related illness.	N/A	N/A	N/A	N/A	N/A
Transport Impacts Due to River and Coastal Flooding	Increased energy demand due to more miles traveled.	Also reduced public safety.	Increased travel time. Loss of trips. More miles. More hours.	N/A	N/A	N/A	N/A
River Flooding	Possible disruption in local deliveries.	Increased pathogens in water supply.	Lost trips and increased traffic delay (see Transportation Sector).	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 source pollution.
Sea Level Rise	N/A	N/A	Lost trips and increased traffic delay (see Transportation Sector).	Also could increase river flood losses.	Permanent loss of some coastal land. Temporary loss of land and land activities.	Also salt water intrusion into coastal wells.	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.	N/A	N/A	N/A	Less reliable local supply.	Times when more water withdrawal and thus less dilution.
Water Quality	Also warmer waters could result in loss of local energy production.	Also increased illness due to exposure to water-born diseases.	N/A	N/A	N/A	More treatment necessary.	Less Dissolved Oxygen. More Non-point source pollution. Warmer water.

(Horizontal row is the system impacted by the system in the first column. System-specific RIO impacts are summarized in the gray cells of the table. Additional information is preceded by “also.”)

Table 3 Impacts on environment and 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 Reductions 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 system, 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 losses. In addition, see Transportation. Infrastructure damage.
Water Supply	Less reliable local supply.	Lower streamflows and water tables.	Also, productivity and quality of life losses.
Water Quality	Less DO. More non-point source pollution. Warmer water.	Also ecosystem stress and less biodiversity.	Also productivity, property values, and quality of life losses.

(System-specific RIO impacts are summarized in the gray cells of the table. Horizontal row is the system impacted by the system in the first Column. Additional information is preceded by “also.”)

that system from all the systems we analyzed. Table 3 repeats the RIO impacts on each system as well as shows general effects on the environment and on economy and society.

Table 2 indicates that the RIO negative impacts of climate change on one infrastructure system will, in most cases, also negatively impact the performances of other infrastructure systems. River flooding is a good example. Loss of land and land activity during flood events has negative impacts on all other infrastructure systems and generally negative impacts on the environment, economy and society. Sea level rise also has widespread negative impacts. In general, energy, river flooding, and sea level rise are the systems whose negative impacts from climate change have the greatest secondary impacts on other systems. Water supply and water quality systems impacts are also transmitted to other systems.

Reading the table vertically indicates that health followed by water supply and water quality are the systems most impacted by impacts that occur directly to other systems.

Table 4 Adaptation matrix

	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.	N/A	N/A	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.	N/A	N/A	N/A	N/A	N/A
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 benefits 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.	Manage non-point source pollution and other loads. Increase discharge.

(The gray entries on the diagonal for each of the six systems are an effective adaptation for the system based upon the CLIMB analyses. Reading the table horizontally shows how adaptations in one system will impact another system.)

These interactions are important because they have the potential to magnify any negative impacts caused by climate change in any one system.

Adaptation The research identified a number of possible adaptations to climate change in each of the six major systems: energy use, health, transport, river flooding, sea level rise, water supply, and water quality. Using the metrics specific to each system, it was found that generally anticipatory adaptations were most effective in lessening the impacts of climate change. Since the systems are interrelated, adaptations to address problems in one system will have effects on other systems. In some cases the effects will be complementary, but in others they may work against each other. All of the adaptations will also have environmental impacts other than on climate change and will have broader economic and social implications. Furthermore, all of these adaptations may have impacts on our efforts to mitigate climate change by reducing greenhouse gas emissions.

Table 4 presents a matrix of adaptation interactions. The gray entries on the diagonal for each of the six systems are an effective adaptation for one system based upon the CLIMB analyses. Table 5 repeats the effective adaptation for a system as well as the adaptation's impacts on the Environment, Economy and Society, and greenhouse gas mitigation. Reading Table 4 horizontally shows how adaptations in one system will impact another. Reading the table vertically shows possible impacts upon that system from adaptation actions from all the systems we analyzed. For example, in the case of energy we found that climate change will result in increased summer time electricity loads, which can be addressed either through conservation or through capacity expansion. The impacts of energy management adaptation on other systems depend on which of these options dominates. For example, emissions and air quality – with their attendant impacts on health – will benefit from conservation but may be degraded with expanded capacity. Capacity adjustments may also increase the demand for cooling water, which may have a negative impact on water quality. Economic impacts include rate (i.e., price) increases that may be necessary to support either conservation or capacity expansion. In this case it is evident that consideration of indirect effects will have a major influence on policy choices.

In most cases, however, an effective adaptation action in one system also lessens climate change impacts in another system. For example, actions to improve water quality also have the potential to improve water supply, health, and the environment. Water quality adaptations, however, may result in increased water management rates.

The interactions of adaptations with other systems are most widespread in the case of management of future river flooding. Adaptations include increased use of flood proofing, retreat from flood plains, and increased recharge rates of surface runoff. Retreat from flood plains will be beneficial to transport in the sense that fewer trips will begin and end in flooded areas so the impact of floods on system performance will be less. If land use restrictions lead to denser development, there will also be a benefit in terms of less residential energy use, which may in part offset the need for more air conditioning. Retreat from flood plains will also have the environmental benefits of less displacement of natural flora and fauna in these ecologically rich areas. These same areas may also serve as greenways, which benefit mitigation efforts. Increased recharge rates, which actually serve to reduce the extent of flooding, have very widespread benefits in terms of improved water supply and water quality.

With the exception of the Energy and the Health (as represented by heat stress mortality) systems, in the CLIMB region effective adaptations actions taken by one system have the potential to improve the service of other systems as well as the environment, social and economic conditions. In order to capture these complementarities, a high level of cooperation by different infrastructure agencies in decision-making and implementation will be needed.

The last column in Table 5 shows the effect of various adaptation actions on greenhouse gas mitigation. In cases such as river flooding and sea level the adaptations are complementary to the cause of mitigation. In others, complementarity depends on policy decisions. Increased demand for air conditioning may be addressed by capacity expansion or by improved efficiency in all end uses. Clearly the former will increase greenhouse gas

Table 5 Adaptation impacts on environment, economy and society, and mitigation

	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 sub-sectors.	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).
Transport	Expand public transport. Increase road network redundancy.	Reduced emissions and congestion. If coastal roads minimized, might allow landward migration of coastal wetlands under SLR.	More reliable transport network.	Public transportation will reduce GHG, more roads may increase GHG.
River Flooding	Flood proofing. Retreat. Increase recharge to reduce amount of surface runoff.	Retreat and increased recharge have positive environmental benefits.	Less flood 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 resource uses.
Sea Level Rise	Flood proofing. Protection in high density, developed areas. Retreat.	Less coastal uses are positive for environment.	Less flood damages and overall less homeowner expenses.	If wetlands can be re-established, similar to river flooding.
Water Supply	Demand Management. Joint regional system.	If less water demand, improved water quality.	More reliable water supply.	Less energy use in water supply.
Water Quality	Manage non-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.

(The gray entries for each of the six systems are an effective adaptation for the system based upon the CLIMB analyses. Reading the table horizontally shows how adaptations in one system will impact other sectors.)

emissions while the latter will reduce them. In the case of transportation, the vulnerability to weather related disruptions may be addressed by increasing system redundancy through more road construction or by investments in public transport options. Again, the effect on mitigation is positive or negative depending on the policy approach. These interrelationships call for an integrated approach to addressing the problem of climate change through mutually supportive adaptation and mitigation measures. For example, policy may dictate that wherever possible adaptation options that reduce emissions be chosen over alternatives that increase them.

6 Interactions with planning and management activities

Analysis of CLIMB research results also indicate there are interactions with other planning activities that merit consideration.

7 Land use planning

Present and future land use planning greatly affects the magnitude of the impacts of climate change on all infrastructure systems. This is because the distribution of the population affects the location of infrastructure and hence the impacts, but also how the land is developed affects flood magnitudes and losses, water quality, water availability, and local heat island effects. Prohibition of new development – and where possible, flood proofing or retreat of existing development – in flood zones is an example of land use regulation that can both decrease potential damages to property and improve hydrological conditions, thereby decreasing the severity of flooding. Our transportation analysis further suggests that it may also be important to avoid commercial or residential development in areas that are chronically vulnerable to becoming inaccessible during extreme weather events. In general, the threat of climate change reinforces the importance of good land use planning and in particular, planning or lack thereof should certainly not increase present vulnerabilities.

A question that naturally arises is whether local governments, which have authority over land use planning, can be expected to take difficult policy steps in response to threats of climate change, especially when the federal and state governments have done relatively little. An interesting finding of the stakeholder outreach component of the CLIMB project was local government officials were often the most highly motivated by climate related policy issues. Local flooding, energy supply interruptions, heat related health crises and other weather related emergencies call for immediate action by municipal agencies, so local officials are most sensitive to the increased frequency of such events. For this reason, land use planning may hold the greatest potential for adaptation policy.

8 Environmental management

Since the emphasis of the research was upon impacts on infrastructure, impacts upon the environment were not directly considered. Potentially significant environmental impacts such as poorer air and water quality and wetland loss could accompany direct impacts on infrastructure. Generally, an adaptation action that best lessens an infrastructure impact also lessens environmental impacts. It also mitigates greenhouse gas emissions. One clear exception is expansion of air conditioning to manage heat stress mortality.

A key consideration is that infrastructure elements such as highways, power plants, and flood management systems must conform to specific environmental regulations, especially at the time of their construction. For example, a new highway in a non-attainment area where present air quality goals are not met cannot result in a net increase in certain emissions. At present these regulations, which often originate at the federal level, do not take account of likely climate change. For example, the increase in the number of hot days in the summer may require a greater reduction in ozone precursors than would be needed in the absence of climate change. In order to encourage adaptation at the local and regional level it will be necessary for federal agencies to start taking account of climate change when determining the most beneficial regulations.

9 Socio-economic impacts

The impact and adaptation analyses through the use of various indicators measured some of the socio-economic impacts of climate change on the region's infrastructure. The incremental damage to properties in river flood and coastal zones under an increased frequency of extreme weather events is the most profound of the measurable economic impacts. The analyses, however, did not capture how impacts and the possible benefits of adaptation might be distributed throughout the region by economic sector and type of household (distinguished, for example, by age distribution, ethnic mix, economic prosperity and other factors which may influence an individual's ability to adapt).

Another economic effect that was not fully addressed in the CLIMB project is the potential for extreme weather events to disrupt complex supply chains. The economy of the Boston Metro region is an open system, where goods, services and financial flows pass in and out to and from other states and other countries. Disruptions, especially to transportation and communication systems, can therefore lead to breakdowns in production systems whose damage is difficult to measure.

10 Adaptation actors and institutions

The adaptation responses considered in this research will require actions by many institutions ranging from private citizens to the federal government. As we have already noted, local levels of government (municipalities and counties) will play an especially critical role in adaptation. Due to the complementarities of effective adaptation actions, a coordinated response strategy will be necessary.

11 Conclusions

The CLIMB study is based upon the hypothesis that the operation and services provided by urban infrastructure will be impacted by climate change as they are sensitive to climate. Using various indicators, our research has shown that compared to conditions of just population growth, climate change impacts are significant on many infrastructure systems. What is more, the impacts on each infrastructure system give rise to secondary impacts on other systems. Since these secondary impacts tend to be mutually reinforcing (negative impacts on one system create negative impacts on other systems), impacts measured for a single system in isolation will tend to be underestimated. An ideal analysis would be of a single, diversified infrastructure system to provide for all the needs of the urban area. In the absence of such an analysis, however, the second best option is to carefully identify interaction effects among systems.

We have identified some specific actions and policies that can be taken in the near-term future to lessen some of the negative impacts. These adaptation actions are not intended to be optimal in terms of timing, location, or even action, but they do show that taking anticipatory actions well before 2050 results in less total adaptation and impact costs to the region than taking no action. Similar results for other sectors of the US economy have been reported by Easterling et al. (2004). Because of the interrelations among infrastructure systems, we have found that it is critical to take account of the effect that an adaptation action designed to lessen the effect of climate change on one system has on other systems. For the most part these cross-system effects are complementary in nature. But there are important exceptions, so an integrated approach to adaptation policy formulation is needed. Furthermore, adaptation efforts must be chosen and implemented so as not to confound mitigation efforts.

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