RFF REPORT

Adapting to Climate Change

The Public Policy Response

Public Infrastructure

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Executive Summary

This paper assesses the threats and needs that multidimensional climate change imposes for public infrastructure, reviews the existing adaptive capacity that could be applied to respond to these threats and needs, and presents options for enhancing adaptive capacity through public sector investments in physical, planning, and human resources. The paper considers four types of infrastructure: transportation; energy generation and transmission; water, sewer, and telecommunications; and coastal defense. The main threats presented by climate change to these assets include damage or destruction from extreme events, which climate change may exacerbate; coastal flooding and inundation from sea level rise; changes in patterns of water availability; effects of higher temperature on operating costs, including effects in temperate areas and areas currently characterized by permafrost conditions; and demand-induced effects.

In almost all cases, some adaptive capacity exists to respond to these threats, through both public and private sector actions. Most public infrastructure is maintained as a capital asset, with annual operating, maintenance, and repair functions and a periodic replacement schedule. In many cases, infrastructure maintenance and replacement budgets are already under strain; climate change will add further stress and, in some cases, may require a new way of doing business to adequately respond to climate threats. Our recommendations for policy responses to these threats include the following.

- **The need for integration of planning.** In both the transportation and coastal defense areas, and to some extent sewer infrastructure, studies have concluded that resources could be allocated more efficiently if infrastructure planning were better integrated with land-use planning. A key obstacle noted to this integration, however, is that such planning typically occurs across several levels of government, with land-use planning usually carried out at the local level. Studies also note the need to integrate planning across transportation modes to ensure redundancy during emergency situations. Integrated planning may also help facilitate financial sector adaptation (e.g., insurance schemes), which some have argued is much easier, more flexible, and more robust than technical adaptation. Finally, there is an emerging need to integrate adaptation and mitigation planning—this need is most acute in the energy sector.

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- **The need to encourage innovation in technology and updating of standards.** Many of the studies reviewed here note that a change in climate will present technological challenges that may require more resilient infrastructure capital. Centralized efforts to update building standards may be one means to spur the needed technological change. The Canadian government has already launched several efforts in this direction.
- **The need to take best advantage of replacement opportunities, including extreme events.** More frequent and destructive extreme events, such as recent hurricanes and riparian floods, have already proven to be a huge challenge to maintaining public infrastructure. At the same time, many studies note that adaptation to climate stresses is more cost-effectively accomplished during the design phase of projects, rather than as a retrofit to existing capital. Although extreme events are devastating to affected regions, the rebuilding process can be used as an opportunity to replace damaged infrastructure with more resilient capital.

1. Introduction

Public infrastructure is vital to the smooth functioning of the U.S. economy and encompasses a wide range of assets. For the purposes of this paper, we begin by narrowing our definition of public infrastructure to the physical structures that form the foundation of development in the United States. Within our definition, infrastructure includes wastewater and waterworks systems, electric power generation and transmission systems, communications networks, road and rail networks, transit and transportation facilities and ports, and oil and gas pipelines and associated facilities. In the climate change context, our scope includes both current infrastructure that may be at risk (e.g., transportation, energy, water and communications, utilities) and new infrastructure that may be needed to effectively and efficiently adapt to climate risks (e.g., seawalls). The purpose of this paper is therefore to assess the threats and needs that multidimensional climate change imposes for these physical assets, review the existing adaptive capacity that could be applied to respond to these threats and needs, and present options for enhancing adaptive capacity through public sector investments in physical, planning, and human resources.[1]

The scope of our assessment differs from several prior well-known assessments. Chapter 7 of the Intergovernmental Panel on Climate Change (IPCC) 2007 Working Group II report, for example, evaluates impacts to industry, settlement, and society, a much broader scope that includes public infrastructure but also private assets and natural resources, with the goal of assessing impacts to "the structure, functioning, and relationships of all of these components of human systems…" (Wilbanks et al. 2007, 360). We have chosen to exclude direct consideration of private industry

[1] As stated, our focus is on the direct impacts of climate on infrastructure, rather than the impacts of climate policy on infrastructure. For example, the California Air Resources Board has begun efforts to link transportation infrastructure decisions to greenhouse gas intensity, a good example of a carbon policy–induced link to infrastructure planning, but not a direct climate impact. Planning for public infrastructure and land-use/urban planning tasks clearly interact and overlap, but the scope of our interest in assets affected by climate change does not specifically encompass land-use planning, except as a tool to adapt.

assets and natural resources, making our scope and purpose far narrower than the IPCC effort in this area. Nonetheless, because infrastructure is designed to support those assets and to provide a means for the development of human settlements and industry, there are links to private sector assets and climate-related threats and needs.

Other efforts, such as a recent National Academy of Sciences report on the impacts of climate on transportation (Transportation Research Board [TRB] 2008) and a recent U.S. Climate Change Science Program (CCSP) report on the impacts of climate on energy infrastructure (U.S. CCSP 2007), have somewhat narrower scopes, limited to particular types of public infrastructure. Our topical scope is more in line with the recent Alaska assessment of climate impacts on infrastructure (Larsen et al. 2008), although we have a geographic scope that includes all U.S. states and regions. None of these prior assessments is focused on identifying public sector enhancements to adaptive capacity, which is our main focus, but particularly because this chapter does not provide a new impact assessment, each of these prior works provides valuable information toward our end, and we rely heavily on them here.[2]

Our focus on public infrastructure could be interpreted as one that is limited to those assets directly owned and operated by the public sector. Limiting our scope in that way would, in our opinion, be arbitrary and would exclude many important infrastructure resources that have a public sector presence and for which public planning and regulation has proven essential (e.g., electric energy transmission systems). In addition, a "current ownership" distinction might also exclude assets where climate change might have an influence on future ownership patterns. For example, coastal defense systems, such as seawalls and beach nourishment, in the present day are usually publicly funded, but as needs for these systems increase in the face of rising sea levels, we can anticipate public funds growing more limited and are likely to see more privately funded coastal defense efforts. In fact, in some places, such as certain coastal barrier islands where the use of federal funds for this purpose is prohibited, we have already seen privately funded beach nourishment (U.S. CCSP 2008a). An important public planning and investment function in the coastal zone remains; however, that falls largely under the umbrella of infrastructure planning to enhance and protect development. Our scope therefore includes some privately owned assets that meet our definition of "physical structures that form the foundation for development."

Throughout this paper, we organize our presentation by referring to four major categories of infrastructure:

- transportation;
- energy utility provision, including electric, natural gas, gasoline, and oil pipeline networks;
- nonenergy utility provision, including water, sewer, communication, and solid waste management networks; and

[2] Public health infrastructure is not included in the scope of this chapter, but adaptation of the public health system is addressed elsewhere as part of the overall research effort.

- coastal and flood defense networks.

We also make reference to several common qualities and stylized facts concerning public infrastructure, regardless of type.

- Infrastructure is generally long-lived, but requires periodic maintenance and eventual replacement.
- Most infrastructure assets have at least some aspects of a public good, exhibiting some qualities of jointness and nonexclusivity in the provision of benefits, if not always in costs. As a result, infrastructure may be subject to the same *free rider* pitfalls as many other public goods.
- Infrastructure assets, as they are constructed and maintained in this country, need not have an independent, intrinsic market value, and may not themselves be profit-making enterprises; instead, they tend to yield value as an input to the production of something else. As a result, from time to time, basic maintenance and repair of infrastructure has received low public priority, a fact that may leave infrastructure even more vulnerable to climate-induced damage.

The remainder of this paper is organized in four sections. Section 2 identifies key climate change threats to infrastructure, and links those threats, both descriptively and spatially, to current U.S. infrastructure resources at risk. Section 3 assesses and incorporates the current adaptive capacity to respond to those threats and concludes with identification of the key remaining vulnerabilities of public infrastructure to climate change. Section 4 identifies new opportunities for enhancing adaptive capacity through public and private sector initiatives. Section 5 concludes by attempting to develop a priority list of public sector actions that are most critically needed to enhance adaptive capacity in response to the threat of climate change to public infrastructure.

2. Impacts

Identifying the impacts of climate change on infrastructure, as distinct from other influences on our need to maintain, repair, and replace infrastructure, benefits from some explicit attention to a conceptual model for impact assessment. We focus here on the *marginal* impacts of climate change. It is useful to avoid thinking that the full cost of infrastructure maintenance and replacement could be attributable to climate change—it is important, rather, to net out costs that would have been incurred under the stable, or current, climate. The most robust attempts to isolate the marginal effects of climate on infrastructure, therefore, model infrastructure as long-lived assets that, with a stable climate, will require a reasonably anticipated level of annual, or at least periodic, maintenance, repair, and eventual replacement. The marginal impact of a stressor such as climate change on existing resources therefore could involve a change in the maintenance period, changes in maintenance costs, or both; a change in the need for repair, perhaps because of a change in the frequency of damaging events (e.g., storms); or a change in the replacement cycle (Larsen et al. 2008). It is reasonable to conclude that the engineering process for much long-lived infrastructure capital considered historical climate conditions when the infrastructure was originally built, and that it was designed to be optimal for those historical conditions. As climate changes, however, the design grows suboptimal, and therefore damages are incurred relative to the world where climate would have remained stable (see Hallegatte 2008).

In this model, one of the key adjustments that will be needed to respond to climate change is to recognize that infrastructure planners will now need to think about a world with an expectation of a changing, rather than stable, climate. In some cases, not only the magnitude but also the sign of change will be unpredictable, and the temporal profile for such factors as precipitation and floods will also be more uncertain. As Hallegatte (2008) has noted, adapting the planning process for long-lived assets is not as simple as reoptimizing infrastructure and capital planning for a new climate—with an uncertain climate it requires a new way of thinking. We will return to these concepts in Sections 4 and 5, where we discuss adaptation.

The remainder of this section reviews the impacts literature for each of our four categories of infrastructure. Our definition of *impact* derives from the IPCC Third Assessment: a climate impact occurs when exposure to climate change intersects climate sensitivity (McCarthy et al. 2001). In other words, this section identifies infrastructure resources at risk.[3]

Transportation Infrastructure

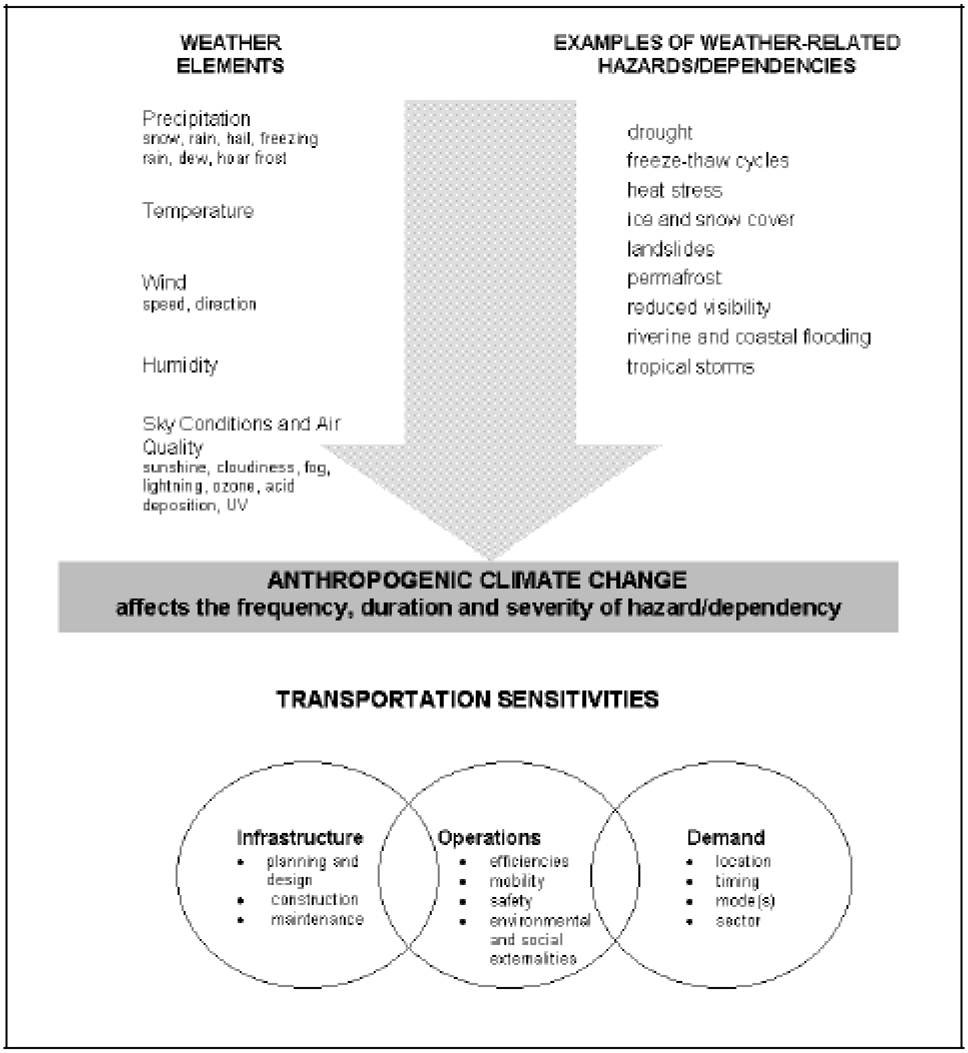
One of the most important and comprehensive recent studies on the impacts of climate change on transportation infrastructure was completed by the National Academy of Sciences TRB (2008). A background paper for this effort (Mills and Andrey 2002) presents a general framework for the consideration of climate impacts on transportation, which is summarized in Figure 1.

Mills and Andrey (2002) describe a conceptual model with three basic elements. First, they enumerate baseline weather conditions and episodic weather-influenced hazards that make up the environment in which infrastructure is built, maintained, and used. Second, they note that the weather-related context will change with climate change, affecting the frequency, duration, and severity of the hazard. In concept, these hazards have the potential to affect transportation infrastructure itself, its operation, and the demand for transportation. The last of these can arise from a variety of sources—one example would be climate effects on agriculture that alter the location of agricultural production and, therefore, the need and mode for shipping agricultural products.

The TRB (2008) study, and most existing literature, focuses on the first category of impact, the physical infrastructure and its maintenance, and to some extent on operations, sometimes in great detail (Peterson et al. 2008). Currently, however, almost no literature evaluates the effect of climate change on transportation demand (Mills and Andrey 2002).

[3] Note that in many cases, work that we reference here first addresses physical impacts, then incorporates adaptive capacity to estimate remaining vulnerabilities.

Figure 1. Aspects of Transportation That May Be Sensitive to Changes in Climate



Source: Mills and Andrey 2002.

With the focus on the infrastructure and its maintenance and operation, the TRB (2008) study highlights five climate changes of particular importance to transportation.

- **Increases in very hot days and heat waves:** High temperatures can damage road beds and rails, for example.
- **Increases in Arctic temperatures:** Melting of permafrost is a severe problem for Arctic infrastructure because it causes an otherwise relatively stable land surface to become an unstable land surface, making surface-based transportation hazardous.

- **Rising sea levels:** Inundation of road and rail networks, as well as episodic flooding of these and of subway transit systems, could be widespread in coastal areas. Bridges and port facilities may also be threatened.
- **Increases in intense precipitation events:** Increased runoff can wash away roads and overwhelm existing drainage systems or, in the case of underground transit, pumping systems.
- **Increases in hurricane intensity:** Hurricanes have the potential to destroy critical transportation resources; bridges may be particularly vulnerable.

The TRB (2008) study concludes that the greatest impacts of climate change for North America's transportation systems will probably be the flooding of coastal roads, railways, transit systems, and runways because of global rising sea levels, coupled with storm surges and exacerbated in some locations by land subsidence. Other transportation-related impacts resulting from climate change that are featured in the report include the following.

- Drier conditions resulting in lower water levels in the Upper Midwest river system, the St. Lawrence Seaway, and the Great Lakes could reduce capacity to ship agricultural and other bulk commodities, although a longer shipping season could offset this effect.
- Thawing permafrost in Alaska could create settlement and subsidence problems for roads, rail lines, runways, and pipelines.
- Higher temperature extremes in some regions could lead to more frequent buckling of pavement and misalignment of rail lines.
- More severe weather events with intense precipitation could increase the severity of extensive flooding events.
- The marine transportation sector could benefit from longer shipping seasons in the Arctic.
- Rising temperatures in cold regions could lead to reduced costs associated with snow and ice removal.

Several regional-scale studies of the impacts of climate on transportation infrastructure highlight many of the same effects. For example, CCSP Synthesis and Assessment Product (SAP) 4.7 (U.S. CCSP 2008b) focuses on the effects in the Gulf Coast area and highlights the effects of inundation from relative sea level rise (SLR).[4] The study concludes that, with a relative SLR of up to 1.2 meters (4 feet), 27 percent of the major roads (a total of more than 2,400 miles), 9 percent of the rail lines, and 72 percent of the ports are currently at or below 122 centimeters (4 feet) in elevation, although portions of these assets are currently guarded by protective structures, such as levees and dikes.

The potential for flooding and damage from storm activity in the Gulf Coast region is also great. The CCSP study examined the potential for short-term flooding associated with a 5.5- and a 7.0-

[4] Relative SLR is the combined effect of a eustatic change in sea level and the change in land level. In many parts of the Gulf Coast region, particularly the Mississippi River delta, land subsidence rates are very high.

meter (18- and 23-foot) storm surge. It concludes that more than half of the Central Gulf Coast's major highway infrastructure is subject to temporary flooding, including 64 percent of interstates and 57 percent of arterials. In addition, almost half of the rail miles, 29 airports, and virtually all of the ports are currently subject to periodic flooding.

The Gulf Coast study also notes that a temperature increase could raise costs related to the construction, maintenance, and operations of transportation infrastructure and vehicles; furthermore, an increase in the severity of extreme precipitation events could increase the potential for short-term flooding due to heavier downpours. The study does not present quantitative estimates of the extent or magnitude of these impacts, however.

Two recent studies expand on issues of infrastructure vulnerability unique to Arctic zones, particularly Alaska. The first, the Arctic Climate Impact Assessment (Instanes et al. 2005), addressed the full range of climate impacts but included a chapter specific to infrastructure.[5] The chapter notes infrastructure impacts associated with permafrost warming and degradation, coastal erosion, and transportation routes, among others. Impacts on infrastructure from changes to permafrost due to higher temperatures vary depending on the type of permafrost (continuous or discontinuous), as follows.

- In areas of continuous permafrost, climate change is not likely to pose an immediate threat to infrastructure if proper permafrost engineering design procedures have been followed. Maintenance costs are likely to increase, but it should be possible to gradually adjust Arctic infrastructure (through replacement and changing design approaches over time) to a warmer climate.
- Projected climate change is very likely to have a serious effect on existing infrastructure in areas of discontinuous permafrost. Permafrost in these areas is already at temperatures close to thawing. The authors believe that engineering experience already employed to address warming and thawing brought on by human activities and construction can help address this.
- Long-term thaw of the permafrost layer in discontinuous permafrost can be expected, and cost-effective design strategies to address land transportation vulnerabilities are currently unavailable. As a result, it is likely that existing road, rail, or airport embankments will experience increasing failure rates in both the continuous and discontinuous permafrost zones.
- A continued decrease in Arctic sea ice extent this century is very likely to increase seasonal and year-round access for Arctic marine transportation and offshore development. New and revised national and international regulations, focusing on marine safety and marine environmental protection, are likely to be required as a result of these trends. Another probable outcome of changing marine access will be an increase in potential conflicts between competing users of Arctic waterways and coastal seas.

[5] The full reference to this chapter is as follows: Arctic Council and the International Arctic Science Committee, (2004), Arctic Climate Impact Assessment. Chapter 16, Infrastructure: Buildings, Support Systems, and Industrial Facilities.

The ACIA also highlights an interesting transportation benefit of climate change; it states that a longer navigation season along the Arctic Coast is very likely and that trans-Arctic (polar) shipping is possible within the next 100 years. The benefits of a longer shipping season in the Arctic, with the possibility of easy transit through the Northern Sea Route and Northwest Passage for at least part of the year, are likely to be significant. Other benefits are likely to include deeper drafts in harbors and channels as sea level rises, a reduced need for ice strengthening of ship hulls and offshore oil and gas platforms, and a reduced need for icebreaker support. At the same time, the need to cope with greater wave heights, as well as possible flooding and erosion threats to coastal facilities, is likely to result in increased costs.

The second Arctic-focused study, conducted by researchers at the University of Alaska, Fairbanks, is focused on the effects of climate change on public infrastructure, and provides an exceptional level of detail (Larsen et al., 2008). The study is particularly noteworthy for developing a detailed inventory of potentially vulnerable infrastructure; it also relies on a sophisticated capital maintenance and replacement methodology to estimate the marginal economic impact of climate and the timing of expenditures necessary to respond to climate vulnerabilities. The authors use three different global circulation model (GCM)-based temperature and precipitation scenarios, which they characterize as "warm," "warmer," and "warmest" based on their GCM results for Alaska. The vulnerability of infrastructure is assessed based on location—infrastructure that is located in the presence of permafrost and in close proximity to a coast or a floodplain is considered potentially vulnerable to climate change. The key result of the approach is an estimate of the total present value of maintenance and replacement cost of infrastructure under three assumptions: no climate change (i.e., historical climate), climate change with no adaptation, and climate change with adaptation.

The scope of the Larsen et al. (2008) study includes transportation infrastructure, such as airports, bridges, harbors, major roads, and railroads. The net present value of maintenance and replacement costs for transportation infrastructure in their inventory through 2030 is approximately $24.5 billion (in 2006$). The authors estimate that, under climate change with no adaptation, transportation systems could incur increased maintenance and replacement costs of $2.3 to $4.3 billion, or about 9.3 to 17.7 percent of the base case expenditures, depending on the climate scenario. They found similar ratios of base case expenditures and climate-attributed increases in costs for their projection of costs to 2080.

A regional study in the Boston Area, Climate's Long-term Impacts on Metro Boston (or CLIMB; see Kirshen et al. 2006), provides some additional insights into the effects of climate in an urban area. The authors note that increases in the frequency of extreme weather events will result in a major increase in delays and lost trips due to road flooding over the course of the 21st century. They conclude that the economic impact of these delays and lost trips will be relatively small compared with those of flood damages to residential, commercial, and industrial properties. They also conclude that, in some areas with increased flood discharges in rivers, bridge foundations could be threatened.

A similar study in Washington State finds that SLR could force costly redesign of some long-term investments in shoreline protection that are already underway, including Seattle's Alaskan

Way seawall, and other infrastructure, such as bridges and culverts (Casola et al. 2005). The study also notes that the availability of certain types of off-road transportation could decrease because of a shorter freezing season.

Energy Utility Provision, Including Electric, Natural Gas, Gasoline, and Oil Pipeline Networks

Climate change will apply pressure to much of the energy production and delivery infrastructure on which U.S. households and businesses depend. The pathways through which climate change affects this infrastructure vary by energy source and region, reflecting the effect of climate change on energy production and delivery as well as climate-related changes in energy demand. A growing body of literature on these effects will help inform decisionmakers of the key challenges they face in adapting the nation's energy infrastructure to a changing climate.

CCSP's 2007 synthesis document on the effects of climate change on energy production and use represents one of the most recent and thorough assessments of this topic (U.S. CCSP 2007). Although the CCSP document does not present new research on the impacts of climate change, it summarizes current knowledge on the effect of climate change on energy supply and demand and highlights how these changes may act as stressors on the U.S. energy infrastructure. The document also identifies key uncertainties regarding the magnitude of these effects.

With respect to energy supply, the CCSP synthesis document states that climate-related changes in temperature, precipitation, water resources, severe weather events, and SLR may all impact the country's energy generation and distribution infrastructure (U.S. CCSP 2007). For fossil fuel and nuclear electricity-generating units, these impacts include the following.

- **Reduced thermal efficiency:** As noted in the CCSP document, changes in temperature directly affect the efficiency of gas-fired turbines. Based on a study by Davcock et al. (2004), CCSP estimates that an increase in temperature of 10°F would reduce the output of a gas turbine by approximately 3 to 4 percent. In addition, the CCSP document cites U.S. Energy Information Administration data (EIA 2004) showing that an increase in temperature has a small but measurable effect on the efficiency of coal-fired and nuclear units. Therefore, to the extent that climate change increases ambient temperature (particularly during peak demand periods when gas turbines are frequently used), it would also reduce available generating capacity.
- **Reduced availability of cooling water in specific regions:** Although the extent of regional changes in water availability is uncertain, climate models generally agree that climate change will result in a redistribution of water. Because power plants typically require significant amounts of water for cooling purposes, reduced water availability in some areas could limit generation at existing plants and constrain the siting of new capacity.
- **Power plant susceptibility to SLR:** Many power plants are at an elevation of three feet or less and are therefore vulnerable to damage from rising sea levels, such as equipment damage from flooding and/or erosion.

Although impacts to fossil fuel and nuclear units are of particular concern because of their large contribution to U.S. electricity production, the CCSP document emphasizes that the productivity of the country's renewable energy infrastructure is even more sensitive to climate change (U.S. CCSP 2007). This reflects the reliance of renewables on several weather-related variables (e.g., wind, solar radiation, and precipitation). Key impacts of climate change noted by CCSP with respect to the U.S. renewable energy infrastructure are as follows:

- **Hydroelectric dams:** Climate change may impair the effective generating capacity of hydroelectric dams by altering the amount or timing of runoff. For example, climate-related projections of reduced water storage in snow pack and glaciers suggest that climate change will reduce generation at dams during the spring and summer months. The literature examining the sensitivity of hydroelectric generation to changes in precipitation and river discharge suggests at least a 1 percent change in generation for each 1 percent change in precipitation.
- **Wind farms:** Changes in wind patterns and intensity due to climate change could affect the productivity of existing wind farms and the development of future sites. Studies modeling the effect of climate change on wind speed suggest a reduction in average wind speed for the United States, but project that some areas in Texas, Oklahoma, and the Pacific Northwest would experience an increase in wind speeds. It is important to note, however, that the changes in wind speed predicted by these studies differ significantly. For example, one analysis based on the Hadley Centre climate change circulation model predicts a minimal reduction in average wind speed, whereas circulation model output from the Canadian Climate Centre shows reductions of 10 to 15 percent by 2095 (Breslow and Sailor, as cited in U.S. CCSP 2007). The difference between these results highlights the uncertainty of climate change's effect on wind resources; this uncertainty alone could hinder the development of infrastructure for wind-based generating capacity.
- **Photovoltaic systems:** The CCSP document cites two studies suggesting that climate change will reduce the effectiveness of the U.S. photovoltaic (PV) energy infrastructure. A 2004 analysis based on the Hadley Centre circulation model estimates that climate change will reduce solar resources by as much as 20 percent on a seasonal basis in 2040 because of increased cloud cover, particularly in the West. Increased temperatures associated with climate change may also affect generation from PV systems. Fidje and Martinsen estimate that a 2 percent reduction in global solar radiation will lead to a 6 percent reduction in solar cell output (as cited in U.S. CCSP 2007).

In addition to the impacts outlined above, the CCSP document notes that climate change may lead to more frequent and severe extreme storm events, resulting in the following impacts to the country's energy infrastructure.

- More frequent and extensive downing of electric transmission and distribution lines (and more frequent interruptions of service): The existing literature does not estimate the magnitude of these impacts.

- Incapacitation of refineries: High winds can knock down key structures at refineries (e.g., cooling towers), and refineries in low-lying areas are susceptible to flooding during major storm events.
- Damage to oil and gas platforms: Storm surge and high winds may disconnect oil and gas platforms from their moorings and damage platform decks.
- Structural damage to undersea pipelines: The force of extreme weather events can dislodge underwater pipelines from the seabed and cause structural damage to pipelines (e.g., dents and kinks and separation of pipelines from risers).

The CCSP document and recent congressional testimony also highlight that much of the country's energy distribution and exploration infrastructure is concentrated in the Gulf of Mexico region. Approximately one-third of U.S. refining and gas processing capacity is located on coastal plains adjacent to the Gulf and is vulnerable to inundation and coastal erosion (U.S. CCSP 2007). In addition, citing data from the U.S. Energy Information Administration, Charles Drevna, President of the National Petrochemical & Refiners Association, testified before Congress that the Gulf of Mexico region represented 28.5 percent of total U.S. crude production and 19.2 percent of the nation's total natural gas production in 2005.

Climate change may also lead to changes in energy demand that may ease or worsen the burden on U.S. energy infrastructure. Based on a series of studies conducted since 1990, a lead author of the CCSP document testified before Congress that an increase in temperature of 1°C would reduce U.S. demand for heating fuels by an estimated 3 to 15 percent and increase electricity demand for cooling by 5 to 20 percent (Wilbanks 2008). Overall, empirical studies suggest that the effect is likely to be a net savings in delivered energy consumption in the north and a net increase in energy consumption in the south for both residential and commercial buildings, with the national balance slightly favoring net savings of delivered energy (U.S. CCSP 2007). It is important to note, however, that these studies do not consider the energy demand impacts of potential greenhouse gas (GHG) mitigation measures (e.g., demand responses to increased energy prices resulting from a carbon tax) or residential and commercial adaptations to warming itself (e.g., changes in migration patterns or improvements in building efficiency).

A number of regional studies support the research findings summarized in the CCSP document. For example, the Northwest Power and Conservation Council (NWPCC) simulated the effect of climate change on the Columbia River hydroelectric system for the years 2020 and 2040. The study estimated annual and seasonal changes in electricity generation associated with three climate projections, one of which suggested that climate change would result in a 333-megawatt increase in generation in 2040. The other two scenarios suggested reductions of 477 megawatts and 2,033 megawatts, respectively (NWPCC 2005). All three climate modeling scenarios projected an increase in generation during the winter and a reduction in generation during the summer months. This reflects a projected increase in rainfall during the winter but a decline in snowfall. As a result of this shift, stream flow increases in the winter but less water is available from melting snowpack in the spring and summer.

Larsen et al. (2008) note that warming could potentially affect the trans-Alaska oil pipeline. As temperatures increase and permafrost becomes more susceptible to thawing, soil subsidence could threaten the structural integrity of certain sections of the pipeline. In 2001, the Joint State–Federal Pipeline Office estimated that approximately 22,000 of the pipeline's 80,000 vertical support members might be experiencing problems caused by climate change (Joint Pipeline Office, as cited in U.S. Arctic Research Commission 2003).

Water, Sewer, Communication, and Solid Waste Management Networks

Climate change may act as an important stressor on the infrastructure of several nonenergy utilities, including municipal waterworks, stormwater sewer systems, and telecommunications networks. Although climate change may affect the infrastructure of nonenergy utilities in many areas, the nature and extent of these impacts are likely to vary by region because of regional differences in the design and condition of existing infrastructure and because the meteorological effects of climate change (e.g., changes in precipitation and temperature) will not be uniform across regions. Therefore, much of the impacts literature on nonenergy utilities focuses narrowly on impacts in a specific city or region.

Focusing on the New York metropolitan area, the 2000 Metro East Coast Study (Major and Goldberg 2000) examines several potential climate-related impacts specific to the region's water systems, including the following.

- **Impacts related to changes in temperature:** Rising temperatures will lead to an increase in evapotranspiration, reducing available water flows for municipal water supplies. In addition, a warmer climate may increase demand for recreational uses (e.g., swimming pools), resulting in further stress to the area's water supply systems.
- **Precipitation:** The effect of climate change on precipitation in the Metro East Coast region is uncertain, but a severe drop in precipitation would reduce water flows and substantially reduce the safe yield of area water systems. Increased precipitation would have the opposite effect, increasing the capacity of these systems.
- **Sea level rise***:* As sea levels rise, saltwater may intrude into coastal aquifers, such as those on Long Island, resulting in the degradation of water supplies from groundwater.

The study did not quantify the impact of these stressors on municipal water systems in the region but instead used outputs from the Canadian Centre and Hadley Centre global climate models to estimate the impact of climate change on hydrological conditions in the region (i.e., the probability of drought or flooding). As a result of uncertainty regarding the impact of climate change on precipitation in the region, the analysis reached no definitive conclusions.

The CLIMB study (Kirshen et al. 2006) examined the impact of climate change on the reliability of municipal water systems in the Boston region. The study found that the cumulative reliability of self-supplied water systems in the Boston area—measured as the percentage of the time that they can fully meet demand over a given period—could decline for the 2000–2050 period from 93 percent to 86 percent because of climate-related stresses (Kirshen et al. 2006). Even if aggressive demand management measures are taken to reduce demand to 65 percent of current levels by

2025, reliability is still projected to fall to 87 percent. The CLIMB analysis also examined the reliability impact of climate change on local water systems in the Boston area that rely on water from large reservoirs in the central part of the state and found that the reliability of these systems would remain at or near 100 percent through the year 2100. This suggests that these reservoir-based systems would be resilient to changes in climate through the rest of the century. We note, however, that the CLIMB analysis does not account for climate-related changes in water demand.

The CLIMB study did, however, estimate impacts of climate change on water quality for the Assabet River. The Assabet is located in the northwest Metro Boston area, and flows through several municipalities that range in development intensity from suburban to rural. The watershed land use is about 35 percent urban (developed), 6 percent agricultural, and 50 percent forested. The four major treatment plants along the river are, along with nonpoint source runoff, the largest contributors to periodic dissolved oxygen (DO) water quality issue in the river. Kirshen et al. (2006) estimate that the maintenance of a DO standard of water quality would require a combination of best management practices on land and capital upgrades to reduce effluent from the treatment plants that would cost $22.5 million in capital costs and $210,000 in annual operating costs under the base case, without climate change. With climate change, maintaining the DO standard is more difficult, and these costs increase to $30 to $39 million in capital costs and $300,000 to $600,000 in annual operating costs (Kirshen et al. 2006). Estimating damages from climate change based on the cost to maintain a given standard, including upgraded infrastructure costs, is one method commonly used in water quality studies that consider the effects of climate change, in part because the costs to upgrade infrastructure are available and fairly readily determined. This method can be problematic as an estimate of the expected impacts of climate change, however, if these costs cannot be shown to exceed the value of the effects they are designed to avoid (that is, the upgrades pass a cost–benefit test and are therefore considered the most cost-effective response), or if they cannot be established as required expenditures under existing law.

Climate change could be particularly problematic for water systems in the Pacific Northwest that rely on storage from snowpack, reservoirs, and groundwater to supplement water available from streams. Water systems that service the large population centers in Western Washington (e.g., Seattle) have low reservoir storage capacity relative to annual river flows; therefore, dry and/or warm winters that result in low snowpack can significantly reduce water availability for these areas during the summer months (Casola et al. 2005). Recent studies of the region have examined the impact of rising temperatures on the timing and volume of stream flow and the subsequent impact on summertime reservoir inflow, storage, and yield. One such study found that water levels associated with Seattle's 50-year low flow would return every 10 years (Wiley as cited in Casola et al. 2005). In addition, a similar study of the water system in Portland, Oregon, found that climate change could reduce the minimum storage of the system by 1.3 billion gallons, which is more than10 percent of the system's current storage capacity (Palmer and Hahn 2002).

In addition to impacting municipal water systems, climate change may also act as a stressor on municipal stormwater sewer systems. As noted by the IPCC (Wilbanks et al. 2007), SLR may interfere with the functioning of sewer outfalls, and flooding from more frequent and/or severe storm events could damage these units. Increased storm intensity could also overload storm sewers in some areas, causing local flooding. To assess the potential impacts of increased rainfall intensity on stormwater management systems, Burian (2006) conducted a case study of these impacts for a hypothetical, small-scale sewer system in Houston, Texas, designed according to current engineering standards. The analysis found that increased rainfall intensity for a series of model storm events (e.g., the 10-year storm) could overload much of the system. For example, if the intensity of the 10-year storm were to increase by 40 percent, 12 of the 17 pipes in the model storm drain system would operate under surcharge conditions. In contrast, under the base 10-year storm, none of the pipes in the model storm drain would operate under surcharge.

Two U.S. Environmental Protection Agency (EPA)-funded efforts have examined the impacts of climate change on sewage treatment and the performance of combined sewage systems. Furlow et al. (2006a) provide an economic analysis of the impacts of climate change on water quality compliance costs for publicly owned treatment works (POTWs) in the U.S. Great Lakes region. They conclude that climate change could have a significant effect on efforts to set emissions limits based on stream flow considerations—the incremental effect of climate change for 147 POTWs in the region would total $8 million to $97 million per year, equivalent to an average annual cost increase of $54,000 to $660,000 per facility. In addition, Furlow et al. (2006b) examine the impacts of changes in hydrology, specifically low-frequency storm events, on the likelihood of combined sewer overflows (CSOs) within the Great Lakes and New England regions. By comparing projected storm intensities against the benchmark storm event (based on historical storm intensities, the event corresponding to four CSOs per year), the impacts of climate change were characterized in terms of (a) the extent to which systems may be "underdesigned" and (b) the additional system capacity required to meet the mitigation target in the future. They found that, for both GCMs they employed, additional system capacity would be required in the Great Lakes region, with perhaps a significant need for increased capital investment in the capacity of the pipe network, but the effect in New England was ambiguous, with one GCM showing a need for additional capacity and the second showing no need.

Our survey of the literature identified very few studies regarding the impacts of climate change on telecommunications networks. The Australia-based Commonwealth Scientific and Industrial Research Organisation (CSIRO) conducted a qualitative risk assessment for the state of Victoria, Australia, in 2006 on the impacts of climate change on the state's telecommunications infrastructure, including both fixed lines and mobile telephone networks (CSIRO 2007). Overall, the study concluded that more frequent and severe storm events associated with climate change represent a more significant risk to Victoria's fixed-line telecommunications networks than its mobile phone systems. Exchange station flooding from extreme rainfall events and storm surge represents the most significant climate-related hazard for Victoria's fixed-line networks. Other impacts that CSIRO identified for land-line networks include

- damage to phone lines from lightning and wind;
- transmission line damage from bushfires, to the extent that such fires ignite more frequently as a result of climate change;

- reduced stability of towers and other structures resulting from increased fluctuations in soil moisture content; and
- degradation of cables from increased solar radiation.

With respect to Victoria's mobile phone infrastructure, CSIRO identified wind damage to transmission towers as the main climate-related risk.

Coastal and Flood Defense Infrastructure

As noted above, SLR is expected to be an important stressor to transportation infrastructure; it will also affect other aspects of the coastal built environment, including residential, commercial, and industrial structures. In some areas, such as the Sacramento/San Joaquin River delta in northern California, the combination of SLR and a potentially increased risk of extreme precipitation events and riparian flooding present a dual threat to low-lying areas. Protecting these lands and structures from inundation and worsening storm damage will require another type of infrastructure—seawalls, dikes, and beach sand projects that can armor land and structures from the damage of the seas.[6]

Expectations for the magnitude of SLR in the United States over the next century have not changed dramatically since the IPCC Third Assessment Report in 2001 (Houghton et al. 2001). According to the recently completed Fourth Assessment Report, the lowest-GHG emissions scenarios could result in a global SLR of 18 to 38 centimeters by 2100, and the highest-GHG emissions scenarios could result in 26 to 59 centimeters by 2100 (Meehl et al. 2007). Although impact assessors and adaptation planners might be tempted to use these estimates directly in their work, the IPCC emphasizes that these estimates exclude "future rapid dynamical changes in ice flow." (Meehl et al. 2007, 13). Increasing evidence suggests that the Greenland Ice Sheet and other sources of land-based ice may account for a greater share of SLR projections than previously thought (Meier et al. 2007), and one oft-cited estimate that incorporates the impact of this melting concludes that projected SLR might be 0.5 to 1.4 meter by the end of this century (Rahmstorf 2007). A very recent study concludes that the upper bound for ice sheet melting in this century is roughly equivalent to two meters of global SLR, which would clearly be devastating to many areas, particularly areas such as parts of the Gulf Coast, where the effects of land subsidence are also substantial (Neumann et al. 2000). In addition, SLR increases beyond 2100, which are discussed in some impact assessments but not in most economic analyses, are expected to be much higher than this one- to two-meter range. SLR of up to one meter in this century would probably imply a huge investment in adaptation—through seawalls, beach nourishment, and structure elevation—as several analysts have concluded that these measures are efficient responses to the threat; we discuss those analyses further in the next section.

The best recent work summarizing U.S. impacts is the ongoing CCSP SAP 4.1, *Coastal Elevations and Sensitivity to Sea Level Rise* (U.S. CCSP 2008a), a report that focuses on the Mid-Atlantic region.

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[6] Note that increased storm damage could occur either from more intense and frequent storms, or from the greater storm surge damage potential that results from SLR, which provides a higher sea level "base" and therefore allows storm surges to stretch farther inland and to deeper flood levels.

The most recent review draft notes that rising water levels can submerge low-lying lands, erode beaches, exacerbate coastal flooding, convert wetlands to open water, and increase the salinity of estuaries and freshwater aquifers. Built public infrastructure as a response to SLR is largely confined to addressing the first three of these effects, although in some cases tidal dikes can be employed to extend the life of wetlands, and freshwater aquifer contamination may be an important issue for some public water supply enterprises. In assessing the extent of lands vulnerable to SLR, the report reaches the following conclusions:

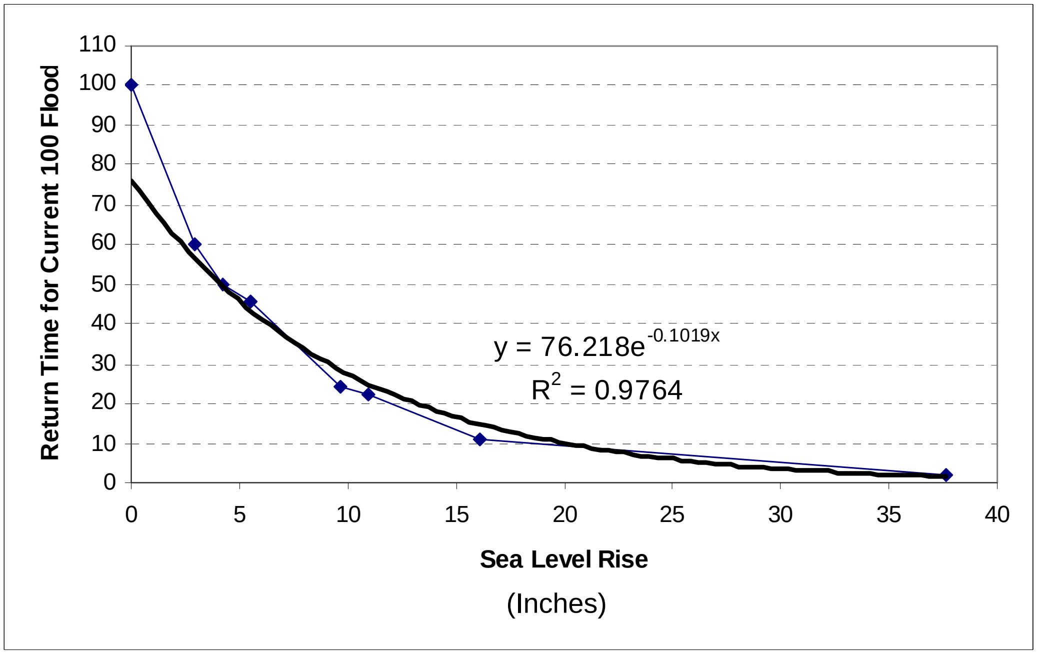
- approximately one-sixth of the nation's land close to sea level is in the Mid-Atlantic (see also Titus and Richman, 2001);
- sea-level rise is virtually certain to cause some areas of dry land to become inundated; and
- approximately 900–2100 square kilometers (350–800 square miles) of dry land, half of which is in North Carolina, would be flooded during spring high tides if sea level rises 50 centimeters (20 inches).

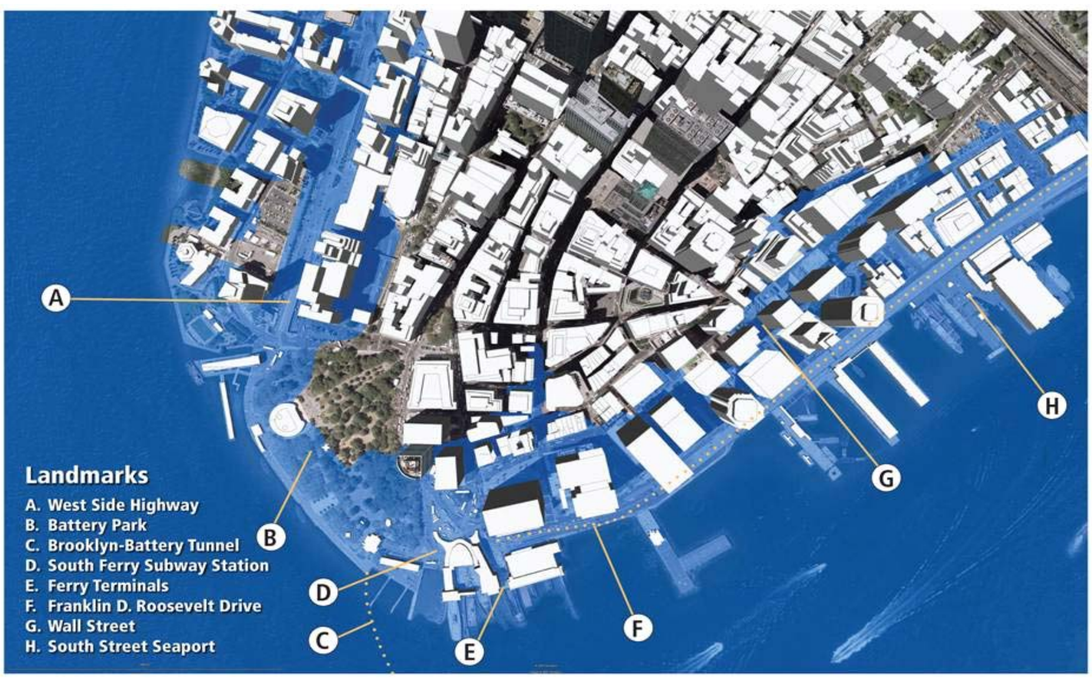
Work to estimate the U.S. acreage and value of land and structures potentially vulnerable to SLR is ongoing. A few local-scale assessments suggest that the value of vulnerable lands may be very large in some areas—for example, in Dade County, Florida, alone (which includes the city of Miami), approximately 5,000 acres of land with a current market value of approximately $10 billion lies at an elevation of 65 centimeters or less.

Prior national-scale synthesis work in this area (Neumann et al. 2000) concluded that the areas of the United States that are most vulnerable to SLR are located in the Mid-Atlantic and South Atlantic states (because of the low-lying topography, high economic value of the land, and relatively high storm frequency) and along the Gulf Coast (because of low-lying topography and rapid land subsidence). Parts of New England are also at risk, particularly coastal islands in southern New England (e.g., Block Island). The West Coast is generally at lower risk, with the exception of San Francisco Bay and Puget Sound. The recent Northeast Climate Impacts Assessment (Frumhoff et al.2007) arrived at similar conclusions.

Work to evaluate the extent of vulnerability of coastal lands to periodic storm surge flooding is ongoing. Some evidence suggests that climate change could increase the frequency and intensity of storms, but it is unlikely that scientists will be able in the near future to develop a best estimate of this effect. In the short-term, however, the CLIMB study team has developed an innovative approach to communicating relevant storm risk information to local infrastructure planners. As illustrated in Figure 2, researchers have developed methods to estimate the relationship between SLR and the risk of the 100-year flood and applied the approach to New York City (Frumhoff et al. 2007) These *return time* estimates for the 100-year flood are not a function of any presumption that the intensities or frequencies of coastal storms will change with climate along the New York coastline. They are, instead, simply the result of rising sea levels on storm surges associated with storms that now occur more frequently (for example, the current 25- or 50-year flood anomalies that will, with rising sea level, portray inundation patterns now associated with the 100-year flood anomaly).

Figure 2. Return Times for the Current 100-Year Flood Anomaly in New York City and FEMA's Current View of 100-Year Flood



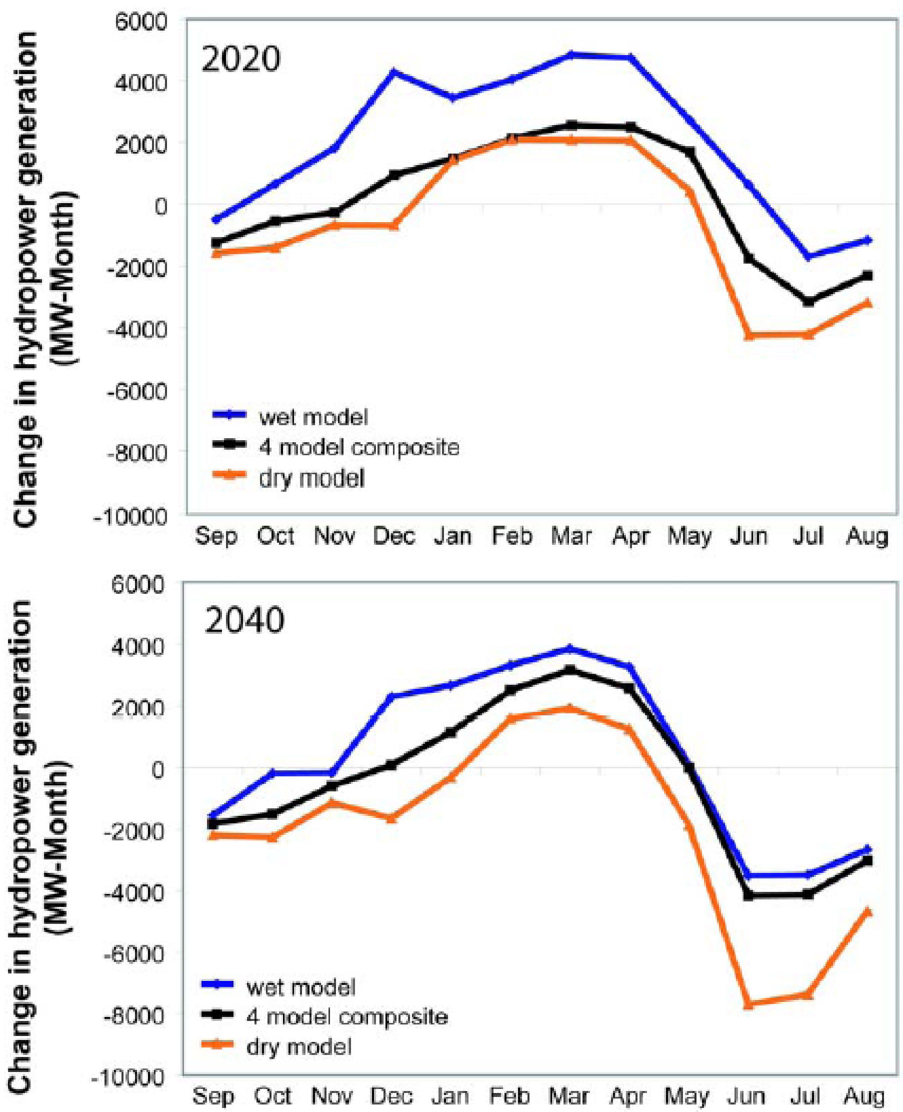


www.climatechoices.org/ne/

Source: Frumhoff et al. 2007.

The cumulative effect on 100-year anomaly return time is exponential in SLR, such that an event with the extent of flooding that would be seen in the current 100-year storm, with 25 centimeters of SLR, could occur on average every 30 years, and with 50 centimeters of SLR, every 10 years (see Figure 3). Such risk metrics, which could be readily calculated from available data for virtually all locations, are information that local emergency planners seem to understand well and that they can use to more effectively plan infrastructure responses.

Figure 3. Projected Impacts of Climate Change on Hydroelectric Generation in Washington in 2020 and 2040*



*Units are in megawatt-months change in generation relative to current generation.

Other notable work focused on assets exposed to risks from SLR includes an international study by Nicholls et al. (2008) that ranks 136 large port cities based on the population and property value exposed to possible inundation, storm surge, or wind damage from coastal storms. Based on 2005 population levels, 3 of the top 10 cities with the highest degree of exposed population are in the United States: Miami (4th), New York (7th), and New Orleans (10th). In addition, 5 U.S. cities, including the top 3, rank in the top 10 cities with total property value exposed to these risks: Miami (1st), New York (2nd), New Orleans (3rd), Tampa-St. Petersburg (9th), and Virginia Beach (10th). Nicholls et al. (2008) project that, by the 2070s, both total population and total assets exposed to these threats is expected to grow substantially because of the combined effects of climate change (SLR and increased storminess), subsidence, population growth, and urbanization. The authors note that exposure does not necessarily translate into impact because of the role of protective infrastructure; additionally, even the most effective measures would probably leave exposed population and assets dependent on protection that can fail.

3. Vulnerabilities

Much of the existing literature evaluates the potential impacts of climate change on infrastructure, and many of these studies also make some mention of the role of existing adaptive capacity. Some of these studies take their analysis a step further and quantitatively evaluate how existing adaptive capacity may mitigate these effects. One of the best examples of a quantitative analysis of adaptation is the Larsen et al. (2008) study of Alaskan infrastructure. As noted above, the authors generated estimates of the total present value of maintenance and the replacement cost of infrastructure under three assumptions: no climate change (i.e., historical climate), climate change with no adaptation, and climate change with adaptation. The difference between the first two scenarios represents the impact of climate change; the difference between the last two scenarios illustrates how existing adaptive capacity can be deployed to mitigate impacts.

In this section, we review both the qualitative and quantitative evidence of existing adaptive capacity for each of our four major categories of infrastructure.

Transportation Infrastructure

The most prominent climate threats to transportation infrastructure include extreme events, such as flooding, gradual inundation, heat stress, and permafrost melting. The basic adaptive capacity of agencies responsible for infrastructure construction and maintenance consists largely of full replacement or altered maintenance and repair procedures. At replacement, further opportunities exist to re-engineer the replacement capital to be better suited to a new or perhaps more uncertain climate than the historical climate record might imply. Another mechanism for adaption is on the demand side: changing modes. Even under current climate conditions, individual modes of transportation are frequently impaired or even destroyed (e.g., by natural disasters or even by accumulated neglect of maintenance). The response by consumers to current closures of the infrastructure is often to change the mode of transportation. Although some climate impacts will yield transportation benefits—for example, reduced ice conditions for high-latitude water-based shipping and reduced snow removal costs in some regions—most of the required adaptive measures come at a cost.

We identified only one study, the Larsen et al. (2008) Alaska infrastructure study, that estimated the cost of adaptive measures such as strategic redesign and replacement. The Larson study scope includes transportation infrastructure, such as airports, bridges, harbors, major roads, and railroads. They estimate, with climate change but with no adaptation, that transportation systems could incur increased maintenance and replacement costs (if infrastructure is destroyed) of $2.3 to $4.3 billion, or about 9.3 to 17.7 percent of the base case expenditures, depending on the climate scenario. Their "adaptation case," however, assumes that agencies responsible for managing infrastructure will act strategically to design replacement infrastructure in a way that is better tuned to the changed climate conditions. In the Alaskan context, the main climate stressors are SLR and changes in the extent of discontinuous permafrost, which are representative of the stressors in all parts of the country. Deploying this type of adaptive capacity reduces the estimate of damages by up to 13 percent by 2030; the maximum effect is seen when the model is applied for the most extreme, "warmest," climate model inputs. In the short-term (that is, by 2030), their modeled adaptation has no effect for the warm climate scenario, and only a modest, 2 percent, effect for the warmer scenario. Interestingly, though, the effect of adaptation in reducing damages is much more pronounced in the long-term—by 2080, adaptation reduces damages by an estimated 10 to 45 percent overall.[7] The reason for an increasing long-term effect is that, as the useful life of existing infrastructure is exhausted, there are more opportunities to replace that infrastructure with strategically designed capital that is more resilient to the changed climate.[8]

The TRB (2008) study notes a wide range of potential adaptation possibilities to reduce the impacts of climate on transportation resources, but many of the best insights from the TRB work is the identification of barriers to the most effective adaptation. The study notes many prominent challenges in effectively responding to climate threats, including the following.

- **Differences in planning horizons:** Although climate scientists describe the future in terms of outcomes that unfold over decades to centuries, the long-term planning horizons for transportation infrastructure rarely exceed 30 years. Therefore, transportation planners often perceive that the impacts of climate change will occur beyond the time frame of their long-term plans and fail to realize that today's decisions will affect how well the infrastructure responds to future changes in climate.
- **Treatment of uncertainty:** Climate change introduces uncertainties into the transportation planning process that make it difficult to plan and design infrastructure that can accommodate these impacts. In addition, these uncertainties are unfamiliar and uncomfortable for many planners. Climate scientists often describe the future in

[7] These estimates of the impact of adaptation on reducing damages to Alaskan infrastructure are roughly equivalent whether one considers the full scope of infrastructure evaluated in the Larsen et al. (2008) study or only those resources in the transportation sector.

[8] Note that one process modeled in this study that leads to the replacement of infrastructure is as a result of the destruction of resources by an extreme event, which in some cases may be influenced by climate changes.

probabilistic terms, whereas transportation professionals typically focus on knowns. This narrow focus represents an obstacle to developing dynamic decisionmaking processes that can adapt to new information and accommodate feedback as knowledge about climate change changes over time.

- **Poor alignment between climate change impacts and transportation organizational arrangements**: The decentralized and modally focused organizational structure of the transportation sector may not align well with climate change impacts, which do not always follow modal, jurisdictional, or corporate boundaries.
- **Resource constraints:** Climate change in some U.S. regions may necessitate permanent, expensive changes. Many infrastructure management agencies are already financially stretched, a reality highlighted periodically in the media after catastrophic infrastructure failures.
- **Resistance to change**: Transportation professionals typically adopt incremental rather than radical solutions when faced with a new problem, such as a break from a historical trend. This may hamper timely responses to issues such as climate change that involve risk and uncertainty.
- **Lack of relevant information:** Transportation planners often lack sufficiently detailed information on which to take appropriate action. Although climate scientists tend to describe projected changes in climate in terms of global, continental, or subcontinental averages, transportation planners need data at the finest level of geographic detail because infrastructure is regional and local.

Energy Infrastructure

To address potential climate-related impacts to the country's energy infrastructure, the public and private sectors may employ a variety of adaptive measures with proven capabilities. Although some of these measures reflect policies pursued by government, many reflect the financial incentives of energy suppliers to protect their investments. In addition, although few of these measures were designed specifically to address climate change, they nonetheless render the U.S. energy system more resilient to the potentially adverse impacts of a changing climate.

Importantly, the adaptive measures described in this section may interact dynamically with (a) policies that the government may pursue to mitigate climate change and (b) consumer responses to warming itself. As indicated in the impacts discussion above, climate change may, in effect, reduce the generating capacity of thermoelectric, and some hydroelectric, power plants. Although this could create imbalances between supply and demand, policies such as a carbon tax or a cap on GHG emissions may induce consumers to conserve energy. This demand response could offset warming-related capacity losses.

Similarly, the dynamic effects of warming itself could also offset these losses. For example, as temperatures increase, consumers and businesses would have a financial incentive to use more efficient cooling systems that require less energy. In addition, warming could hinder or reverse the population migration to the southern United States, which would reduce energy demand for cooling.

To adapt to climate-related losses in generation, electricity suppliers may take measures to improve generating efficiency or expand capacity. As noted by the CCSP, turbine designers have developed a variety of tools for addressing local ambient conditions. These include inlet guide vanes, inlet air fogging (i.e., cooling and mass flow addition), inlet air filters, and various techniques for washing compressor blades (to manage salt and dust deposited on compressor blades; U.S. CCSP 2007). Power plants could deploy these tools to address changes in ambient conditions associated with climate change. In addition to these maintenance measures, electricity suppliers could, if necessary, install additional generating capacity to offset climate-related reductions in generation at existing plants. Electricity generators have a proven ability to construct generating capacity to meet increases in demand and to replace retiring units. For example, the U.S. Energy Information Administration projects approximately 25,600 megawatts of capacity additions in 2009 at new generating facilities (EIA 2007).

To address climate-related reductions in the availability of cooling water at power plants, many power plants can be retrofitted with cooling systems that consume less water. For example, recirculating cooling systems use approximately 95 percent less water than once-through systems, and dry cooling systems—which run boiler steam through radiator-like coils—use virtually no water (California Energy Commission 2005). In addition, power plants are increasingly using treated wastewater and water purchased from offsite to meet their cooling water needs (U.S. EPA 2000).

Competing water resource objectives may complicate adaptation to reduced water availability at power plants. In areas where climate change reduces the availability of water for power plants, it will also reduce the availability of water for agriculture, municipal use, recreation, and in-stream flow protection for endangered species. Therefore, an integrated approach to adaptation will be necessary in these areas.

Although extreme weather events associated with climate change are inherently unpredictable, capacity exists to adapt to more frequent and intense extreme weather events, as described below.

- **Expansion of refinery capacity in less vulnerable areas:** As indicated above, much of the refining capacity of the United States is concentrated in the storm-prone Gulf of Mexico region. The construction of additional refineries (or the expansion of existing refineries) in interior regions would reduce the refining sector's vulnerability to more frequent and severe storms in the Gulf region.
- **State and local measures for electricity transmission and distribution:** In testimony before Congress in May 2008, Lisa Edgar, a commissioner on the Florida Public Service Commission, described several adaptive measures that the state of Florida is implementing to make its transmission and distribution infrastructure more resilient to climate change (Edgar 2008). For example, in response to concerns that wooden utility poles do not adequately withstand hurricane-force winds, the Commission has established a more thorough and systematic pole inspection program. In addition, the Commission now

requires all electric utilities in Florida to prepare a pre–hurricane season briefing each year, which gives the Commission an opportunity to ensure that each utility is prepared for the storm season.

To encourage the construction of power lines underground, the Florida Public Service Commission has amended its rules to reduce the costs of undergrounding for individual ratepayers (Edgar 2008). Under Commission rules, ratepayers that request underground service are responsible for paying the difference between the cost of the underground project and the cost of a comparable overhead project. This cost differential, referred to as the contribution-in-aid-of-construction (CIAC), has historically served as a deterrent to undergrounding. To encourage additional undergrounding, the Commission modified its rules to

  - require that utilities include the cost differentials in long-term operating costs in the CIAC, including the costs of storm restoration;
  - distribute the costs of undergrounding at a specific location to all ratepayers if the project will provide quantifiable benefits to customers outside of the immediate area; and
  - allow customers to pay CIAC charges over time.

- **Strategic Petroleum Reserve:** The Strategic Petroleum Reserve represents a potentially important mechanism for alleviating storm-related interruptions in the production and/or delivery of crude oil. For example, in response to Hurricane Katrina in 2005, the federal government released 9 million barrels of crude oil from the reserve to lessen the economic damage caused by the storm (Drevna 2008).
- **Harden coastal areas:** Flood protection measures, such as seawalls and bulkheads, could potentially protect refineries, power plants, and other coastal energy facilities from flooding during extreme storm events.[9]

As indicated above, warming in the Arctic represents a potential threat to the structural integrity of sections of the trans-Alaska oil pipeline. Both Larsen et al. (2008) and McBeath (2006) indicate, however, that pipeline operators already use thermosyphons to dissipate heat away from the vertical support members that serve as the foundation of the pipeline. As the Arctic continues to warm, pipeline operators can employ this practice more extensively.

Water, Sewer, and Communications Utilities

As indicated above, the potential for reduced water supplies in some areas represents a key climate-related threat for nonenergy utility providers. Municipal water systems, however, have a demonstrated capacity for implementing measures to avoid potential shortfalls in water supply. For example, the Massachusetts Water Resources Authority (MWRA), implemented the following

[9] These measures are described in greater detail in the discussion below on coastal and flood defense infrastructure.

measures in the 1990s that could be replicated by other areas to address climate-related reductions in supply (MWRA 2000).

- **Leak detection**: Between 1991 and 1995, MWRA conducted a leak detection survey of more than 6,000 miles of water pipes and detected 2,374 leaks responsible for 30 million gallons per day (mgd) of leakage.
- **Demand management/conservation**: To encourage conservation at the residential level, MWRA began providing low-flow devices to households free of charge in the 1990s. MWRA estimates that the installation of these devices systemwide would yield savings of between 5 and 6 mgd.
- **Demand management for industrial, commercial, and institutional users:** For industrial, commercial, and institutional (ICI) water users, MWRA began a water audit program to identify opportunities for water savings. In addition, MWRA initiated an incentive program under which regulated sewer users could reduce their permit fees by reducing their industrial discharge volumes, creating an incentive for ICI users to conserve.

In addition to these measures, the interconnection of existing water supply systems may help ensure stable supplies at the local level. For example, although many cities and towns in the metropolitan Boston area operate and maintain their own water supply systems, several of these municipalities supplement their supplies with water from MWRA reservoirs (Kirshen et al. 2006).

The replacement of existing infrastructure and the construction of new infrastructure represent significant, and perhaps the most cost-effective, opportunities to adapt storm sewer systems to a changing climate. Expanding the conveyance and storage capacity of these systems would be a costly and time-consuming endeavor, as these systems often serve areas covering several square miles and are difficult to access underground. During routine maintenance or the construction of new sewer systems, however, the incremental costs of additional capacity would be limited. Nevertheless, adaptive measures implemented through system expansion and routine maintenance may not be sufficient to address climate-related threats to sewer networks in some areas. Because potential changes in climate for specific areas are highly uncertain, agencies that manage storm sewer systems may lack the information necessary to determine the appropriate level of adaptive investment during routine maintenance and system expansion.

Similar to the undergrounding of power lines for electricity providers, the undergrounding of overhead telephone lines represents a potential adaptive measure to reduce climate-related vulnerabilities for land-line telecommunications networks. The cost of undergrounding varies by location, but Pacific Gas & Energy estimated in 1999 that the cost of undergrounding telecommunications lines in Hawaii would be approximately $250,000 per mile (Martin 1999). Similarly, the Virginia State Corporation Commission (2005) estimates undergrounding costs of approximately $230,000 per mile in Virginia.

Coastal and Flood Defense Infrastructure

Effective, efficient adaptation to coastal SLR and storm risks associated with climate change will almost necessarily involve the construction of new infrastructure. A national economic impact analysis that estimated the economically efficient response to SLR at 30 representative sites along the Atlantic, Gulf, and Pacific coasts found that retreat or partial retreat (that is, avoiding construction of seawalls or bulkheads or actively replenishing beach sand through beach nourishment projects) was an efficient response at approximately one-third of the sites (Yohe et al. 1999). That implies that fully two-thirds of the vulnerable, low-lying coast could require some flood protection infrastructure response, at a capital cost of perhaps $1,000 per foot for an ocean-facing seawall. In follow-up work that focused on the relatively highly developed and valuable California coast, the construction of protective measures was justified by a site-specific cost–benefit test at *all* of the potentially vulnerable sites assessed (Neumann and Hudgens 2006). Absent these adaptive measures, damages from inundation could be much greater.

One conclusion from this research is that the costs of protective infrastructure are much greater than proportional to the rate of SLR for three reasons. First, higher levels of SLR bring more areas into the vulnerable elevation range. Second, protective structures, such as seawalls, are not constructed of uniform thickness—the shape is tapered, to absorb and diffuse wave energy, so the thickness must be greater if the height of the structure is greater. Some engineering research says that the volume increases with the 1.2 power of the height of the structure (see Yohe et al. 1999). Third, the volume of sand needed to nourish a beach also increases greater than proportionally with sea level, because as sea level increases, the area requiring nourishment—even within a given site—can be greater. The result of these factors can be dramatic. In the California study (Neumann and Hudgens 2006), the annualized capital and annual maintenance costs for coastal protection in the year 2100 to respond to a 50-centimeter SLR were estimated at roughly $200 million (in year 2000$); the comparable figure for a 1-meter SLR was more than $1.5 billion. As a result, a critical element of efficient adaptation is an accurate estimate of future SLR—at minimum, infrastructure planners need a reliable estimate of SLR during the expected useful life of the coastal defense project.

Another conclusion from the coastal vulnerability research is that timing matters. In the California study, the authors note that significant uncertainty remains about whether coastal structures can be built at an optimal time (that is, just before inundation occurs). Waiting implies lowered costs, because of the time value of money, but waiting too long negates the main benefit of adaptation, that is, prevention of property loss. The effect can be very important: the authors estimate that, if protective seawalls were constructed 10 years sooner than optimal, in all cases, their discounted capital costs would increase by 35 to 63 percent; if 20 years too soon, it would increase costs by 81 to 165 percent (Neumann and Hudgens 2006). Gradual SLR over time could make it possible to plan "just-in-time" adaptive measures, but one factor that potentially tilts the timing to an earlier date is that much of the time, coastal structure damage does not result from gradual inundation, but from the repeated effects of storms. Over time, SLR makes storm surges more damaging, as a higher ocean level allows the surge to spread farther inland and with more wave energy to damage structures. In those cases, an interim adaptive measure, such as elevation of the structure, may cost-effectively be used as a stop-gap measure, to buy time before the much more expensive seawall construction project is necessary. Such elevation is already occurring in many areas (Easterling et al. 2004), sometimes in response to Federal Emergency Management Agency (FEMA) flood insurance requirements (Heinz Center 2000; U.S. CCSP 2008a).

An important tool in enhancing coastal adaptive capacity is the insurance market. Currently, flood risks in the coastal zone are insured through the FEMA National Flood Insurance Program (NFIP). Other risks from coastal storms, however, such as wind damage, are privately insured as part of property insurance coverages. In many, if not most, coastal areas, however, the realization of large wind-related hurricane damages and the inability of insurers and reinsurers to spread these risks over a wide pool of rate-payers has severely curtailed the availability of property insurance. As a result, many states, even those that have not traditionally been hurricane-prone (e.g., Massachusetts and California), now find themselves to be the insurers of last resort for coastal property owners. The increasing role of state and federal government agencies in continuing to keep this adaptation tool available for homeowners has been highlighted in recent literature as well (Kirshen et al. 2006).

4. Opportunities for Building Adaptive Capacity

The prior section provided a brief overview of existing adaptive capacity that can be brought to bear to address climate impacts on infrastructure. In this section, we discuss options for enhancing adaptive capacity, with a particular focus on actions that can be taken in the public sector. Our focus on the public sector is not meant to discount the possibility of private sector enhancements to adaptive capacity—on the contrary, we believe that climate change impacts and potential mitigation policies (such as pricing carbon) are likely to provide clear incentives to the private sector to improve resiliency to a changed and more uncertain future climate. A great deal of evidence suggests that the private sector is already engaged in these actions (see for example, Easterling et al. 2004, and U.S. CCSP 2007).

In the area of infrastructure, however, the high degree of public ownership and regulation suggests that a wholly private sector–based adaptation strategy would probably leave many productive and cost-effective enhancements to adaptive capacity unfulfilled. Although it is difficult to quantify precisely, it appears that public ownership is especially high in the areas of transportation, water, and sewer infrastructure, but can vary by subsector and location. Energy infrastructure, both generation and transmission, tends to be privately owned but highly regulated by the public sector. Large-scale flood defense infrastructure is most often financed and maintained in the public sector, often with cost-sharing from multiple layers of government, but private sector armoring and beach nourishment projects are not uncommon and appear to be increasingly pursued, even at the level of single properties. In the remainder of this section, we review public sector options for enhancing adaptive capacity for each of these categories of infrastructure.

Transportation

Almost all major U.S. road transportation and public transit infrastructure is publicly owned, as are airports, but rail networks and port facilities are more commonly privately owned and operated. The degree and quality of public sector planning and maintenance of infrastructure varies a great deal; periodic catastrophic failures of nodes in the system tend to catalyze planning efforts, as illustrated by the widely publicized Interstate 35 bridge collapse in Minneapolis in August 2007. As a result, there is potentially a great need to improve transportation infrastructure planning for the baseline, without climate changes; this need may be further motivated over time by climate uncertainties and extreme events. In some cases, as noted below, new efficiencies might be realized by a greater integration of transportation and land-use planning capabilities.

The TRB (2008) analysis provides a comprehensive list of potential enhancements to adaptive capacity. It first categorizes the types of possible adaptations.

- **Operational responses**: The most rapid response to the impacts of climate change is likely to come through changes in transportation operating and maintenance practices. These changes involve incorporating responses to more extreme weather events into routine operations, improving collaboration with emergency managers, recognizing weather emergency management as an integral function of transportation agency operations, and widely sharing best practices.
- **Design strategies**: Adapting to climate change will require reevaluation, development, and regular updating of design standards that guide infrastructure design. Options regarding engineering design decisions include the following.
    - Develop more robust standards without a full understanding of future risks and presumably a greater cost. This would be appropriate for major facilities in vulnerable locations (e.g., critical bridges and evacuation routes).
    - Build infrastructure with shorter design lives. This option may not be viable in the United States because of the disruption and negative public reaction resulting from more frequent retrofits.
    - Hedge by building to current standards or making marginal improvements, recognizing that the infrastructure remains at risk and may require major improvements in the future.
- **New infrastructure investment, transportation planning, and controls on land use:** The Transportation Resource Board analysis (TRB 2008) states that one of the most effective strategies for reducing the risks of climate change is to avoid placing people and infrastructure in vulnerable locations, such as coastal areas. This is a challenge, however, given the limited perspective of local land-use planning in most of the United States. A potential strategy for overcoming this limited perspective is the integration of transportation and land-use planning, which would recognize the impact of transportation investments on regional development and vice-versa. With this integrated approach, planners could implement scenario-based approaches to examine the social, economic, and environmental impacts of a range of regional growth scenarios. In addition, FEMA could reevaluate the risk reduction effectiveness of the NFIP.
- **Monitoring technologies and new materials:** Better technologies and systems for monitoring the impacts of climate change on infrastructure could provide engineers with an early warning of problems, buying time to make necessary modifications. In addition, research and development into materials that can withstand the more severe extremes of climate change could be productive.

- **Data, models, and decision-support tools**: More refined data (e.g., better elevation data for flood plain mapping, more accurate data on surface temperatures) and improved modeling—from weather forecasting to modeling of expected storm surge and real-time evaluation scenarios—are needed as well.
- **New partnerships and organizational arrangements**: Adapting to climate change will require new partnerships and organizational arrangements that better align with climate impacts than do current modal, jurisdictional, and corporate boundaries around which decisionmaking in the transportation sector is structured.

From among these options, the TRB (2008) highlighted the following specific recommendations.

- Federal, state, and local governments and the owners and operators of infrastructure should inventory critical transportation infrastructure in light of climate change projections to determine whether, when, and where projected climate changes might be consequential.
- State and local governments and private infrastructure providers should incorporate climate change into their long-term capital improvement plans, facility designs, maintenance practices, operations, and emergency response plans.
- Transportation planners and engineers should use more probabilistic investment analyses and design approaches that address trade-offs between the costs of making infrastructure more robust and the economic costs of failure. These approaches could be used to communicate trade-offs to policymakers who make investment decisions and authorize funding.
- The National Oceanic and Atmospheric Administration, the U.S. Department of Transportation (DOT), the U.S. Geological Survey, and other relevant agencies should work together to develop a process for better communication among transportation professionals, climate scientists, and others; these agencies should also establish a clearinghouse for transportation-relevant climate change information.
- Research at federal and state agencies and universities that provide climate data and decision-support tools should include the needs of transportation decisionmakers. Needed tools include digital elevation maps for coastal areas and greater use of scenarios that include climate change in the development of long-range regional transportation plans to pinpoint vulnerabilities.
- Transportation agencies and service providers should build on the experience in those locations where transportation is well integrated into emergency response and evacuation plans.
- Federal and academic research programs should encourage the development and implementation of monitoring technologies that could provide advance warning of pending failures due to weather and climate extremes on major transportation facilities.
- Transportation research and professional organizations should develop a mechanism to encourage sharing of best practices for addressing the potential impacts of climate change.

- DOT and civil engineering professional organizations should initiate immediately a federally funded, multiagency research program for ongoing reevaluation of existing—and development of new—design standards.
- In the short term, state and federally funded transportation infrastructure rehabilitation projects in highly vulnerable locations should be rebuilt to higher standards, and greater attention should be paid to the provision of redundant power and communications systems to ensure rapid restoration of transportation services in the event of failure.
- Federal planning regulations should require that climate change be included as a factor in the development of public-sector, long-range transportation plans; eliminate any perception that such plans should be limited to 20–30 years; and require collaboration in plan development with agencies responsible for land use, environmental protection, and natural resource management to foster more integrated transportation–land-use decisionmaking.
- FEMA should reevaluate the risk reduction effectiveness of the NFIP. At a minimum, updated flood zone maps that account for SLR should be a priority in coastal areas.

Energy

Most of the energy infrastructure in the United States is privately owned and, as demonstrated in 2005 by Hurricanes Katrina and Rita, this infrastructure is vulnerable to climate-related stresses. In addition, because the U.S. economy relies significantly on reliable supplies of energy, climate-related impacts to energy producers also affect the economy more broadly. Therefore, a role exists for government to ensure that the U.S. energy infrastructure is resilient to climate change.

As noted above, a key vulnerability of the U.S. energy infrastructure is that much of it is concentrated along the Gulf Coast, where hurricanes are fairly common during the summer and fall. If climate change leads to more frequent and intense storm events in the Gulf region, this concentration of energy assets along the Gulf Coast could be particularly costly. Depending on the extent to which climate change leads to increased storm frequency and severity in the Gulf, energy producers, in the long run, may find it in their economic interest to shift their productive capacity to safer areas. The federal government could play a constructive role in informing these investment decisions by periodically updating climate risk analyses for the region.

Hurricanes Katrina and Rita demonstrated the importance of the Strategic Petroleum Reserve in ensuring the stability of energy supplies. As extreme weather events become more frequent and severe because of climate change, the federal government could bolster the economy's ability to recover from these events by expanding the capacity of the Strategic Petroleum Reserve. This expanded capacity could be particularly valuable in the event of successive disruptions in supply.

Government incentives (e.g., tax deductions, tax credits, or subsidies) for decentralized power generation could also serve as an important tool for expanding adaptive capacity. These decentralized systems could include fossil-based distributed generation, rooftop PV units, or (in some areas) household geothermal units. The expanded use of these systems would, in effect, spread climate-related risk over a large geographic area, thereby reducing the impact of climate-related events (e.g., a hurricane) focused in a specific area.

At the state and local level, more widespread storm planning for refineries, power plants, and other facilities would minimize storm-related damage to these facilities and reduce the amount of time required for them to recommence regular operations following major storm events. The state of Florida's storm planning efforts could serve as a model for other states and municipalities. Based on the measures implemented in Florida, key components of expanded storm planning could include (a) the development and implementation of storm hardening plans on a periodic basis to ensure that power plants, refineries, and other facilities are able to withstand high winds, storm surges, and flooding; (b) annual briefings from utilities and refineries prior to the storm season to ensure storm readiness; and (c) regular inspections of vulnerable infrastructure (e.g., wooden utility poles).

Finally, as the United States considers potential policies to mitigate GHG emissions, it will be important for the government to develop an integrated approach to impact and mitigation planning. An integrated approach will ensure that impact and mitigation planning do not work at cross purposes and will help identify potential synergies between the two (e.g., energy conservation could reduce GHG emissions and reduce the impacts of potential disruptions in energy supply). This integrated planning may be of particular importance for renewable energy sources. For example, as indicated above, climate change may reduce the generating capacity of hydroelectric dams in the Pacific Northwest during the summer months. Under an integrated planning approach, adapting to this effect through energy conservation (i.e., reducing demand) would be preferable to increasing generation from a coal- or gas-fired power plant, which would increase GHG emissions.

Water, Sewer, and Communications

Although adaptive capacity exists among municipal water providers to address potential reductions in water supply associated with climate change, additional action by federal, state, and local government agencies may be required to ensure the stability and reliability of water supplies. As indicated above, addressing climate-related reductions in water availability may require the integration of local or regional water systems to link water supplies with cities and towns vulnerable to climate-related shortfalls in supply. The government could play a key role in facilitating the integration process by designing or modifying the institutions that manage these water-sharing arrangements, helping to define and enforce equitable operating rules for integrated systems, and helping to resolve water disputes as they arise. In addition, because the establishment or expansion of integrated water systems could potentially interfere with other water uses (e.g., agricultural use or stream-flow requirements for endangered species), government intervention is necessary to strike the appropriate balance between these uses and the provision of municipal water supplies. For example, the congressionally chartered Delaware River Basin Commission manages these competing water-use goals for the Delaware River watershed.

Addressing potential climate-related imbalances between water demand and supply may require significant conservation in some areas to reduce demand. To encourage more widespread conservation, local and regional water authorities will need to pursue a variety of measures. One of the most straightforward to implement is an increase in water prices. These increases could take several different forms including (a) increasing prices uniformly for all water supplied, (b) repealing volume discounts, (c) instituting seasonal rates, (d) implementing increasing block rate pricing, or (e) any combination of the above. Whatever their form, price increases would provide an incentive for households, businesses, and other water users to identify opportunities for conservation. Based on a review of approximately 100 studies on water demand, Beecher (1994, as cited in Stallworth 2003) estimates that the likely range of elasticity of residential water demand is –0.20 to –0.40, meaning that a 10 percent increase in price lowers demand by 2 to 4 percent, and that the range for industrial demand is –0.50 to –0.80. As these results indicate, the demand for water is relatively inelastic (i.e., it does not change significantly with changes in prices). Therefore, other government-led conservation efforts to complement rate increases would be appropriate, including the distribution of low-flow devices free of charge and more frequent bans on certain types of discretionary water use (e.g., filling swimming pools, lawn and garden watering, and washing cars).

With respect to sewer systems, climate change will probably require local governments to update their standards for the design of these systems. Because of the uncertainty associated with future changes in climate, local governments should update these standards on a recurring basis (e.g., once every 10 years). The federal government could help municipalities address this uncertainty by developing, and periodically updating, regional sewer design guidelines that reflect the best available information on projected changes in rainfall at the regional level. Although these guidelines would not reflect rainfall projections specific to any given city or state, they would provide municipalities with an approximation of the extent to which they should alter their design standards in anticipation of climate change.

Coastal and Flood Defense

Coastal and flood defense infrastructure, although typically publicly owned, financed, and maintained, is most often designed to protect private property. As a result, many of the risks presented lend themselves well to a private sector approach that internalizes these risks. Nonetheless, most large-scale coastal protection projects are most efficiently designed and carried out at the collective level, particularly in urban contexts but also in areas where a single line of coastal defense makes much more sense than a series of rings around individual properties. As a result, a public planning role in the design of coastal defense is probably unavoidable.

Clear communication of public intentions and limitations for defensive infrastructure could have three clear benefits for private and public actors: (a) it would resolve uncertainty about whether a particular property would be protected, helping to channel private investment in coastal development toward those areas where protection is most likely; (b) it could serve as a focal point for public investments in other types of infrastructure, presumably avoiding investment in roads, bridges, and water and sewer utilities in those areas that are currently marginal or undeveloped; and (c) it would facilitate some forms of temporary, private adaptive measures, such as elevating structures above flood level or small-scale armoring in those areas that might be threatened early but where more extensive armoring projects would be most cost-effectively constructed on a just-in-time basis, just prior to large-scale inundation. Targeting the provision of protection infrastructure, however, may require large doses of political courage—for example, it has proven extremely difficult to tell constituencies in the most threatened areas of post-Katrina New Orleans that the public sector may not invest in protection for their neighborhoods.

Effective adaptation in this sector is not limited to building infrastructure. As in transportation, there is much to be gained by integrating planning for coastal defense with land-use planning. As noted in Nicholls et al. (2008), one reason for concern about coastal losses is the trend of increasing development and property value in coastal areas, both because of the amenity value of coastal proximity and the reality that U.S. urbanization remains strong in most coastal cities. The public sector could take a proactive stance in land-use planning and thereby limit the growth of coastal resources at risk, either through regulatory measures or by developing new and more compelling information on the increasing risks of climate change to coastal development. One limiting factor in local and state attempts to adopt a regulatory approach has been the legal issue of property takings – these issues may arise when land-use restrictions limit development options, leading private landowners to challenge the restrictions by invoking the constitutional government "takings" clause (Whitelaw and Visgilio 2005). Policy approaches that clarify the limits of public sector willingness to protect coastal properties built or improved "in harm's way" might serve to reinforce the private incentive to internalize coastal risks, which can serve to reduce the expected value of damages over time.

Insurance models are also relevant, but the recent rapid expansion of risk in the coastal zone, a result of both increases in the value of coastal property and increases in destructive extreme events (after a roughly three-decade lull in hurricane activity that ended in the early 1990s), has presented new limits to risk-sharing. The result has been an increasing trend toward the public sector as insurer of last resort, not just for flood risks, where the NFIP long ago filled the gap in availability of private sector coverage, but also for the more run-of-the-mill property casualty insurance.

Another reason for public sector involvement is a public interest in maintaining recreation and access. A fully privatized system of planning protective structures might lead to a U.S. coastline that is armored to a great extent. Because hard armoring can lead to significant or even total loss of beach width, as wave energy below the seawall scours sand from the beach, armoring may reduce options for beach recreation in some areas. Public demand for recreational beach and boating access might inadvertently serve as a catalyst for land-use planning in the coastal zone that limits the construction of hard protection infrastructure and encourages other options, such as beach nourishment.

5. Conclusions and Looking Forward: Steps toward Adaptation Policy

In the prior sections of this paper, we reviewed major vulnerabilities, existing adaptive capacity, and possible enhancements to adaptive capacity. We present what we view as the most important conclusions from these summaries in Table 1 for each of the four major categories of infrastructure we address. In thinking about needs for adaptive capacity enhancements across all types of infrastructure, three themes emerge that have clear implications for federal government policy.

- **The need for integration of planning.** In both the transportation and coastal defense areas, and to some extent sewer infrastructure, studies have concluded that resources could be allocated more efficiently if infrastructure planning were better integrated with land-use planning. A key obstacle noted to this integration, however, is that such planning typically occurs across several levels of government, with land-use planning usually carried out at the local level. Studies also note the need to integrate planning across transportation modes to ensure redundancy during emergency situations. Examples of integrated planning are rare, but at least one state (New Jersey) has developed a state-level planning process that uses as its "base layer" an aggregate land-use plan built up from local land-use plans. The resulting state plan is then used by the state budgeting office to determine where state infrastructure funds will be allocated. The result provides clarity on where the government plans to support infrastructure development (and replacement), which can leverage private investment by sending signals about geographic areas where development is supported. Integrated planning may also help facilitate financial sector adaptation (e.g., insurance schemes), which some have argued is much easier and more flexible and robust than technical adaptation (Hallegatte 2008). Finally, there is an emerging need to integrate adaptation and mitigation planning; this need is most acute in the energy sector.
- **The need to encourage innovation in technology and updating of standards.** Many of the studies cited above note that a change in climate will present technological challenges that may require more resilient infrastructure capital. Centralized efforts to update building standards may be one means to spur the needed technological change, although in the United States, new efforts to streamline this process may be necessary (Meyer 2008). The Canadian government has already launched several efforts in this direction (Canadian Standards Association 2007a–c, 2006, 2005; Infrastructure Canada 2006).
- **The need to take best advantage of replacement opportunities, including extreme events.** More frequent and destructive extreme events, such as recent hurricanes and riparian floods, have already proven to be a huge challenge to maintaining public infrastructure. At the same time, many studies note that adaptation to climate stresses is more cost-effectively accomplished during the design phase of projects, rather than as a retrofit to existing capital. Although extreme events are devastating to affected regions, the rebuilding process can be used as an opportunity to replace damaged infrastructure with more resilient capital.

Consistent with these three general themes, we developed the following initial priority list for new public policy action regarding the key infrastructure resources at risk as important steps for enhancing adaptive capacity.

- Initiate targeted building code and building standards reform and refinements. The Canadian efforts in this area may be a model for U.S. actions.
- Develop a system for sharing and communicating projections of downscaled climate data—for both sudden and gradual climate change—to support better local planning.

- Enhance public provision of risk information and tools to support good private decisionmaking. A complementary product would be capacity-building demonstration projects that show the proper use of probabilistic modeling concepts to identify cost-effective adaptation projects that are robust in the face of climate uncertainty.
- Adapt federal infrastructure planning to climate risks by seeking to target the federal infrastructure funding effort to those areas where development can best be supported in the face of climate risks. By taking these actions, the government can facilitate "soft" adaptation options, such as new insurance schemes, and limit cases where federal infrastructure investments stimulate development in areas that increase private resources at risk.
- Explore "no-regret" and reversible options for infrastructure capital, using existing or new technologies, and particularly in areas at high risk from extreme events (e.g., the Gulf Coast). Although it runs counter to much conventional thinking on infrastructure planning, lessening time horizons for capital investments can actually enhance resiliency in the face of climate uncertainty (Meyer 2008; Hallegatte 2008).
- Foster *inter-regional technology transfer* among areas that might provide a current spatial analog, where possible. Infrastructure planners in the Mid-Atlantic may have insights for those in the Northeast, for example.
- Expand regional networks for infrastructure provision and build links among local networks as a risk-spreading strategy. Such efforts have been particularly effective in the electric energy sector in increasing the reliability of service delivery, but might also be more effectively applied in water resource provision to respond to increased drought risk.
- Adopt a risk-based approach to infrastructure planning that involves a conversation between planners and climate scientists. The role of infrastructure planners in this conversation would be to define the information they need to do their job well, such as thresholds of temperature, precipitation, and the likelihood of extreme events (see, for example, Peterson et al. 2008 for an example in the transportation sector). Climate scientists and other analysts could use this information to provide assessments of the current and projected future risk of crossing those thresholds under various future climate scenarios. Other analysts might then look at the likelihood of correlations with other nonclimate factors that can affect planning.

Table 1. Summary of Findings

	Key Sensitivities	Existing Adaptive Capacity	Enhancements to Adaptive Capacity
Transportation	- Road/rail/transit and coastal extreme events - Road/rail/transit inundation - Permafrost	- Integration with land-use planning - Current planning, maintenance and replacement system - Adjustment of industry-wide standards - Spatial analogs	- Updated building standards - Further integration with land-use planning - Establishing further redundancies and multimodal transportation capabilities
Energy	- Inundation of low-lying generating capacity - Extreme events (power lines, refinery damage, platform damage) - Cooling water availability - Reduced efficiency of thermal units - Hydropower operation - Consistency and availability of wind and solar	- Strategic Petroleum Reserve - Low- or no-water cooling techniques - Undergrounding power lines - Capacity expansion - Geographic shift of capacity to safer areas	- Updated risk analysis to ensure stable supply - Expansion of Strategic Petroleum Reserve - More widespread storm planning - Integration of impacts and mitigation planning
Water/Sewer/ Telecomm	- Reduced water supply in some areas - Precipitation and saltwater intrusion - Overloading of sewer systems due to more frequent and severe storms - Damage to phone lines and cell towers from extreme events	- Current maintenance and replacement systems for sewer - Undergrounding of phone lines - Water demand management (e.g., pricing and outreach) - Addressing unaccounted-for water - Integration and consolidation of water supply systems	- Updated design standards - Facilitation of integration and consolidation of water supplies - Increased pricing to encourage conservation
Coastal	- Inundation of low-lying property - Extreme events damaging or flooding port and urban areas	- Coastal protection projects (e.g., seawalls and beach nourishment) - Insurance - Land-use planning	- Clarification of responsibility for risk - Monitoring - Risk communication

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