Adapting Infrastructure and Civil Engineering Practice to a Changing Climate

Committee on Adaptation to a Changing Climate

Edited by J. Rolf Olsen, Ph.D.

ASCE

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Sponsored by the
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Contributors

Lead Coordinating Author

J. Rolf Olsen, Ph.D., A.M.ASCE, U.S. Army Corps of Engineers, Senior Technical Lead, Institute for Water Resources

Lead Authors

Bilal M. Ayyub, Ph.D., P.E., F.ASCE, University of Maryland, Professor, Civil Engineering, Director Center for Technology and Systems Management

Ana Barros, Ph.D., P.E., M.ASCE, S.M. IEEE, F.AMS, F. AGU, Duke University, Professor, Civil and Environmental Engineering and Earth and Ocean Sciences

Wayne Lei, Ph.D., Portland General Electric

Franklin Lombardo, Ph.D., Rensselaer Polytechnic Institute, Research Assistant Professor

Miguel Medina, Ph.D., F.ASCE, Duke University, Professor Emeritus

Constantine Samaras, Ph.D., A.M.ASCE, Carnegie Mellon University, Assistant Professor, Civil and Environmental Engineering

Orson P. Smith, Ph.D., P.E., D.CE, D.PE, M.ASCE, University of Alaska, Professor, Civil Engineering

Eugene Z. Stakhiv, Ph.D., U.S. Army Corps of Engineers, Visiting Scholar, Institute for Water Resources and International Center for Integrated Water Resources Management (ICIWaRM), Johns Hopkins University

Jonathan Tan, A.M.ASCE, Solution Evolution Manager, Smart Integrated Infrastructure, Black and Veatch

Ted S. Vinson, Ph.D., P.E., G.E., M.ASCE, Oregon State University, Professor Emeritus, Civil Engineering, Chair, ASCE CACC

Dan Walker, Ph.D., A.M.ASCE, ClimateMonkeys LLC

Richard Wright, Ph.D., NAE, Dist.M.ASCE, National Institute of Standards and Technology, Retired Director of Building and Fire Research Laboratory, Vice-Chair, ASCE CACC

Contributing Authors

Brian Beucler, P.E., M.ASCE, Federal Highway Administration

Ben Harding, P.E., M.ASCE, AMEC Environment and Infrastructure Inc.

Miriam Heller, Ph.D., M.ASCE, MHI Tech Systems, Principal, Stanford University, mediaX, Dist. Visiting Scholar, Johns Hopkins University, Adjunct

Nir Y. Krakauer, Ph.D., A.M.ASCE, City College of New York, Assistant Professor, Civil Engineering

Jay, R. Lund, Ph.D., F. EWRI, M.ASCE, University of California Davis Professor and Director for Watershed Sciences

Joel Smith, Stratus Consulting, Principal

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Executive Summary

Civil engineers are responsible for the planning, design, construction, operation and maintenance of physical infrastructure. Infrastructure includes buildings of all types, communication facilities, energy generation and distribution facilities, industrial facilities, transportation networks, water resource facilities and urban water systems. Infrastructure is expected to remain functional, durable and safe for long service lives, typically 50 to more than 100 years. They are exposed to, and potentially vulnerable to, the effects and extremes of climate and weather, such as droughts, floods, heat waves, high winds, storm surges, fires and accumulated ice and snow. Engineering practices and standards are intended to provide acceptably low risks of failures regarding functionality, durability and safety over the service lives of infrastructure systems and facilities.

There is strong evidence that the Earth is warming. Increases in atmospheric and ocean temperatures, increases in extreme precipitation and intensity in many areas, and global sea-level rise have already been observed. These trends are projected to continue into the future. While there is considerable evidence that climate is changing, understanding the significance of climate change at temporal and spatial scales relevant to engineering practice is more difficult.

Global climate models (GCMs) are the primary tools that climate scientists use to make quantitative projections of future global and regional climate. Climate models project systematic changes in climate and weather conditions. Climate projections introduce additional climatic uncertainties beyond those that can be estimated from observations of the past. For example, there is significant uncertainty regarding the magnitude and rate of climate change over the design life of the systems and elements of our built environment. Engineering design is primarily concerned with climate and weather extremes, but the projection of future extreme events and their frequency of occurrence have even greater uncertainty than changes in mean conditions. GCMs tend to underestimate the variance and serial persistence in observed climate, which implies that they may underestimate climate extremes. Engineering design and planning is generally conducted at the regional and local scales, but GCMs perform better at lower spatial resolution and over longer time scales. Regional modeling currently performed with downscaling techniques is used to obtain higher-resolution regional and local projections. However, the uncertainty is much larger on regional and local scales. Generally, uncertainty increases as the planning horizon increases with scenario-related uncertainties dominating other types of uncertainty such as model and parameter uncertainties.

The long-lived nature of infrastructure and the even longer-term influence of the associated right-of-ways and footprints suggest that the climate of the future should be taken into account when planning and designing new infrastructure. Considering the impacts of climate change in engineering practice is analogous to including forecasts of long-term demands for infrastructure use as a factor in engineering design. However, even though the scientific community agrees that climate is changing, there is significant uncertainty about the location, timing and magnitude of the changes over the lifetime of infrastructure. The requirement that engineering infrastructure meets future needs and the uncertainty of future climate at the scale of the majority of engineering projects leads to a dilemma for practicing engineers. This dilemma is a gap between climate science and engineering practice that must be bridged.

This gap can be bridged by characterizing and quantifying (to the degree possible) uncertainty in future climate and taking such findings into consideration when planning and designing infrastructure. Risk analysis and management is the primary approach engineers take to deal with future uncertainty. Engineering practices and standards are typically based on assumed stationarity of extremes of climate and weather – that the frequencies and intensities of extremes observed in the past adequately represent those that will occur in the future. This assumption may not be valid under a changing climate. However, it is also problematic to estimate the probabilities of future climate events from climate models, as the uncertainty of future climate is not adequately quantifiable. Models themselves change to incorporate new scientific understanding and better computational technology. Engineers can attempt to make plans and designs adaptable to a range of future conditions of climate, weather, extreme events and societal needs for infrastructure. However, there will be a tradeoff between the cost of increasing system reliability and the potential cost and consequences of potential failure.

Considering the above information, the following recommendations are appropriate:

- Engineers should engage in cooperative research involving scientists from across many disciplines to gain an adequate, probabilistic understanding of the magnitudes of future extremes and their consequences. Doing so will improve the relevance of modeling and observations for use in the planning, design, operation, maintenance and renewal of the built and natural environment. It is only when engineers work closely with scientists that the needs of the engineering community become fully understood, the limitations of the scientific knowledge become more transparent to engineers, and the uncertainties of the projections of future climate effects become fully recognized for engineering design purposes.
- Practicing engineers, project stakeholders, policy makers and decision makers should be informed about the uncertainty in projecting future climate and the reasons for the uncertainty, as elucidated by the climate science community. Because the uncertainty associated with future climate is not completely quantifiable, if projections of future climate are to be used in engineering practice it will require considerable engineering judgment to balance the costs of mitigating risk through adaptation against the potential consequences of failure.
- Engineers should develop a new paradigm for engineering practice in a world in which climate is changing, but cannot be projected with a high degree of certainty. When it is not possible to fully define and estimate the risks and potential costs of a project and

reduce the uncertainty in the timeframe in which action should be taken, engineers should use low-regret, adaptive strategies such as the observational method to make a project more resilient to future climate and weather extremes. Engineers should seek alternatives that do well across a range of possible future conditions.

- Critical infrastructure that is most threatened by changing climate in a given region should be identified, and decision makers and the public should be made aware of this assessment. An engineering-economic evaluation of the costs and benefits of strategies for resilience of critical infrastructure at national, state and local levels should be undertaken.

This document summarizes relevent climate science methodologies, defines potential impacts on engineering practices and civil engineering sectors, and offers decision criteria and potential solution pathways to address the impacts. The needs, approaches and changes in practice presented in this document are applicable not only to civil engineering but also to many other engineering disciplines.

1 Introduction

The American Society of Civil Engineers (ASCE) adopted Policy Statement 360 on the Impact of Climate Change:

> Civil engineers are responsible for design and maintenance of infrastructure projects that facilitate economic development and protect human health, welfare and the environment. Climate change may result in significant impacts to this infrastructure. Civil engineers and government policy makers must work together to anticipate and plan for these impacts. ASCE, its members, leaders, and resources are ready to develop and implement prudent policies as part of their mission to serve the public good (ASCE, 2012).

The purpose of the ASCE Committee on Adaptation to a Changing Climate (CACC) is to identify and communicate the technical requirements and civil engineering challenges for adaptation to climate change. Based on the recommendations of this white paper, response activities may be planned in the constituent committees of the Committee on Technical Advancement, the Institutes, and other elements of ASCE. These activities may result in recommendations for initiatives related to climate change and its effect on the safety, health and welfare of the public as it interfaces with civil engineering infrastructure. These activities may also inform recommendations made for standards, loading criteria, evaluation and design procedures for the built and natural environment, as well as for related research and monitoring needs.

The purpose of this white paper is to:

- foster understanding and transparency of analytical methods necessary to update and describe climate, including possible changes in the frequency and intensity of weather and extreme events, and for planning and engineering design of the built and natural environments
- identify (and evaluate) methods to assess impacts and vulnerabilities caused by changing climate conditions on the built and natural environments
- promote communication of best practices in civil engineering practice for addressing uncertainties associated with changing development and conditions at the project scale, including climate, weather, extreme environments and the nature and extent of the built and natural environments

The white paper consists of the following sections:

- Section 2, “Review of climate science for engineering practice,” provides an overview of the current knowledge of climate and weather science, as well as its limitations and relevance, to engineering practice.

- Section 3, “Incorporating climate science into engineering practice,” presents the challenges of incorporating climate change and weather science into engineering practice.
- Section 4, “Civil engineering sectors,” reviews the impacts of climate change on specific sectors, including codes and standards that might be affected, and includes recommendations for action.
- Section 5, “Research, Development and Demonstration needs,” proposes research and other activities to advance civil engineering practices and standards to effectively address climate change impacts.
- Section 6, “Summary, Conclusions and Recommendations,” concludes the white paper with a discussion on near-term decision making and recommendations for research, development and implementation of improved practices.

2 Review of Climate Science for Engineering Practice

2.1 Introduction

Weather and climate are a factor in civil engineering design and practice. Weather is defined as "the state of the atmosphere with respect to wind, temperature, cloudiness, moisture, pressure, etc." (NWS, 2013). Weather generally refers to short-term variations on the order of minutes to about 15 days (NSIDC, 2012). Climate, on the other hand, "is usually defined as the average weather, or more rigorously, as the statistical description in terms of the mean and variability of relevant quantities over a period of time ranging from months to thousands or millions of years" (IPCC, 2007a). Lovejoy (2013) points out that on the time scale for atmospheric processes, weather can be considered the high-frequency regime and climate the low-frequency regime of a process that exists on all time scales.

Changes in the statistical character of climate-related observations can be driven by natural variability on a variety of spatial and temporal scales (see Figure 2.1). Shorter-term variability (at the seasonal-to-interannual scale out to the decadal scale) is associated with cyclic variability within atmospheric and oceanic systems, and typically occurs at the continental or sub-continental level. By definition, global climate change produces a signal that is detectable at the global scale and persists over multiple decades (generally considered to persist for at least 30 years). Anthropogenic global climate change would produce a globally persistent signal that could not be attributed to natural variability (for example, due to internal variability of the ocean-atmospheric system or external variability due to changes in solar input or orbital mechanics).

In its most recent global assessment, the Intergovernmental Panel on Climate Change (IPCC, 2013) concluded: "Warming of the climate system is unequivocal, and since the 1950s, many of the observed changes are unprecedented over decades to millennia. The atmosphere and ocean have warmed, the amounts of snow and ice have diminished, sea level has risen, and the concentrations of greenhouse gases have increased." The National Climate Assessment (NCA) (Melillo et al. 2014) reached a similar conclusion: "Evidence for climate change abounds, from the top of the atmosphere to the depths of the oceans. Scientists and engineers from around the world have meticulously collected this evidence, using satellites and networks of weather balloons, thermometers, buoys, and other observing systems. Evidence of climate change is also visible in the observed and measured changes in location and behavior of species and functioning of ecosystems. Taken together, this evidence tells an unambiguous story: the planet is warming, and over the last half century, this warming has been driven primarily by human activity." (See Box 2.1 for a summary of key findings of the NCA.)

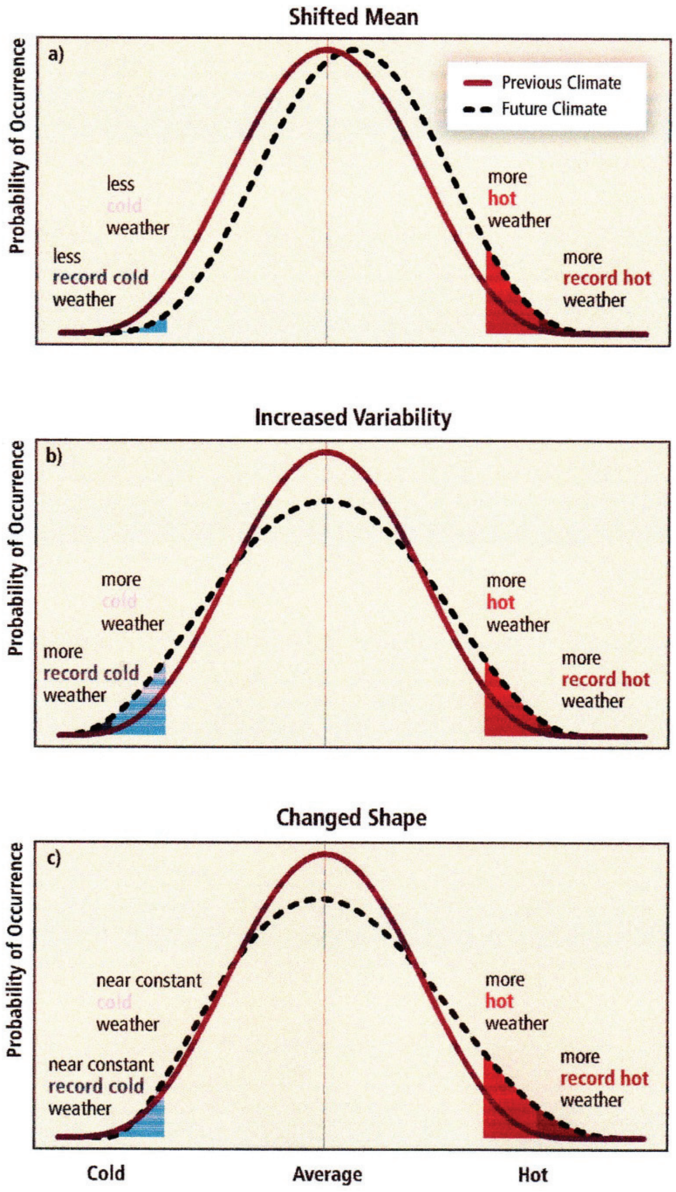


Figure 2.1. The effect of changes in temperature distribution on extremes. Different changes in temperature distributions between present and future climate and their effects on extreme values of the distributions: a) effects of a simple shift of the entire distribution toward a warmer climate; b) effects of an increased temperature variability with no shift of the mean; and c) effects of an altered shape of the distribution, in this example an increased asymmetry toward the hotter part of the distribution.

Source: Based on IPCC 2012: Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Report of Working Groups I and II of the Intergovernmental Panel on Climate Change, Table 3-1. Cambridge University Press. Reproduced with permission from IPCC.

Box 2.1 Key Messages from Climate Change Impacts in the United States: The Third National Climate Assessment (Melillo et al. 2014)

1. Global climate is changing and this change is apparent across a wide range of observations. The global warming of the past 50 years is primarily due to human activities.

2. Global climate is projected to continue to change over this century and beyond. The magnitude of climate change beyond the next few decades depends primarily on the amount of heat-trapping gases emitted globally, and how sensitive the Earth's climate is to those emissions.

3. U.S. average temperature has increased by 1.3°F to 1.9°F since record keeping began in 1895; most of this increase has occurred since about 1970. The most recent decade was the nation's warmest on record. Temperatures in the United States are expected to continue to rise. Because human-induced warming is superimposed on a naturally varying climate, the temperature rise has not been, and will not be, uniform or smooth across the country or over time.

4. The length of the frost-free season (and the corresponding growing season) has been increasing nationally since the 1980s, with the largest increases occurring in the western United States, affecting ecosystems and agriculture. Across the United States, the growing season is projected to continue to lengthen.

5. Average U.S. precipitation has increased since 1900, but some areas have had increases greater than the national average, and some areas have had decreases. More winter and spring precipitation is projected for the northern United States, and less for the Southwest, over this century.

6. Heavy downpours are increasing nationally, especially over the last three to five decades. Largest increases are in the Midwest and Northeast. Increases in the frequency and intensity of extreme precipitation events are projected for all U.S. regions.

7. There have been changes in some types of extreme weather events over the last several decades. Heat waves have become more frequent and intense, especially in the West. Cold waves have become less frequent and intense across the nation. There have been regional trends in floods and droughts. Droughts in the Southwest and heat waves everywhere are projected to become more intense, and cold waves less intense everywhere.

8. The intensity, frequency, and duration of North Atlantic hurricanes, as well as the frequency of the strongest (Category 4 and 5) hurricanes, have all increased since the early 1980s. The relative contributions of human and natural causes to these increases are still uncertain. Hurricane-associated storm intensity and rainfall rates are projected to increase as the climate continues to warm.

9. Winter storms have increased in frequency and intensity since the 1950s, and their tracks have shifted northward over the United States. Other trends in severe storms, including the intensity and frequency of tornadoes, hail, and damaging thunderstorm winds, are uncertain and are being studied intensively.

10. Global sea level has risen by about 8 inches since reliable record keeping began in 1880. It is projected to rise another 1 to 4 feet by 2100.

11. Rising temperatures are reducing ice volume and surface extent on land, lakes and sea. This loss of ice is expected to continue. The Arctic Ocean is expected to become essentially ice free in summer before mid-century.

12. The oceans are currently absorbing about a quarter of the carbon dioxide emitted to the atmosphere annually and are becoming more acidic as a result, leading to concerns about intensifying impacts on marine ecosystems.

While the weight of evidence of human-induced climate change on global and continental scales is considerable, teasing out the anthropogenic signal at temporal and spatial scales relevant to engineering practice is more difficult. Again, as concluded by the NCA, warming will not be uniform or smooth over time, due to human-induced warming superimposed over natural variations of climate. Short-term fluctuations in the long-term upward trend are thus natural and expected. Complications introduced by the intersection of natural variability and long-term, human-induced changes, such as changes in precipitation, are particularly relevant to engineering practice. The NCA (Melillo et al 2014) concluded, "While significant trends in average precipitation have been detected, the fraction of these trends attributable to human activity is difficult to quantify at regional scales because the range of natural variability in precipitation is large." Across global land regions, climate models driven by known climate forcings consistently underestimate the magnitude of precipitation changes observed over the previous century (Krakauer and Fekete, 2014). Thus, changes in the timing, location and in some cases, magnitude of severe weather events have been observed (see Fig 2.2), and predicting trends in these events will be complicated due to natural variability.

Despite this complication, practicing engineers, as well as planners, land managers and others, face a growing demand to understand and incorporate changes in weather and climate in project design and implementation. This need to anticipate future trends drives attempts to quantifiably simulate climatic processes through numerical modeling. Climate models combine scientific knowledge from a number of disciplines, including atmospheric sciences, oceanography, cryospheric sciences, hydrology, ecosystem modeling and others, to simulate past, present and future climates. They are the best tools available to make quantitative projections of global, continental scale climatic conditions under anthropogenic forcing. However, their value at the project-level scale is the subject of much discussion and debate.

2.2 Climate models

There are two major classes of climate models, Earth System Models (ESMs) and Global Climate Models (GCMs). ESMs include all the features of GCMs and also simulate the carbon cycle and other chemical and biological cycles that are important for determining the future concentrations of greenhouse gases in the atmosphere (see the discussion of *Future Emission Scenarios,* below). Because these models are much newer and their outputs have yet to be evaluated as thoroughly by climate and applications researchers, they are not typically used for climate impacts applications. Some of the ESMs that simulate a wider variety of long-range processes tend to be of lower resolution. In addition, the freedom for vegetation to evolve means that biases exists in land-surface properties for some regions.

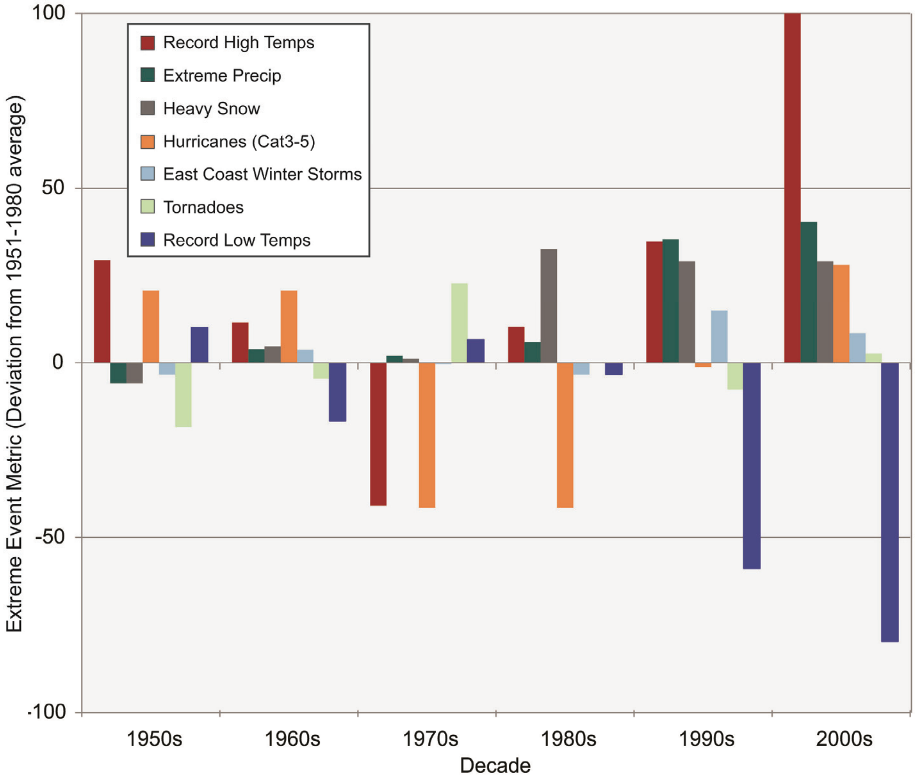


Figure 2.2 Extreme weather metrics for recent decades, including the number of record high monthly temperatures (red) (Karl et al. 2012); the number of daily precipitation events exceeding the threshold for a 1-in-20 year recurrence (dark green); the sum of the number of top 50 snowstorms for the U.S. regions east of the Rocky Mountains (gray) (expansion of analysis in Kunkel et al. 2013); the number of category 3, 4, or 5 hurricanes in the North Atlantic (orange) (http://weather.unisys.com/hurricane/atlantic/); the number of strong East Coast winter storms (light blue) (http://ecws.eas.cornell.edu/ECWS_graphs.html); the number of tornadoes of EF1 intensity or higher (light green) (http://www.spc.noaa.gov/wcm/annualtornadomaps/); and the number of record low monthly temperatures (dark blue). The decade of the 2000s is the 12-year period of 2001-2012. Extreme precipitation events were determined from 3,430 stations in the U.S. GHCN data set with less than 10% missing data for the period 1951-2011 following the methods of Kunkel et al. (2013).

Source: Wuebbles et al., (2014); reproduced with permission from American Geophysical Union.

GCMs are more commonly used to determine climate impacts and typically consist of four main components: atmosphere, ocean, land surface and sea ice (Climate Change Science Program, 2008). These models solve equations for thermodynamics and fluid mechanics for variables of interest. Variables that describe the atmospheric state include temperature, pressure, humidity, winds, and water and ice condensate in clouds. These variables are typically defined on a spatial grid. The spatial resolution for models of the Coupled Model Intercomparison Project Phase 5 (CMIP5) vary from 0.5° to 4° for the atmosphere component, and from 0.2° to 2° for the ocean component (one degree of latitude is approximately 69 miles or 111 kilometers) (Taylor et al. 2012). Processes that occur over areas too small or over time periods too short to resolve on the model grid are parameterized, represented by average or typical tendencies rather than the full underlying fluid mechanics. These processes include cloud formation, dissipation and convection, and turbulent processes near the earth's surface. Topographic features and their effects on local and regional weather and climate are not well represented in the coarser resolution scales associated with GCMs (Climate Change Science Program, 2008).

2.3 Future emissions scenarios

Assumptions about future greenhouse gas emissions are used as input to GCMs. The emissions are converted into atmospheric concentrations of greenhouse gases using Integrated Assessment Models (IAM) that have extremely simplified representations of atmospheric and oceanic fluid dynamics. The greenhouse gas concentrations are then input into the GCMs, which simulate the effect of those concentrations on climate. Future greenhouse gas emissions depend on future social and economic development, land use changes, population changes and technological innovation. However, these factors are difficult to predict and highly uncertain. The IPCC developed scenarios to represent a wide range of the main economic, demographic and technological driving forces that will determine future greenhouse gas emissions, but did not assign probabilities to these scenarios (Nakicenovic et al. 2000). Over the last few years, actual emissions have equaled or exceeded the most "extreme" emission scenarios used for previous IPCC reports (Peters et al. 2013).

The most current generation of climate scenarios does not start with socioeconomic scenarios, but are based on greenhouse gas concentration pathways (time-dependent values in the future) that span the possibilities generated by a number of IAMs. The names of the pathways are determined by their radiative forcing at the end of the 21st century—radiative forcing being the change in the balance between incoming and outgoing radiation caused by changes in greenhouse gas concentrations and other atmospheric constituents, while other aspects of the atmosphere are held constant. A Representative Concentration Pathway (RCP) is associated with each of the radiative forcing trajectories (Moss et al, 2010). In total, a set of four pathways were produced that would lead to radiative forcing levels of 8.5, 6.0, 4.5 and 2.6 watts/square meter by the end of the century. Each of the RCPs covers the 1850-2100 period, and extensions have been formulated for the period thereafter up to 2300 (van Vuuren et al. 2011).

2.4 Projections of future climate

A climate projection is usually based on the results of a single GCM with a specific configuration that is forced by a single scenario. Because the models are forced by the scenario and not by observations, even in the historical runs, the model is not expected to reproduce the exact climate that has occurred or will occur. Instead, it is expected to reproduce characteristics that are representative of the climate forced by the imposed radiative trajectory. Thus, a projection represents one *possible* future, but a future that is statistically representative of other futures under the same climate forcings. GCM output consists of values for dozens of variables describing conditions in the atmosphere and on the surface, but often a subset of these variables, most commonly precipitation and temperature, are used for assessment of future impacts on built and natural systems. GCMs have more skill in simulating temperature than precipitation, and simulate processes over large geographic areas and time scales better than processes over smaller geographic areas and time scales. They are also more skillful at predicting means of precipitation or temperature than variability (Randall et al. 2007; Barsugli et al. 2009; Flato et al. 2013).

The Coupled Model Intercomparison Project Phase 5 (CMIP5) models are executed at a higher spatial resolution and have a more complete representation of external forcing and of physical processes than CMIP3 models (which were considered in the IPCC Fourth Assessment Synthesis Report, 2007). CMIP5 models used RCPs while CMIP3 models used the Special Report on Emissions Scenarios (SRES) scenarios, so comparison of the output is not straightforward. However, model mean comparisons of temperature and precipitation change are similar in CMIP3 and CMIP5. Model agreement for precipitation changes did not improve appreciably between CMIP3 and CMIP 5, implying continuing uncertainty (Knutti and Sedlácek, 2013).

2.5 Uncertainty in climate projections

There are many sources of uncertainty in climate projections. Pielke Sr. (2004) argues that there are limits in scientists' ability to make projections of potential future climate change due to the "imperfect representation of the full complexity of the Earth system, nonlinear spatial and temporal feedbacks, and imperfect foresight of human behavior." The IPCC (2012) lists three main sources of uncertainty in the projections:

- natural variability of climate
- uncertainty in climate model response, or sensitivity, to anthropogenic and natural forcing
- projection of future emissions and other natural and anthropogenic climate drivers

The uncertainty in the response of the climate system to these drivers is manifest in the structure and parameter choices in climate models. Uncertainty in climate model parameters include the uncertainty in representing physical processes, such as the effects of cloud formation and land cover that largely occur at spatial scales smaller than the large spatial scale used in climate models. Some examples of complex and nonlinear feedbacks include biogeographical processes such as changes in the distribution and composition of vegetation, land-use changes caused by man, and deep ocean circulation effects on ocean temperature and salinity. Barsugli et al. (2009) state, "(1) Climate model simulations have generally improved since the early 1990s in their ability to simulate the observed mean climate and seasonal cycle; (2) Despite the increase in model performance over the last two decades, the range of climate projections across all models has not appreciably narrowed; (3) The actual uncertainty of global and regional climate change (as scientists understand it) is larger than the range simulated by the current generation of models."

2.6 Downscaling

Engineers are primarily concerned with planning and designing at the local and regional scale. GCMs have more skill at larger spatial and longer temporal scales. Downscaling techniques are used to obtain higher-resolution regional and local projections from large-scale GCM projections. Statistical downscaling estimates local climate changes, assuming a relationship to large-scale changes, and then adjusts regional projections by matching global, historical simulated and observed climate. Statistical downscaling requires nominal computation and thus permits ensembles of GCM outputs and different scenarios to be simulated over decades and sometimes centuries to capture uncertainty. Statistical downscaling methods typically adjust for the biases in climate models during the historic period, either in an explicit bias-correction step or implicitly, as in regression-based methods. The assumption is made that the statistical relationships developed on past data will also hold into the future.

Dynamical downscaling uses regional climate models (RCM) that are physically based models similar to GCMs but at regional or local scales. These models often include topographic, land use, and vegetation features, increasing complexity and therefore, computational intensity. While dynamic downscaling yields local and regional resolution and may better represent important climatic processes such as convection, land-sea breezes in coastal areas and lake-effect snows, it will not necessarily correct for large-scale errors in the GCM simulations that supply boundary conditions for the RCM runs under future scenarios. The exception is that certain locally determined processes, such as convection, might be improved even in the face of biases in the RCM boundary conditions (Liang et al., 2006. For this reason, a statistical component is generally required for additional bias correction before use (Brown et al. 2008).

Regional climate models used in dynamical downscaling are only approximations of what one would expect to obtain with a hypothetical, high-resolution GCM, because RCMs do not allow the fine-scale simulation to influence the large-scale, and because different parameterizations are used in the RCMs. Therefore, the RCM simulation may not be strictly consistent with the GCM that was used to provide the boundary conditions for the RCM. The extent to which this is a problem for the accuracy of dynamical downscaling can only be revealed by evaluation of the RCM output (Barsugli et al. 2009).

2.7 Probabilities of future climate states

Engineers would like to estimate the likelihood of future conditions for planning and design purposes (see Section 3). Attempts have been made to estimate probabilities from GCMs. An ensemble of climate projections from different GCMs provides a distribution of model outputs spanning a range of emissions scenarios and model structures. Research has attempted to develop probabilistic estimates of impacts based on such ensembles of model outputs (Vinson and Bae, 2002, 2005; Tebaldi and Knutti, 2007; Brekke, et al. 2008). Pierce et al. (2012) developed probabilistic projections for California using 16 GCMs, two statistical downscaling techniques and three nested, dynamical regional climate models. The assumption behind these studies is that the models are random samples from a distribution that has the true climate as its mean (Jun et al. 2008). However, climate models are not independent. The number of effective models in an ensemble of GCMs is much smaller than the size of the ensemble, implying the ensemble underestimates the real extent of climate prediction uncertainty (Pennell and Reichler, 2011). Models have similar resolution and cannot adequately resolve the same small-scale processes and use similar assumptions and parameterizations (Jun et al. 2008). Uncertainties related to the underlying science may lead to similar biases across different models. Climate models represent an unknown fraction of potential future climate conditions (Stainforth, 2010). Another difficulty is that GCM simulations tend to systematically underestimate the variance and serial persistence in observed climate, which implies that GCMs may not be effective at modeling the extremes of natural climate variability (Brown and Wilby, 2012). Still, an ensemble of projections could be interpreted as a minimum bound on future climate uncertainty (Stainforth et al. 2007).

Another method for probability-based climate projections is the use of a large perturbed physics ensemble (PPE), which is created from a single GCM running different values for uncertain model parameters. The United Kingdom Climate Projections, released in 2009 (UKCP09), used this method to produce probabilistic projections of various climate variables at 25-kilometer resolution (Murphy et al. 2009). Each of the model runs was weighted based on its credibility. The probabilistic projections also included 12 other GCMs to account for different structural modeling uncertainties. The ensemble of projections was converted to probabilistic projections using a Bayesian statistical framework. The UKCIP09 did not assign probabilities to emission scenarios, so the probabilistic projections were produced for each of three emission scenarios.

Certain assumptions had to be made on which uncertainties were sampled. One caveat for using the model for engineering design and planning is that the uncertainty in the probability distribution increases at the tail of the distribution. According to Murphy et al. (2009), users should be able to use the distribution from the 10% to 90% probability levels, but not outside this range. The tails of the distribution are often of most concern for engineers. Probabilistic information from GCMs cannot be validated in the same way as probabilistic weather forecasts; the credibility of the resultant distributions relies on a belief that the theoretical approach is valid for the application. Smith and Stern (2014) discuss the range and types of uncertainty in our understanding of climate change, stating that “an insistence on extracting probabilities relevant in the world from the diversity of model simulations exemplifies misplaced concreteness.” They advocate a risk management approach that recognizes the lack of confidence in probabilities.

2.8 Extreme events

There are many sources of uncertainty associated with GCM predictions, including assumptions about future emissions of greenhouse gases. Assumptions about future greenhouse gas emissions are used as input to Global Circulation Models (GCMs), which convert the emissions into atmospheric concentrations of greenhouse gases and then simulate the effect of those concentrations on climate. High-frequency (6-hourly) data from the Geophysical Fluid Dynamics Laboratory (GFDL) CM2.1 model is available for two of the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) experiments: 20C3M (1968-2000) and SRESA2 (2038-2070) (http://www.gfdl.noaa.gov/narccap-cm2-data). Nevertheless, there is quite a gap from global climate projections to obtaining local high-intensity rainfall projections to be used for flood generation and routing; downscaling techniques are used to obtain higher-resolution regional and local projections from large-scale GCM projections. Merging historical data and GCM results to create climate change Intensity Duration Frequency (IDF) curves has been practiced by a few engineering practitioners. Other approaches to calculating both heavy rainfall and floods suggest using a factor by which rainfall is adjusted for each 1 degree Celsius of temperature change (Ministry for the Environment, Tools for Estimating the Effects of Climate Change on Flood Flow, New Zealand, 2010).

As discussed in Section 4.4, increases in the frequency and magnitude of extreme rainfall events have been documented in New York State (Tryhorn, 2010); these are among the largest such changes reported within the United States. Increasing magnitudes and frequencies of extreme precipitation events have also been reported in the Midwest for sites with long historical records (Todd et al. 2006). Others find that increases in global temperature and CO_2 levels do not necessarily result in proportional increases in runoff and streamflow (Hirsch and Ryberg, 2012). It is important to point out that land-use changes (e.g., urbanization) can result in substantial flooding impacts, independent of climatic forcing functions. However, to fully understand urbanization within the context of climate change, a better integrated understanding of the dynamics and interactions between urbanization and the climate system will be required (Romero Lankao, P., 2008).

2.9 Review of extreme climate and weather

Engineering design is primarily concerned with the extremes. The IPCC (2007a) defines an extreme weather event as “an event that is rare at a particular place and time of year.” Extreme weather varies from region to region. An extreme climate event would be a pattern of extreme weather, such as drought or heavy rainfall, that persists for some time, such as a season (IPCC, 2007a). Climate scientists and civil engineers may not agree on how uncommon an event should be in order to be designated as extreme. The IPCC states, “an extreme weather event would normally be as rare as or rarer than the 10th or 90th percentile of the observed probability density function” (IPCC, 2007a). However, in civil engineering terms, “rare” is often defined in terms of the acceptable frequency of failure. Large dams may be designed for events with a mean recurrence interval of about 10,000 years. Flood risk management is concerned with events with mean recurrence intervals of 100 to 500 years. Transportation and stormwater design is concerned with events that occur more frequently, coming closer to the IPCC definition (Bonnin et al. 2011).

The IPCC recently released a Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX). The challenge of coping with extreme weather and climate events is framed as a problem in decision making under uncertainty (IPCC, 2012).

Table 2.1 presents a summary of observed and projected changes to physical impacts that could affect infrastructure at a global scale. The SREX makes a clear distinction between confidence and likelihood. The confidence and likelihood levels are based on subjective expert judgment. The following explains the text in Table 2.1:

- “Confidence in observed changes in extremes depends on the quality and quantity of data and the availability of studies analyzing these data, which vary across regions and for different extremes. Assigning ‘low confidence’ in observed changes in a specific extreme on regional or global scales neither implies nor excludes the possibility of changes in this extreme.”
- For each given assessment, the confidence level is first designated as low, medium, or high.
- “For assessments with high confidence, likelihood assessments of a direction of change are also provided (virtually certain for 99-100%, very likely for 90-100%, likely for 66-100%, more likely than not for 50-100%, about as likely as not for 33-66%, unlikely for 0-33%, very unlikely for 0-10%, and exceptionally unlikely for 0-1%). In a few cases for

which there is high confidence (e.g., based on physical understanding) but for which there are not sufficient model projections to provide a more detailed likelihood assessment (such as ‘likely’), only the confidence assessment is provided.

- For assessments with medium confidence, a direction of change is provided, but without specifying the likelihood.
- For assessments with low confidence, no direction of change is generally provided.”

A central challenge is to understand how weather events relevant to civil engineering practice may change in terms of frequency, duration and intensity of climate change. While various approaches to converting output from GCMs to scales of relevance to civil engineering practice have been explored, converting such information to insights regarding changes in meteorological phenomena at the project scale has not been successfully demonstrated. In 2012, the National Research Council report, *A National Strategy for Advancing Climate Modeling,* recommended that the United States "Nurture a unified weather-climate modeling effort that better exploits the synergies between weather forecasting, data assimilation, and climate modeling (Recommendation 11.1)." Such an effort, if appropriately structured, could provide valuable information to civil engineering practitioners.

Table 2.1: Summary of observed and projected changes that may affect engineering at a global scale.

	Observed Changes	*Projected Changes*
	Weather and Climate Variables	
Temperature	*Very likely* decrease in number of unusually cold days and nights at the global scale. *Very likely* increase in number of unusually warm days and nights at the global scale. *Medium confidence* in increase in length or number of warm spells or heat waves in many (but not all) regions. *Low or medium confidence* in trends in temperature extremes in some subregions due either to lack of observations or varying signal within subregions.	*Virtually certain* decrease in frequency and magnitude of unusually cold days and nights at the global scale. *Virtually certain* increase in frequency and magnitude of unusually warm days and nights at the global scale. *Very likely* increase in length, frequency, and/or intensity of warm spells or heat waves over most land areas.
Precipitation	*Likely* statistically significant increases in the number of heavy precipitation events (e.g., 95th percentile) in more regions than those with statistically significant decreases, but strong regional and subregional variations in the trends.	*Likely* increase in frequency of heavy precipitation events or increase in proportion of total rainfall from heavy falls over many areas of the globe, in particular in the high latitudes and tropical regions, and in winter in the northern mid-latitudes.
Winds	*Low confidence* in trends due to insufficient evidence.	*Low confidence* in projections of extreme winds (with the exception of wind extremes associated with tropical cyclones).
	Phenomena Related to Weather and Climate Extremes	
Monsoons	*Low confidence* in trends because of insufficient evidence.	*Low confidence* due to insufficient evidence.
El Niño and other Modes of Variability	*Medium confidence* in past trends toward more frequent central equatorial Pacific El Niño-Southern Oscillation (ENSO) events. Insufficient evidence for more specific statements on ENSO trends. *Likely* trends in Southern Annular Mode (SAM).	*Likely* anthropogenic influence on identified trends in SAM. Anthropogenic influence on trends in North Atlantic Oscillation (NAO) are about as likely as not. No attribution of changes in ENSO.
Tropical Cyclones	*Low confidence* that any observed long-term (i.e., 40 years or more) increases in tropical cyclone activity are robust, after accounting for past changes in observing capabilities.	*Likely* decrease or no change in frequency of tropical cyclones. *Likely* increase in mean maximum wind speed, but possibly not in all basins. *Likely* increase in heavy rainfall associated with tropical cyclones.

	Observed Changes	*Projected Changes*
Extratropical Cyclones	*Likely* poleward shift in extratropical cyclones. *Low confidence* in regional changes in intensity.	Likely impacts on regional cyclone activity but low confidence in detailed regional projections due to only partial representation of relevant processes in current models. Medium confidence in a reduction in the numbers of mid-latitude storms.
	Impacts on Physical Environment	
Droughts	*Medium confidence* that some regions of the world have experienced more intense and longer droughts, in particular in southern Europe and West Africa, but opposite trends also exist. [	*Medium confidence* in projected increase in duration and intensity of droughts in some regions of the world, including southern Europe and the Mediterranean region, central Europe, central North America, Central America and Mexico, northeast Brazil, and southern Africa. Overall *low confidence* elsewhere because of insufficient agreement of projections.
Floods	*Limited to medium evidence* available to assess climate-driven observed changes in the magnitude and frequency of floods at regional scale. Furthermore, there is *low agreement* in this evidence, and thus overall low confidence at the global scale regarding even the sign of these changes. *High confidence* in trend toward earlier occurrence of spring peak river flows in snowmelt- and glacier-fed rivers.	*Low confidence* in global projections of changes in flood magnitude and frequency because of insufficient evidence. *Medium confidence* (based on physical reasoning) that projected increases in heavy precipitation would contribute to rain-generated local flooding in some catchments or regions. *Very likely* earlier spring peak flows in snowmelt- and glacier-fed rivers.
Extreme Sea Level and Coastal Impacts	*Likely increase* in extreme coastal high water worldwide related to increases in mean sea level in the late 20th century.	*Very likely* that mean sea level rise will contribute to upward trends in extreme coastal high water levels. *High confidence* that locations currently experiencing coastal erosion and inundation will continue to do so due to increasing sea level, in the absence of changes in other contributing factors.
Other Impacts (Landslides and Cold Regions)	*Low confidence* in global trends in large landslides in some regions. *Likely* increased thawing of permafrost with likely resultant physical impacts.	*High confidence* that changes in heavy precipitation will affect landslides in some regions. *High confidence* that changes in heat waves, glacial retreat, and/or permafrost degradation will affect high mountain phenomena such as slope instabilities, mass movements, and glacial lake outburst floods.

Source: Modified from Table 3-1, IPCC 2012: Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Report of Working Groups I and II of the Intergovernmental Panel on Climate Change. (http://www.ipcc-wg2.gov/SREX/). Reproduced with permission from the IPCC.

3 Incorporating Climate Science into Engineering Practice

This section provides a review of engineering practices and discusses how engineers can consider climate change in their practice, given the uncertainty of the future.

3.1 Climate change dilemma for engineering

Engineers build long-lived infrastructure. The right-of-ways and footprints of the infrastructure have even longer-lasting influences. These facts suggest that the planning and design of new infrastructure should account for the climate of the future. Considering the impacts of climate change in engineering practice is analogous to including forecasts of long-term demands for infrastructure use as a factor in design. However, even though the scientific community agrees that climate is changing, there is significant uncertainty about the spatial and temporal distributions of the changes over the lifetime of infrastructure designs and plans. The requirement that engineering infrastructure meets future needs, and the uncertainty of future climate, leads to a dilemma for practicing engineers.

Infrastructure designs and plans, as well as institutions, regulations and standards to which they must adhere, will need to be adapted and even be adaptable to accommodate a range of future climate conditions. Secondary effects from a changing climate—such as changes in land cover and use, resource availability and demographics in population—will be similarly uncertain and will require flexibility in infrastructure location and design. The standards, codes, regulations, zoning laws, etc., that govern infrastructure are often finely negotiated or delicately balanced, which often makes them slower to adapt. In addition, different stakeholders may exploit the uncertainties associated with climate change to argue for a position they prefer. Incorporating climate change into engineering practice will require engineering judgment to balance costs and potential consequences of failure.

3.2 Uncertainty and statistical methods for risk assessment

Engineering practice recognizes and accounts for uncertainties in future conditions. Uncertainty can be broadly defined as deficiency in information and knowledge. Engineers have developed specific methods to account for uncertainty. These methods include designing for a flood or wind velocity of a particular magnitude, including safety factors or freeboards, and employing probabilistic and statistical methods. Engineers use statistical methods to quantify uncertainty for empirical probability distributions used in engineering design. Sampling error is relatively easy to quantify with statistical methods such as confidence intervals.

However, there are other sources of uncertainty that are much more difficult to quantify, such as model uncertainty. The statistical model may not be representative of future hydrologic events.

The assumption of stationarity implies that the statistical properties of hydrologic variables in future time periods will be similar to past time periods. Recent papers have noted that potential climate change undermines this assumption (Milly et al. 2008). Even without climate change, climate varies naturally on decadal and longer time scales, and the observed record is a relatively short time period compared to the potential range of climate variability. There are also multiple other sources of change and uncertainty: changes in demand for infrastructure and services, changes in land use, urbanization, population increase, and economic development in vulnerable areas such as floodplains, deserts, shorelines and earthquake zones. Population and development may stress natural resources, such as increased groundwater depletion, surface-water withdrawals and deforestation. In addition, society and engineers are increasingly concerned about the natural environment. Changes in ecosystems and species composition are particularly uncertain.

The Observational Method. Civil Engineers have dealt with uncertainty in geotechnical engineering practice with the observational method (OM), originally proposed by Karl Terzaghi, described in a widely-used book by Terzaghi and Peck (1948), and discussed in a paper by Ralph B. Peck (1969). A succinct definition of the OM is provided in UK CIRIA guide 185 (1999): "The Observational Method [in ground engineering] is a continuous, managed, integrated, process of design, construction control, monitoring and review that enables previously defined modifications to be incorporated during or after construction as appropriate. All these aspects have to be demonstrably robust. The objective is to achieve greater overall economy without compromising safety."

It may be possible to employ a modified version of the OM to accommodate the inherent uncertainty in future climate. Using the OM in geotechnical engineering, initial construction costs are reduced by designing infrastructure based on the most probable conditions rather than the most unfavorable conditions. Uncertainty in the available information is augmented during the life of the infrastructure by observations of the performance of the infrastructure. The specific steps in a climate change OM are as follows (modified after Terzaghi):

- Project design is based on the most probable climate condition(s) rather than the most unfavorable. The most unfavorable conceivable deviations from the most probable conditions are identified. Defining the "most probable climate conditions" is problematic with climate change. As discussed in Section 2, climate model projections cannot determine accurate probability distributions for future climate. In this step, engineers must use engineering judgment to determine reasonable conditions for design. In addition, there may be reasonable disagreement among stakeholders on what those conditions should be.
- A course of action or design modification is devised (in advance) for every foreseeable unfavorable climate deviation from the most probable condition(s). The most serious

error in applying the OM is failing to select an appropriate course of action for all foreseeable deviations of initial design assumptions disclosed by observation. The OM should not be used unless the engineer has preselected a course of action for every unfavorable situation that might be disclosed by the observations.

- The performance of the project is observed over time (using preselected quantities) and the response of the project to observed changes is assessed. The observations must be reliable, must reveal the significant phenomena, and must be so reported as to encourage prompt action. In practice, an OM applied to climate change requires a continuous (and funded) monitoring program that observes relevant metrics.
- Design and construction modifications (previously identified) can be implemented in response to observed changes. For the OM to be effective with a changing climate, infrastructure owners must have funds, authority, and a willingness to make design modifications if conditions have changed and a new course of action is required.

The engineer must devise in advance solutions to all problems that could arise under the least favorable conditions. Under the original philosophy of the OM, if the engineer cannot solve these hypothetical problems (even if the probability of their occurrence is very low), then it becomes necessary to base the design on the least favorable conditions. An advantage of the OM is that it often permits a more economic design while assuring safety, provided that changing conditions can be observed and the design can be modified over time.

The OM has been extensively studied and discussed in the European engineering community (Eurocode 7, 2004; Nicholson et al. 1999, 2006; UK CIRIA guide 185, 1999). Patel et al. (2007) provided a comprehensive review of the OM as applied in the European engineering community and summarized how the OM should be applied across Europe within the design and contractual framework of an engineering project. They state, “The OM is most effective where there is a wide range of uncertainty.” Korff et al. (2013) suggest that projects particularly amenable to OM entail low risks, but unacceptable a priori probabilities of exceedance with significant consequences or projects with multiple stages or incremental construction processes. The OM is appropriate for gradual changes such as sea level rise or melting permafrost due to warming temperatures. The OM may be less appropriate if there are safety concerns about the impacts of sudden extreme climate events that can occur and inflict damages before changing conditions are observed.

Risk-based planning and design. Risk analysis and management is the primary approach engineers currently take to deal with future uncertainty (Ayyub, 2014). The OM is a risk management tool that has been employed in geotechnical engineering practice for over 50 years. Figure 3.1 shows a generic risk management framework proposed by the International Standards Organization (2009b). The ISO (2009a) defines risk as a measure of the likelihood and consequence of uncertain future events. Risk is commonly measured as the probability of occurrence of an event and the outcomes or consequences associated with occurrence of an event (Ayyub, 2014). According to Kaplan and Garrick (1981), risk assessment is primarily concerned with three questions:

(1) What can happen? (i.e., what can go wrong?)
(2) How likely is it to happen?
(3) If it does happen, what are the consequences?

Risk assessment systematically identifies potential uncertain events or hazards, determines the consequences if the event occurs, and estimates its likelihood of occurrence.

Climate impact assessment methods. One of the first steps in a risk assessment is to identify risks. There have been numerous studies of the potential impact of climate change and the vulnerability of human and natural systems. Impact and vulnerability are often used interchangeably, but the IPCC defines impact and vulnerability assessments differently. Impact assessments evaluate the potential effects of climate change on natural and human systems. Vulnerability assessments evaluate the degree to which a system is susceptible to, and unable to cope with, adverse effects of climate variability and change. Vulnerability is a function of the character, magnitude and rate of climate change and variation to which a system is exposed, its sensitivity, and its adaptive capacity (IPCC, 2007b). Engineers are tasked with developing systems that are less susceptible to adverse climate impacts.

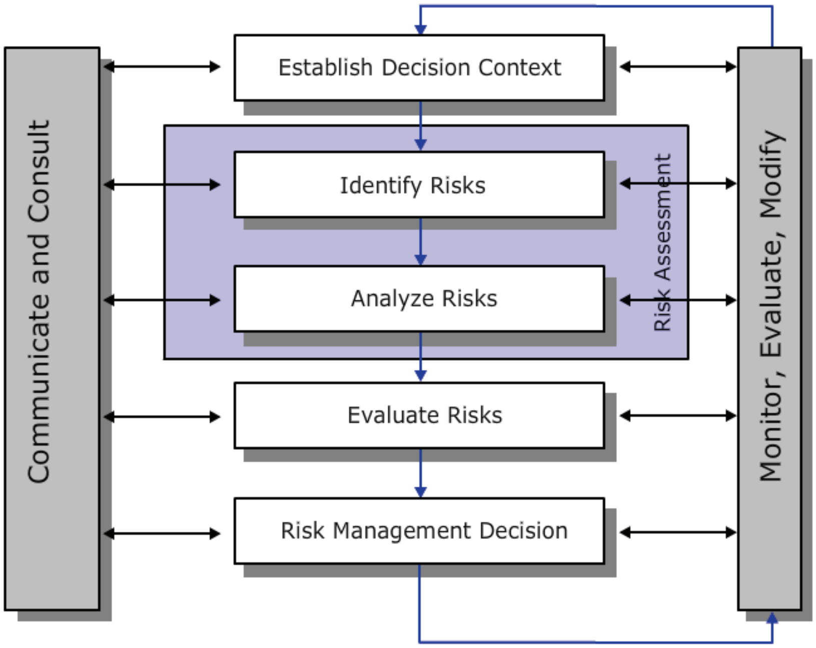


Figure 3.1: Risk management framework.

Source: This figure is adapted from Figure 1 of ISO 31000:2009 and cannot be considered an ISO figure. Permission granted by ANSI on behalf of ISO. (c) ISO 2014. All rights reserved.

Vulnerability assessments can be "top-down," where GCM projections are downscaled to a local or regional scale and the results are used to determine the effects on the system. Alternatively, a "bottom-up" vulnerability assessment determines thresholds where a system fails and then the plausibility of that threshold being exceeded is assessed based on available evidence (Dessai and Hulme, 2004). The bottom-up approach is more akin to traditional engineering failure analysis in that modes of failure and the consequences are first assessed. The top-down approach considers a limited number of scenarios from climate projections. (See Figure 3.2)

In addition to assessing what can happen and the potential consequences, risk assessment also includes an estimate of the likelihood of these events happening. With climate change uncertainty, it is problematic to estimate the probabilities of future climate events, particularly extreme events. Probabilities based on a statistical analysis of observed past events may no longer be representative of future likelihood. As noted in Section 2, climate models show a subset of the range of possible future climates (Stainforth, 2010). Subjective probabilities based on expert judgment are another potential method. The IPCC uses expert judgment to provide confidence assessments in observed and projected changes. For example, there is high confidence that temperature and sea level will rise, although the magnitude and rate of these changes is uncertain. On the other hand, in the case of some regional precipitation projections, there may be uncertainty in both the magnitude and the direction of change. The IPCC also gives a subjective assessment of the likelihood of the direction of future changes if there is high confidence in the information.

3.3 Risk management

Risk management uses the risk assessment information to make informed decisions to either accept the risk or reduce it. Risk management must consider the potential consequences and likelihood of future events, including the confidence in the information. It must then balance future risks and the costs of risk reduction measures. There will generally be a tradeoff between designing to reduce risks for a larger range of uncertain events and minimizing project costs.

Planning and evaluation techniques. Benefit-cost analysis (BCA) is often used to evaluate the tradeoffs between alternative plans and designs. However, BCA requires a probability distribution of future conditions in order to calculate the expected future benefits and costs of a project. The estimate of the probability distribution may be more uncertain with a changing climate, so planners and designers must recognize the uncertainty in the benefit-cost analysis. Other decision criteria should be considered, such as selecting alternatives that provide flexibility to make future changes that accommodate a range of possible future conditions.

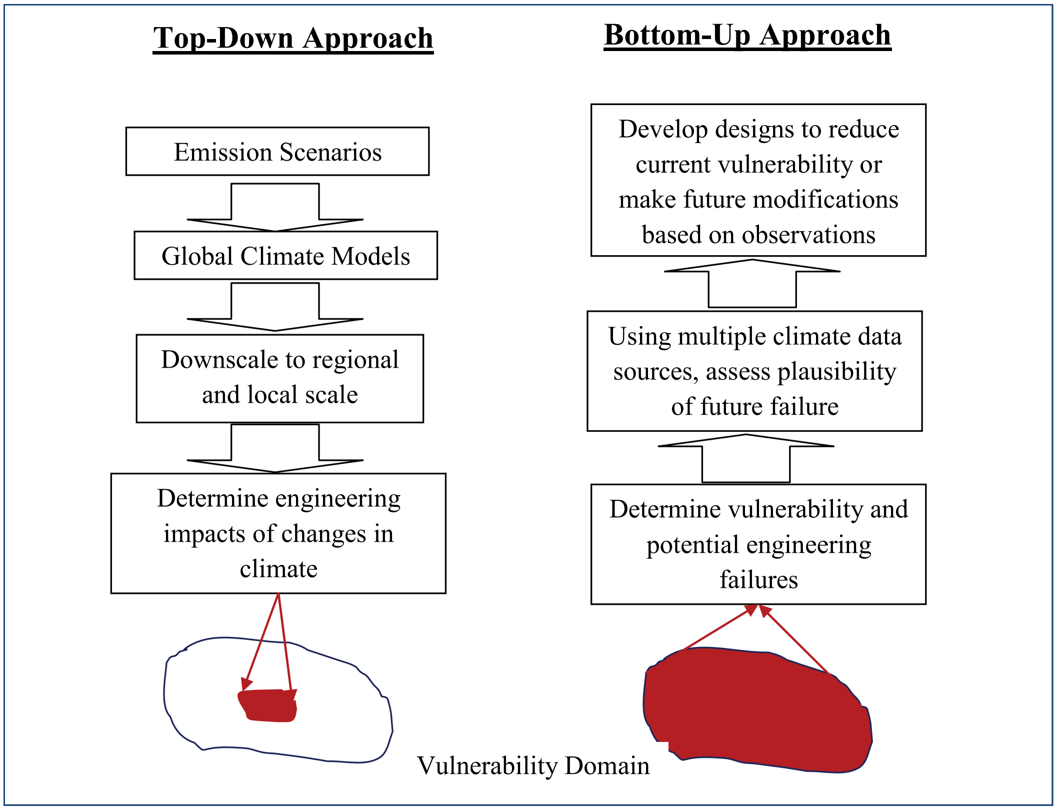


Figure 3.2: A comparison of top-down and bottom-up approaches to climate change adaptation.

An approach that considers incremental cost of additional actions may be helpful in making cost-effective decisions. If a system or project can be designed or planned in incremental features, the incremental costs and incremental benefits of each feature can be determined. When evaluating scenarios or conducting sensitivity analysis, planners can evaluate the additional cost of meeting risk-reduction objectives for incrementally more severe conditions. Incremental features can be added to reduce failure risks as long as the incremental benefits are perceived to exceed the incremental costs. Planners can evaluate whether it is cost effective to include additional measures that perform well under a broader range of future conditions.

Low-regret strategies and robust design. The uncertainty associated with future climate is not completely quantifiable and therefore, if it is to be used in engineering practice, will require engineering judgment. Decision methods that account for this uncertainty may be employed, such as robust decision making (Groves and Lempert, 2007; Groves et al, 2008; Lempert et al. 2003). This approach to decision making identifies robust alternatives that do well across a range of possible future conditions. The case study on Lake Superior regulation, described in Appendix A, used robustness as a decision criterion in choosing regulation rules.

Here, the mathematical objective could be to minimize the maximum regret, where regret is the difference between a plan payoff in a given scenario and the payoff of the best performing plan under that same scenario. In common usage, low-regret strategies are policies that would work well under both the current climate and an uncertain future climate. “No regret” is a term that is commonly used; however, most alternatives usually have a cost that is borne by someone who may “regret” the policy.

Flexible, adaptive engineering. Engineers will not be able to predict every potential condition for future infrastructure and systems. In addition to anticipating a range of possible future conditions, designs should be flexible. Flexible design includes the ability to change size and/or functions in the future. Flexible designs would also include redundant systems to protect against failures (de Neufville and Scholtes, 2011).

Using a risk management framework should ensure that a system can be updated over time as conditions change. Such a framework would include a monitoring program to evaluate system performance over time and flexibility to make needed changes. A climate-change risk management program can be incorporated into an organization’s asset management program. An asset management system is a “strategic and systematic process of operating, maintaining, upgrading, and expanding physical asset effectively throughout their life cycle” (FHWA, 2012). Asset management programs usually collect performance data over the life cycle of a system that can be used to evaluate the system’s performance under new and changing conditions. However, life-cycle cost incentives between owners, funders, designers and users are sometimes misaligned, making an asset management approach challenging for various private and institutional infrastructure investments. Creatively aligning incentives, including the sharing of risks and rewards of new and robust design approaches, is one method to maximize life-cycle cost effectiveness (Samaras et al. 2013).

The concept, “loose fit” expressed by Alex Gordon, president of the Royal Institute of British Architects, in the 1970s, presents a useful design guide consistent with the Observational Method. Loose fit means making infrastructures adaptable to conditions that could not be foreseen during the original design—a quality already widely exemplified by older systems and components in useful service today. (Gordon, 1972).

Risk Communication. Risk communication is an iterative process to exchange information and opinions among practicing engineers, project stakeholders and decision makers (Ayyub, 2014). Stakeholders include individuals and institutions that are affected by the results of the planning and design process or those who have a role in implementing the plans or designs. Risk communication is necessary for effective decision making and the communication process should address whether or not a risk is acceptable. An acceptable risk is a risk whose likelihood of occurrence is small or whose consequences are considered minimal. Risk communication should include discussion of the uncertainty of future climate and inform decision makers and stakeholders that the likelihood and potential consequences of future events cannot be precisely predicted. The decision to accept a level of risk will require a balancing of risks, costs, benefits and other social values to determine an acceptable threshold.

3.4 Engineering standards and regulations

Engineering design standards. Civil engineers use standards-based designs for hydraulic and structural systems, such as designing for a flood of a certain return period. Engineering standards will need to be revised to account for the uncertainty of a changing climate. Engineering standards are generally developed in consensus procedures that involve producers, users and regulators. How can climate information be effectively used to revise design standards? There will be a tradeoff between designing for a larger range of uncertain events and minimizing project costs. The development of engineering standards can follow a risk management approach and balance the potential consequences of failure with the cost of risk reduction measures.

Development of engineering standards and regulations. The decisions that determine the planning, design, construction, operation, maintenance, renovation and removal of infrastructure are guided and governed through regulation by the standards and practices of the civil engineering community. The infrastructure communities extend beyond the engineers and other professionals concerned with infrastructure to include owners, financial interests, product manufacturers, public officials, regulators and other stakeholders. All of these stakeholders have a voice in the development and implementation of standards and practices, as many will be concerned with safety, health, and economic and social consequences. Climate and weather experts should participate with the engineering community to develop useful engineering standards and regulations. Here are some suggestions to foster such participation among all concerned:

- The process for development of standards and model codes requires openness to participation of all stakeholders, balloting of proposed provisions and explicit response to all negative votes.
- The adoption of standards and/or model codes in regulations is a public policy process in which all stakeholders can present their concerns for safety, health, economic and social costs and benefits.
- Climate and weather scientists, engineers and other professionals need to demonstrate scientifically and technically sound, risk-based rationales for proposed standards, model codes and regulations.
- Engineers and social scientists must define the economic and social costs and benefits for proposed standards, model codes and regulations.

The development of recognized consensus standards is a crucial step in gaining credibility for criteria for design extreme events. The private sector role in the development of standards is described at www.standards.gov. Federal policy recognizes this path. Circular A-119 of the United States Office of Management and Budget www.standards.gov/standards-gov/a119.cfm#1 directs agencies to use voluntary consensus standards in lieu of government-unique standards, except where inconsistent with law or otherwise impractical. Thus, vision, reason and policy support the critically needed engagement of the federal research and programmatic agencies with the infrastructure communities for adaptation to climate change.

Regulatory criteria. Building codes, hazard zones and exclusion zones include regulatory criteria for public and private infrastructure. An example of regulatory criteria is the Special Flood Hazard Area that is determined by the flood that has a 1% chance of exceedance in any year. This flood's magnitude will likely change with a changing climate. However, existing laws and authorities may make it difficult or impossible to set a different standard that accounts for future climate change. In general, there will be a tradeoff between costs and more stringent regulatory criteria to account for future climate uncertainty, and the costs will generally be borne by the public.

3.5 Guiding principles for adaptation

The U.S. Federal Interagency Climate Change Adaptation Task Force (FICCATF) published the following guiding principles for adaptation (FICCATF 2011):

- Adopt integrated approaches: adaptation should be incorporated into core policies, planning, practices and programs whenever possible.
- Prioritize the most vulnerable: adaptation plans should prioritize helping people, places and infrastructure that are most vulnerable to climate impacts and be designed and implemented with meaningful involvement from all parts of society.
- Use best-available science: adaptation should be grounded in the best-available scientific understanding of climate change risks, impacts and vulnerabilities.
- Build strong partnerships: adaptation requires coordination across multiple sectors and scales and should build on the existing efforts and knowledge of a wide range of public and private stakeholders.
- Apply risk management methods and tools: adaptation planning should incorporate risk management methods and tools to help identify, assess and prioritize options to reduce vulnerability to potential environmental, social and economic implications of climate change.
- Apply ecosystem-based approaches: adaptation should, where relevant, take into account strategies to increase ecosystem resilience and protect critical ecosystem services, thereby minimizing vulnerability of human and natural systems to climate change.

- Maximize mutual benefits: adaptation should, where possible, use strategies that complement or directly support other related climate or environmental initiatives, such as efforts to improve disaster preparedness, promote sustainable resource management and reduce greenhouse gas emissions, including the development of cost-effective technologies.
- Continuously evaluate performance: adaptation plans should include measureable goals and performance metrics to continuously assess whether adaptive actions are achieving desired outcomes.

4 Civil Engineering Sectors

This section reviews the challenges for engineering practice posed by climate variability for the following traditional infrastructure sectors and special themes:

- **buildings and other structures** (buildings of all types and structural aspects of other infrastructure)
- **transportation** (highways, culverts, bridges, rail, airports, ports, navigation, pipelines)
- **water resources** (dams, levees, irrigation, reservoir management, flood risk management, drought management)
- **urban water systems** (stormwater, water supply and wastewater systems)
- **coastal management** (erosion, seawalls, groins, dredging)
- **energy supply** (power generation: hydropower, wind engineering, thermal plant cooling, fuel supply)
- **cold regions** (freeze-thaw cycling, changes to permafrost environments, snow accumulation and distribution)

4.1 Buildings and other structures

Scope of the sector and its major engineering practices. The term *structure* in engineering and architecture means a body or assemblage of bodies in space to form a system capable of supporting loads. Examples include buildings, aircrafts, ships, bridges, etc. Constructed structures are divided into buildings and non-buildings (i.e., other structures) erected or constructed for particular functions and make up the infrastructure of a human society. Built structures are composed of structural elements such as columns, beams and trusses. The particular case of buildings as a subset of structures can have a permanent or temporary nature, are usually enclosed by walls and a roof, and are constructed to provide support or shelter for an intended occupancy. Buildings and other structures include all attached apparatus, equipment and fixtures.

ASCE/SEI Standard 7-10 (2010) provides minimum design loads for buildings and other structures for general structural design and includes means for determining dead, live, soil, flood, snow, rain, atmospheric ice, earthquake and wind loads, as well as their combinations, that are suitable for inclusion in building codes and other documents.

Performance requirements within this scope include serviceability, safety, durability, constructability and sustainability (economic, environmental and social aspects) over the whole lifecycles of buildings and other structures. For each performance requirement, engineers need to consider changes in demands due to climate change (e.g., increased storm frequencies and intensities, environmental loads and fire hazards, etc.) and changes in strength or capacity (e.g., increased corrosion rates). The scope exceeds that of structural engineering to include environmental conditioning systems and fire safety systems; these are within the scope of ASCE's Architectural Engineering Institute and are important considerations for building codes and building regulations.

A life-cycle approach offers a rational basis for examining climate change adaptation for structures. A typical life cycle includes:

- planning (Is this the right structure in the right place? Can it be situated well above projected flooding levels?)
- conceptual design (an important opportunity to control hazards – for example, a buried power line is free from wind and ice loadings but might be exposed to flooding)
- design (applying a low-regret approach or an observational approach while complying with applicable codes and standards)
- construction (e.g., nighttime placement of concrete in case of heat waves and monitoring moisture content)
- commissioning
- operation
- maintenance
- renovation or removal and disposal

The development of an adaptation plan for structural engineering practices should include the reconsideration of the following key aspects:

- natural hazards (fire, flooding, drought, waves, rain, snow, ice, wind, etc.)
- loads and load combinations (service load demands, such as building occupancy, and human-caused hazards, such as terrorist attacks, may be affected by climate change, but attention here is focused on natural hazards)
- strength and degradation models (corrosion, fatigue, air quality degradation due to drought, etc.)
- installation, construction, renovation and removal practices

Examining structural engineering practices for climate adaption purposes should include reviewing and evaluating the following relevant engineering practices for the purpose of identifying necessary changes and optional changes within a low-regret or observational decision framework:

- ASCE/SEI Standard 7-10, Minimum Design Loads of Buildings and Other Structures (ASCE/SEI 2010)

- The American Society of Heating, Refrigerating, and Air-Conditioning Engineers Standard 169, Weather Data for Building Design Standards (ASHRAE 2006), currently undergoing revision to account for climate change effects
- The International Code Council (ICC) International Building Code (ICC 2013), a model building code that references the above standards and is adopted by state and local governments as the basis for their legal building codes
- The National Fire Protection Association NFPA 1144: Standard for Reducing Structure Ignition Hazards from Wildland Fire (NFPA 2013), a model code that is adopted by state and local governments as the basis for protection from wind driven conflagrations and wildfire
- Envision™ (ISI 2012), the sustainability rating system for infrastructure of the Institute for Sustainable Infrastructure that addresses adaptation

Implications of current climate and weather science. A review of the IPCC AR5 (IPCC 2014) and the Third U.S. National Climate Assessment (Melillo et al 2014) offers an appropriate climate-and-weather scientific basis for potential changes in hazards and new extreme events of interest to structural engineering. The following key areas are grouped under temperatures, precipitation, wind, drought, sea-level rise and multi-hazard environments:

- temperatures
- heat waves and impacts on structures, such as buckling of railroad tracks and rigid pavements
- design conditions for insulation and heating, ventilating and air conditioning systems
- seasonal conditions, such as heating and cooling degree days, for energy usage
- temperature and moisture cycles (such as freezing and thawing and wetting and drying) affecting durability of exposed materials
- precipitation
- water, ice and snow loadings on roofs, power lines, etc.
- riverine and coastal (for example, storm surges) flooding (as they affect structural stability and durability)
- wind
- wind and wind-driven debris loadings
- drought
- wildfires
- adverse impacts on air quality
- desiccation affecting strength and settlement of foundations.
- sea-level rise
- multi-hazard environments (such as wind and flooding with hurricanes)

Limited, authoritative guidance on these environments is available from Seneviratne et al. (2012) (see Table 2.1).

The following are recent studies on assessing the impacts of global climate models (GCM) and other trends applicable to structural engineering practices and standards. Although these studies provide illustrative examples, they do not, on the collective, cover the entire domain of the structural engineering practice. Rozenzweig and Solecki (2010) provide baseline, 2020s, 2050s and 2080s frequencies of exceedance for extreme temperatures and precipitation for New York City. Rosenzweig et al. (2011) provide baseline, 2020s, 2050s and 2080s frequencies of exceedance for extreme temperatures and precipitation for various regions of New York State. Auld et al (2010) describe the climate science and services needed to support infrastructure engineering design, siting and development of improved national codes and standards for current and future climate conditions. In a few instances (e.g., ASHRAE Standard 169), engineering standards are being updated in light of findings from modeling and observations of climate and weather science.

Recommendations for practices and standards. In many or most situations, today's (2014) standards and regulations have not responded to recent findings of climate and weather sciences. With the exception of design temperature minima, climate change is anticipated to increase the magnitudes and likelihood of extreme events over the planned lives of buildings and other structures. Since standards and regulations usually set minimum design criteria, engineers can inform owners and regulators of the likelihood of greater than specified extremes, and recommend (when warranted) more conservative designs, using the low-regret or observational approaches described in Section 3, with improved performance when subjected to extreme events. To disseminate improved practices, engineers can publish case studies of applications of the observational method and the resulting performance during extreme events.

Each standard committee will need to (1) assess climate change effects, (2) review the relevant climate and weather science observations and projections, (3) evaluate the resulting effects of relevant extreme events, and (4) consider cycle costs and benefits to arrive at a consensus on changes in its specific standard. Lessons learned in the processes of revising standards and practices should be shared across the standards community to help coordinate standardization efforts to avoid conflicts and discordances.

Adaptation Options. Various uncertainties along with the small scale of infrastructure design (i.e., the area of building footprint) makes determining the effect of climate change difficult. Even if specific environmental extremes are determined not to have significant changes in frequency or intensity, or that changes cannot be determined, changes and uncertainties in socioeconomic conditions, such as population, can cause changes in vulnerability and risk assessments (Melillo et al, 2014).

Regardless, engineers and scientists in relevant fields have an obligation to understand and take into account the possible changes due to climate, the probabilities and uncertainties (NRC 2012) thereof, and how changes may affect future designs. These groups also have obligation to work together to clearly communicate information to the stakeholders and the public in an iterative process (Melillo et al, 2014) to arrive at strategies for climate adaptation.

Changing existing building codes would offer a direction toward adapting structural engineering practices to climate change. For example, increasing design loads to account for wind, precipitation and temperature creates a more robust set of building standards. Of course, these changes would increase the cost of the structures. Raphaël et al. (2009) identified the following strategies to change our current loading requirements:

- not changing building codes until observing full evidence of such effects on structures and the extent of the impacts;
- changing building codes to design safely for the next fifty years and periodically considering additional updates; and
- changing building codes by including a climate change factor, which can depend on the year of construction, to follow the trends in climate.

The third option reflects the uncertainty associated with the science and trends. It offers the means to allow for additional time until more detailed studies on the extent of which these loads will change. Typically, such studies should include the climate information on the spatial and time scales that are relevant to structural design, including some projections and trends. Presently, translating climate change scenarios toward loads on structures can now be based on very preliminary assumptions, thus introducing uncertainties. Having such uncertainties might require increasing the margin of safety; however, further study might result in its reduction or increase. A key challenge is to identify rare events and their associated frequencies that have not yet been observed, but may become relevant in a typical design lifetime.

Another important consideration that goes beyond making changes to building codes is the development of guidelines to assess existing structures. Comprehensive guidelines for assessing existing structures are not available. Existing buildings, designed, built and possibly retrofitted according to the current loading standards, might have an overall level of safety below acceptable levels with increasing climatic loads. The owners of existing structures should be encouraged or perhaps stimulated to take climate change effects into account when renovations are carried out or additions are planned. Such guidelines would help owners to make appropriate decisions within a risk framework.

Need for science and engineering research. In the short term, engineering standards committees and associated researchers may: study trends in the pertinent extreme environments in cooperation with climate and weather scientists; assess current and projected hazard, load and load combination probabilities; assess the uncertainties associated with these projections and the risks and vulnerabilities of the buildings and other structures, and; seek consensus on design loads. Achieving this consensus will be bolstered in part by the targeted acquisition of data from extreme events. This data would include information on the event itself and its subsequent impacts on the built environment and the complexities therein (Seneviratne et al, 2012).]

Interdisciplinary climate, weather and engineering research should attempt to "bridge the gap" between the sometimes disparate communities (Wright et al. 2013). This includes seeking the probabilistic knowledge needed for engineering standards and practices. Such research for extension of climate and weather modeling to the probabilistic forecasting of extreme environments is treated in the National Research Council report *A National Strategy for Advancing Climate Modeling* (NRC 2012, p 202).

Note that large eddy simulation techniques for turbulent flows have been successfully applied in fire safety engineering modeling (Baum, 2000). Similar techniques might be used to derive the probabilities of extreme wind forces from climate, weather and wind models.

4.2 Transportation

Scope of the sector and its major engineering practices. Transportation is the foundation for commerce and the economy of the United States. The U.S. transportation system is an intermodal network of highways, rail, inland navigation, deep-draft navigation, ports and aviation. Transportation may be divided into land transportation and facilities, such as roads, highways, rail and runways, and marine transportation that includes both inland navigation and ocean-going deep draft navigation.

Many transportation engineering considerations are affected by environmental conditions. Engineers must try to maximize the reliability and availability of a structure under varying environmental conditions subject to cost constraints. Various transportation modes use different types of infrastructures, but these infrastructures share common design issues. Foundation design reflects subsurface conditions such as soils and saturation conditions. Material selection is another consideration. Asphalt and concrete pavements are affected by highway traffic volume, vehicle weights and freeze-thaw cycles. The erosive action of flowing water can remove bed material from around foundations and structures. This scour can lead to the failure of bridges and other highway and rail structures (FHWA, 2001). Storm drainage systems are designed to provide adequate surface drainage to ensure vehicle safety. Bridges and culverts over streams are designed to be large enough to pass a design flood of an expected frequency of occurrence without inundating the road (Meyer, 2006). See Section 4.1 for additional information on structural issues.

Another consideration of transportation planning is where to locate facilities. Roads, highways, rail and other facilities should avoid hazardous locations such as floodplains. For example, transportation planners use FEMA flood maps to avoid flood-prone areas. Further development often follows new transportation facilities, so the location of facilities in hazardous areas could increase vulnerability to human population and economic development (Meyer, 2006).

Land transportation and facilities. A changing climate may affect both infrastructure and transportation operations. Increases in the number of days with sustained air temperature above 32°C (90°F) may affect pavement integrity such as softening and traffic-related rutting, and cause deterioration in roadway and bridge expansion joints (Schwartz et al. 2014). Increases in very hot days could also cause rail track deformations. A greater number of high heat days per year could also affect construction productivity and costs through curtailed workdays or overnight scheduling (TRB, 2014). Not all potential changes are detrimental; fewer days with freezing, snow and ice may result in less pavement deterioration and frost heave, as well as a longer construction season. Changes in the number of freeze-thaw conditions will vary depending on the location. Fewer days with snow and ice could lead to reduced costs for removal (TRB, 2008). However, agencies might have to plan for larger individual winter storms (TRB, 2014).

Climate projections show that the frequency of heavy precipitation events may increase. More intense precipitation events may lead to overloading drainage systems and road closures due to street flooding, landslides and washouts (TRB, 2014). Increases in erosion could occur more frequently, causing road washout and damage to rail support structures. Soil moisture levels may also increase, affecting the foundations of roads, bridges and other structures (TRB, 2008), especially pavements constructed on expansive clays (TRB, 2014). Scour may increase if heavy flows become more frequent.

The frequency of floods and droughts may change in a changing climate. Bridges and culverts are often designed for floods of a given return period, or in other words, a given frequency of exceedance. If flood frequency and magnitudes increase, the design flood will be exceeded more often than planned. Engineers could use a larger and less frequent design flood, but this action would entail greater costs.

Coastal infrastructure is designed based on potential storm surge and wave action. Rising sea levels and potentially more intense storms, compounded by regional subsidence, might increase the inundation of highways and rail lines in coastal areas (Schwartz et al. 2014; TRB, 2014). Many of these roadways also serve as regional evacuation routes, which could become compromised during extreme weather events. Storm surge and wave action can cause bridge scour and increase erosion of roads and supporting structures (TRB, 2008). Rising sea levels may reduce the vertical clearance of bridges over major waterways, thus limiting the types of navigation that typically use the waterway. Sea-level rise and saltwater intrusion could accelerate infrastructure corrosion in coastal areas, reducing life expectancy, increasing maintenance costs and increasing the potential for structural failure during extreme events (TRB, 2014).

Marine transportation. International navigation infrastructure planning and design guidelines are published by PIANC, the World Association for Waterborne Transport Infrastructure, which is a society of national representation. The U.S. membership in PIANC is administered by the USACE Institute of Water Resources. PIANC has chartered a "Task Group on Climate Change" to provide guidance for sustainable waterborne transport infrastructure for ports and waterways addressing climate change challenges, including protection of the environment from impacts of maritime accidents. An initial report (PIANC, 2008) reviews a wide range of climate change impacts on maritime and inland navigation and identifies potential adaptation responses.

Inland navigation. Almost one-sixth of the nation’s cargo is carried by the inland and Intracoastal Waterway system (USACE, 2009). The inland waterway system in the United States includes 12,000 miles of navigable waterway and 275 lock stations (USACE, 2005). On rivers without locks and dams, navigation is dependent on adequate water flow to provide depth for vessels. Low flows will cause shippers to reduce draft on their barges, increasing transportation costs. Navigation will cease when the flow is too low for vessels’ drafts. Floods could also close inland waterways since fast river flows make navigation treacherous. Inland navigation may shut down during hydrologic extreme events.

River navigation also depends on channel morphology and the supply, transport and deposition of sediments in the channel. As soil erosion is often caused by heavy, intense rains, increases in future sedimentation would cause higher dredging costs. Ice and freezing conditions can cause river closures. As temperatures warm, the number of freezing days may decline, leading to fewer blockages caused by ice (PIANC, 2008).

Climate adaptation measures for inland navigation need to be considered within the context of integrated water resources management. If reservoir storage is available, the option of increasing flow to support navigation must be balanced with other potential water resources uses. There are structural solutions to reduce the impact of hydrologic variability on inland navigation. Dredging can be used to increase channel depth. Locks and dams could be built on free-flowing rivers to provide pools for minimum flow depth. New upstream reservoirs could store water during high flow periods and release it during low flow periods. However, structural solutions are often unpopular due to the environmental impacts.

If low flows are expected to last over the long term, vessel drafts could be decreased with designs that reduce weight and increase width. There are also non-structural measures that could be taken. More skillful forecasts with longer lead times could improve scheduling of barge traffic and potential shifts to other transportation modes. Better channel charts with up-to-date water-depth information would reduce uncertainty margins during periods of low flow and optimize barge loading (PIANC, 2008). See Section 4.3 for more information on water resources issues.

Port engineering. Changes in patterns of wind, water levels and waves will affect efficiency of commercial cargo port facilities. Entrance channels are designed for ship safety in extreme combinations that will otherwise result in delays of ships approaching, being served at, or departing a port. Jetties and breakwaters may suffer expensive damage if their design criteria are regularly exceeded by high waves and water levels. River ports may have bridges whose clearance for ship passage is compromised by sea-level rise or by more extreme river floods. Delays and consequent increased shipping costs will become more common. Moreover, ships, cargo and perhaps lives could be lost and the coastal environment poisoned by spills when natural conditions exceed design criteria for port facilities.

Guidance for the planning, design, construction and modernization of port facilities in the U.S. often follows guidance of the U.S. Navy Facilities Engineering Command (NAVFAC) and the U.S. Army Corps of Engineers (USACE), much of which is presented as Unified Facilities Criteria and Unified Facilities Guide Specifications documents. The policies of these two lead defense agencies toward climate change response are therefore relevant. The "U.S. Navy Climate Change Roadmap" (2010) specifies actions to assess, predict and adapt to global climate change, with a view toward assuring that infrastructure is fully capable in all probable climatic conditions over the next 30 years.

The USACE has recently published port planning guidance to address the future impact of Panama Canal expansion for much larger cargo ships (IWR, 2012). Expansion of U.S. ports to receive ships nearly three times the size of present Panamax-class vessels imposes challenges whose scale overwhelms stand-alone considerations of climate change. The American Association of Port Authorities recognizes climate change challenges, stating, "…Ports also must have …the flexibility to be able to adapt their facilities to the potential effects of climate change…" (AAPA, 2012). The society has in recent articles and presentations focused more on security and renovation, particularly regarding the advent of larger cargo ships.

Agencies guiding the planning and design of port infrastructure are clearly committed to climate change adaptation. Their efforts to guide climate change adaptation through the development of specific design criteria have just begun. At present, port engineers must face climate change adaptation with subjective judgment regarding "best available science" and long-term projections of coastal wind, wave and water level conditions of the future.

Adaptation options and guidance for decision making. Transportation infrastructure stakeholders should evaluate actions to “avoid, minimize and mitigate potential risks” from climate change impacts (TRB, 2014). There is a tradeoff between the reliability and availability of infrastructure and the cost to build and maintain it. Stakeholders should also consider the co-benefits of adaptive transportation infrastructure and decision timeframes needed. A risk management approach would balance the consequences and likelihood of failure with the life-cycle costs of the infrastructure (Meyer, 2006). Consequences of failure include economic and environmental damages and public safety. Critical facilities would likely require more robust design standards. One consideration in a risk analysis is how a failure would affect the performance of the transportation system as a whole. Additional redundancy could be built into the system. As noted earlier, the challenge of a risk approach with climate change is that the probabilities of future climate states are not well defined.

The location of transportation infrastructure is another consideration. There are several options for infrastructure located in low coastal regions or floodplains. Highways, bridges and rail lines could be elevated. Piers and other port facilities could be raised in anticipation of sea-level rise. Potential flooding on critical high-value infrastructure could be reduced with levees or sea walls. Infrastructure could also be relocated to less hazardous areas (TRB, 2008). Since economic development is often sited around transportation facilities, relocation may reduce the vulnerability of other economic sectors.

4.3 Water resources

Scope of the sector and its major engineering practices. The goal of water resources engineering is to find cost-effective solutions to improve human welfare and support economic development while sustaining the natural environment. Water resources infrastructure has been built for flood risk reduction, hydroelectric generation, to support inland navigation, and to provide agricultural, municipal and industrial water supply. Hydrologic extremes such as drought and floods affect the reliability of this infrastructure. A warming climate may increase the severity and frequency of floods and droughts.

The sustainability of the natural environment and aquatic ecosystems is another significant concern of water resources management. Aquatic ecosystems face multiple stressors, including disruption of natural flow patterns, water quality, overharvesting and invasive species. A changing climate may exacerbate these stressors. Rising temperatures will affect the survivability of cold-water species. Hydrologic patterns may change; spring snowmelt may occur earlier. There will be different effects on different species and the species composition in an ecosystem could change. Water managers will need to monitor the impact of these changes, particularly on threatened and endangered species, and may need to consider ecosystem uncertainty in their planning.

In addition to climate, other changes have a significant impact on water resources management. Land-use changes affect infiltration and evapotranspiration rates and alter runoff. Urbanization increases the amount of impervious area leading to reduced infiltration and an increase in runoff. Excessive groundwater extraction can deplete aquifers, reducing available water supply and base flows in streams. Population increase can increase the demand for water. Economic development in coastal flood plains increases vulnerability to coastal storms and floods. Water resources infrastructure deteriorates over time and deferred maintenance may reduce its performance below its design standard (Brekke et al. 2009). All of these factors can interact and evolve at an uncertain pace.

Floods and droughts have a major impact on society. Water resources management has tried to reduce the impact of these hydrologic extremes on society. Flood risk management can employ both structural measures, such as reservoirs to store flood waters and levees to divert flow away from communities and economically valuable land, and non-structural measures, such as buy-outs of homes in vulnerable floodplains and flood warning and evacuation systems. Drought management could include the development of additional infrastructure to store water or non-structural plans to conserve water. A change in the frequency of extreme events presents a challenge to traditional design and planning methods.

Methods of analyses for water resources planning. Both design events and statistical methods have been used to model floods and droughts in water resources planning. For example, the "standard project flood" (SPF) has been used for urban levees and other infrastructure. The "probable maximum flood" (PMF) has been used to design spillways for large dams where the consequences of a failure are large. New methods for estimating the PMF may be needed to account for climate change (Surampalli et al. 2013). Although the SPF and PMF were based on a deterministic analysis of severe combinations of critical meteorologic and hydrologic conditions, the SPF is generally associated with a 0.2% flood (500-year flood) and the PMF with a 0.01% chance flood (10,000-year flood). For low flows, the worst drought on record is often used for calculating a water supply system's safe yield. The drought of record with a short sample size may not be an adequate design standard. Better understanding of paleo-droughts has shown that more severe droughts have occurred in the past.

Hydrologic frequency analysis is used in water resources planning when there is an adequate record of observed data. Flood frequency analysis is used to estimate the 1%-chance flood, or the 100-year flood for the National Flood Insurance Program (NFIP). NFIP requirements have a large influence on community planning. Hydrologic frequency analysis is also used for water resources planning and design. Methods that depend on statistical analysis of observed records generally assume that the statistical properties of hydrologic variables in the future will be statistically similar to the observed record. This assumption is being called into question due to climate change and recognition of other changes. The return period of extremes that exceed a threshold will decrease if there is a gradual increase in the mean of the probability density function (Wigley 1988). For example, the magnitude of the current flood with a return period of 100 years may in the future become the flood with a 70-year return period.

There are flow frequency analysis methods for nonstationary time series (Surampalli et al. 2013). However, in an observed data set, it is difficult to distinguish between the existence of long-term persistence and a trend due to climate change, urbanization or other factors. Decadal climate variability can appear as a trend in a short time series. In addition to climate, land use and urbanization, dam construction and reservoir regulation can cause trends in hydrologic processes. Another question is how to extrapolate a trend into the future. See Appendix B for a discussion of flood nonstationarity in the Southeast and Mid-Atlantic United States.

Water management decisions have long been made under considerable uncertainty in the public sector and various accepted decision processes exist (Stakhiv, 2011). Only recently have water management decision makers been faced with the prospect of incorporating highly uncertain climate change projections into real decision processes that are associated with social, economic and environmental consequences. However, there exists no established method for using climate information for such decisions. A major challenge is to determine how to effectively represent future climate change and then to evaluate the results within a decision framework.

One traditional method for planning water resources projects and choosing among alternative plans is benefit-cost analysis (BCA). BCA generally requires that future hydrologic events and plan outcomes can be characterized by a well-defined probability distribution. Benefit-cost analysis uses the probability distribution to calculate the expected value of future benefits and costs. An optimal solution can be found that maximizes economic development or some other criteria. These probability distributions have generally been based on the observed record and statistically estimated. However, a changing climate calls into question the assumption that future hydrology will be similar to the past observed record. It is also problematic to estimate a probability distribution from climate models. If there is significant uncertainty regarding future hydrology, water resources planning should develop robust plans and designs that perform well over a wide range of possible future conditions, rather than develop an optimal plan for a likely future (Brekke et al, 2009).

Decision-making approaches based on vulnerability assessment. One type of approach for water resources planning with climate uncertainty starts first with the project or system's vulnerability before considering climate projections. These approaches have been called "climate-informed decision analysis" (Hallegatte et al. 2012), "decision scaling" (Brown et al. 2011; Brown et al. 2012), or a "scenario-neutral approach" (Prudhomme et al. 2010). The approach first determines a project's or system's definition of failure and under what conditions such failure would occur. It then evaluates the plausibility of these conditions occurring in the future. Stochastic hydrologic analysis can also be used to determine extremes in a way that avoids many of the concerns related to the huge uncertainties associated with GCMs, yet addresses many of the risk-based issues in an analytically acceptable manner.

Appendix A describes a recent study to evaluate operations on the Great Lakes (IUGLS, 2012). The study used a decision-scaling approach that defined conditions for system operation and failure points. The study undertook traditional hydrologic analyses and stochastic analysis, and considered paleo-climatic evidence and global climate model scenarios to evaluate a range of possible Great Lake conditions. GCM projections were uncertain with both drier and wetter conditions projected, depending on the model. The study used robustness as a primary objective of any new regulation plan, rather than rely on assumptions of particular future climatic and lake level conditions or specific model projections.

4.4 Urban water systems

Scope of the sector and its major engineering practices. Urban water systems are comprised of three primary subsectors: potable or drinking water, wastewater and stormwater. Stormwater is rainwater, snow or any other form of precipitation that has reached the ground or other surface. Stormwater runoff develops rapidly over urban areas that exhibit high imperviousness. The amount of stormwater runoff is directly related to the amount of precipitation falling over a discrete amount of time and space, and is also related to other processes of the hydrologic cycle (e.g., infiltration, evapotranspiration, storage) and land-use factors (e.g., slope of the terrain, roughness, etc.).

Implications of current climate and weather science. Note that demands for infrastructure systems (as well as the design environments) and the natural environments (such as ground cover affecting absorption of precipitation and near ground wind velocities) will be affected by climate change. In Arctic regions, thawing permafrost poses special risks to community water resources that supply urban water systems.

Climate (and climate change) is intricately linked to the hydrologic cycle, in particular, precipitation and evapotranspiration. Municipal stormwater management is further complicated by the multifunctional purpose of the urban infrastructure system and the many different agencies involved.

There is significant uncertainty associated with climate change over the next 20 to 50 years. Changes in the intensity and frequency of precipitation events are expected. Climate change will require that urban stormwater management practices adapt to the uncertainty of extreme events. Increases in the frequency and magnitude of extreme rainfall events have been documented in New York State (Tryhorn, 2010); these are among the largest such changes reported within the

United States. Figure 4.1 illustrates a monotonically increasing mean value of extreme events (greater than 2 inches in 24 hours) for New York State from 1950 through 2007. Increasing magnitudes and frequencies of extreme precipitation events have also been reported in the Midwest (Todd, et al. 2006) for sites with long historical records. Others claim increases in global temperature and CO_2 levels do not necessarily result in proportional increases in runoff and stream flow (Hirsch and Ryberg, 2012). From this study one may conclude that increases in extreme precipitation events did not occur. It is important to point out that land-use changes (e.g., urbanization) can result in far greater flooding impacts, independent of climatic forcing functions.

There is a gap between global climate projections and forecasts of local high intensity rainfall to be used for flood generation and routing. Downscaling techniques are used to obtain higher resolution regional and local projections from large-scale GCM projections. Merging historical data and GCM results to create climate change Intensity Duration Frequency (IDF) curves has been employed by a select number of engineering practitioners. Other approaches to calculating both heavy rainfall and floods suggest using a factor by which rainfall is adjusted for each one degree Celsius of temperature change (Ministry for the Environment, “Tools for Estimating the Effects of Climate Change on Flood Flow,” New Zealand, 2010).

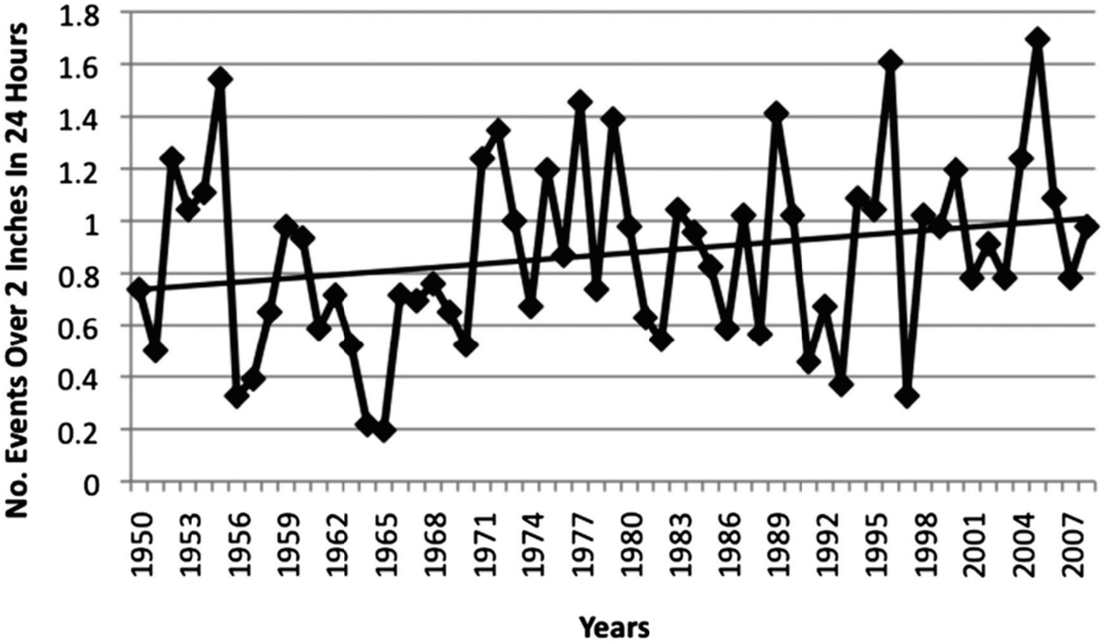


Figure 4.1: Number of Precipitation Events Over 50 mm in 24 Hours for 46 Stations
Source: Figure 1 in Tryhorn (2010); reproduced with permission from American Meteorological Society.

In the Midwest study (Todd, et al. 2006) for sites with long historical records, the 24-hour 100-year recurrence interval rainfall depth increased at 89 % of the study locations, with little change for the higher frequency storms with 2- and 10-year event return periods. Design standards for most common drainage structures are typically based upon the intensity-depth-duration characteristics of extreme storm events with recurrence intervals computed by extreme-value probability distributions: this implies an assumption of *climatic stationarity* (See Sections 2 and 3 for further discussion). In 2004 the National Oceanic and Atmospheric Administration (NOAA) released the Precipitation-Frequency Atlas of the United States, the Atlas 14 (Bonnin et al. 2004). This publication updated the point precipitation frequency estimates for much of the eastern and southwestern parts of the United States. The standard precipitation frequency atlas for the eastern U.S. had been the National Weather Bureau Technical Paper No. 40 (TP-40) (Hershfield, 1961), based upon precipitation data collected up to 1957 with an average of 15 data years.

The Atlas 14 data are considered more suitable for hydraulic design and water resource planning than the TP-40 estimates, since precipitation values are available for the actual sites rather than interpolated values obtained from the TP-40 isohyetal maps. Todd et al. (2006) compared point rainfall data obtained from TP-40 and NOAA Atlas 14 for sites with over 100 years of precipitation records in Illinois, Indiana, Kentucky and Ohio. In the four-state study region, 100-year recurrence interval events generally increased in magnitude from the TP-40 estimates to the NOAA Atlas 14 precipitation depths. All four states had an average increase for the 100-year, 1-hour, 6-hour, 12-hour and 24-hour duration events. Todd et al. (2006) state that communities in the United States that continue to use the TP-40 data (which has been shown to underestimate the precipitation depth for low-frequency, high-magnitude events in this four-state region) should reevaluate their reliance upon this data source in hydraulic analysis and design. Otherwise, use of these dated precipitation statistics could lead to inadequate erosion control and undersized reservoirs, storm sewers, culverts and other drainage and water storage structures—all of which could cause increased flooding.

Deterministic dynamic, physically based rainfall-runoff distributed routing models, such as the U.S. EPA Stormwater Management Model (Huber and Dickinson, 1988; Rossman, 2010), mathematically describe the transformation of precipitation into surface runoff: from rainfall input to subsurface infiltration or generation of overland flow, and then flow into the man-made drainage system. Among the many variables that describe these processes mathematically are the width, area, percent imperviousness, ground slope, roughness parameters of the land cover for both impervious and pervious fractions, and several infiltration rate parameters that depend upon methods chosen.

Recommendations needed for longer-term improvements of practices. The improvements of practices described in the following subsection will take several years for consensus procedures to be implemented. Meanwhile, a rainfall-runoff model, calibrated against measured data, is an excellent planning and design tool, as it is dependent upon a carefully selected precipitation input, whether it is a discrete design storm event or a long-term time series of recorded precipitation events. Guidance for practitioners is needed in order to select the most appropriate methodology for choosing such precipitation inputs.

Given the expected changes in our climate, there is a need to account for uncertainty and variability and to replace standards and practices that were once considered permanent with ones that account for climatic nonstationarity. The primary means of projecting future climate are GCMs, but they are not well suited to simulate temperatures and precipitation over relatively small geographic areas and timescales. Table 2.1 in Section 2 provides an informative summary of changes that may affect engineering at global scales. As noted in Section 3, we must consider how to effectively use climate information to revise design standards. There will be a tradeoff between designing for larger uncertain events and project cost. Thus, decisions about our infrastructure and long-range water resource planning must provide flexibility and viable options, such as:

- designing control systems conservatively to account for potential future increases in rainfall intensities;
- maximizing the infiltration of runoff to the subsurface;
- protecting existing wetlands and constructing more wetlands to hold runoff and recharge groundwater;
- improving the performance of existing systems through enhanced monitoring and improving single-event and multiple-event modeling and feedback;
- updating rainfall statistics frequently and simulate future scenarios accordingly, and;
- implementing real-time internet-based information systems.

In terms of stormwater management, low impact development (LID) runoff control methods or more complex structural Best Management Practices (BMPs) may provide the resiliency required for adaptation implementation. Among the LID methods are the installation of rain barrels, porous pavement, infiltration trenches, vegetative swales and bio-retention cells. Much more efficient structural BMPs are engineered systems and methods designed to provide temporary storage and treatment of stormwater runoff for the removal of pollutants (Muthukrishnan et al, 2004). These include the installation of wet and dry detention ponds, retention ponds and constructed wetlands, as noted earlier. Wetlands in the U.S. are estimated to provide $23.2 billion in storm protection (Foster et al. 2011).

The urbanization of an area alters the local water balance. Often overlooked is the potential interaction with subsurface components, such as groundwater levels, flow and contaminant exchanges. Stormwater management also requires knowledge and understanding of the groundwater and surface water interactions prior to finalizing development; this is particularly critical if constructed wetlands are to be considered a stormwater control and treatment BMP option. The large surface area requirement of constructed wetlands helps to minimize the "extreme" water level fluctuations during all but the larger storm events. The development of a comprehensive wetland model that has both surface flow and solute transport components was presented by Kazezyilmaz-Alhan, et al. (2007). Their model incorporates surface/ground water interactions and accounts for upstream contributions from urbanized areas (see Figure 4.2). The time series of flows and contaminants predicted by a calibrated distributed routing rainfall-runoff model (subjected to an annual time series of 15-minute rainfall) constitutes the upstream component of the wetland model. The occurrence of future extreme climatic events resulting in elongated and more frequent flooding and drought, water quantity shortages, sporadic and uncharacteristic rainfall patterns, increases in high intensity rainfall events, and higher possibility for impaired water quality suggests a probabilistic approach that accounts for uncertainty. The one common theme between nearly all studies related to drought and flood modeling is the use of extreme value theory (EVT) to adequately model these phenomena.

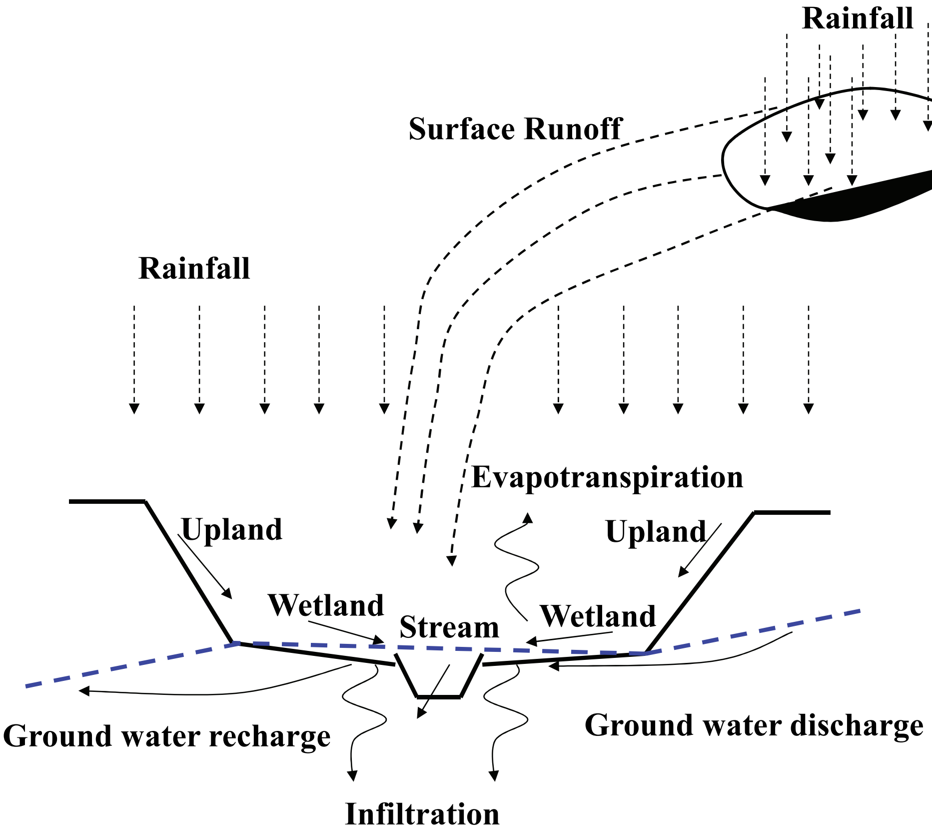


Figure 4.2: Surface/Ground Water Interactions in a Constructed Wetland
Source: Modified from Kazezyilmaz-Alhan, et al. (2007).

A thorough review of stormwater infrastructure design practices is required. The techniques used for developing design storms are quite dated, many of which are based on either rainfall inputs from Technical Paper No. 40 (TP-40) (Hershfield, 1961) for precipitation data collected up to 1957 or Intensity Duration Frequency curves developed assuming Gumbel extreme value distributions.

Thorough evaluations of concurrent rainfall and streamflow records are needed, which perhaps can be accommodated by splitting the available records into large time series, say, first 40 years compared to next 40 years, etc., and comparing the statistical differences. The results from applying both design storms and more modern computational methods would be elucidating. This type of analysis would set a baseline for use of climate change simulation models.

4.5 Coastal management

Scope of the sector and its major engineering practices. When it comes to climate change, flooding and erosion are the primary concerns regarding civil engineering works. As well, adjustments of habitat boundaries in response to changing water level, temperature and salinity are also important considerations. Coastal flooding and erosion risks follow changing frequency, intensity and paths of storms at sea, superimposed on eustatic sea-level rise caused by melting of land ice and ocean thermal expansion. Erosion is also influenced by changes induced by climate change in prevailing coastal winds and by sediment budgets modified by new hydrological patterns of coastal watersheds. Some coastal areas suffer long-term land subsidence. Arctic coastal flooding and erosion problems are made worse by sea ice retreat with diminished ice dampening of winter waves and by thaw settlement of coastal permafrost.

The challenges engineers encounter to develop design criteria for coastal works in a warming world are similar to those for inland water resource developments. Determination of changing probabilities for extreme storm surge using GCMs are not yet reliable. Variable nearshore bathymetry, changed by erosion and new sediment transport patterns, is not addressed in these simulations. Historical trends of shoreline change are useful, especially if they can resolve recent accelerations. Storm surge and erosion risk assessments based on numerical modeling of historical wave generation and propagation (hind-casting) and site-specific measurements remain essential components of well-founded coastal engineering designs.

Design criteria for prevention of damage from coastal flooding to community infrastructure in the United States often follow guidance of FEMA (FEMA 2011). FEMA guidance also addresses design criteria for strong winds that accompany a surge during a storm at the coast, with particular focus on wind, wave and water levels with 1 % joint probability to be exceeded in any year (i.e., the 100-year return period). FEMA criteria are important because they are associated with the National Flood Insurance Program (NFIP). Communities have invested in studies to delineate zones with coastal hazards, as defined by FEMA for the NFIP. The extent of a hazard zone is not stationary in a changing climate. The last 100 years will not have the same statistical characteristics at a particular site as the next 100 years. Changes wrought by global climate change may only begin to be reflected in the last 10 years of measurements, but projections based on so short a record have poor confidence at the level of 100-year return period. FEMA climate change policy (FEMA 2012) promotes additional climate change judgments to define coastal flooding and erosion risks, but does not specify data sources or analytical procedures.

Corps of Engineers guidance for projects intended to prevent or mitigate coastal flooding and erosion damages to property is found in the Coastal Engineering Manual (CEM) (USACE, 2008). CEM guidance discusses alternative responses, including non-structural options, but focuses on structural design concepts and analyses. The CEM is the most widely used technical guidance for coastal engineers in the U.S., but does not provide advice for addressing climate change. The Corps of Engineers does have an Engineer Regulation (USACE, 2013) that requires all coastal activities by the agency to address the impacts from 3 different local sea-level change scenarios, the historical trend, an intermediate projected rise, and a worst-case projected rise.

4.6 Energy supply

Scope of the sector. The U.S. energy supply system broadly consists of the infrastructure and fuels needed to supply the economy with electricity, energy for mobility (through refined oil products), industrial feedstock and heat. Figure 4.3 shows the various fuels that provided approximately 97.5 quadrillion BTUs (about 103 exajoules) of energy to the U.S in 2013. Energy fuels have specific uses in the economy, with about 28 % of U.S. primary energy used for transportation, 22 % for industry, 11 % for homes and businesses, and the remaining 39 % used to make electricity consumed by homes, businesses and industry (EIA, 2014). There are different levels of fungibility and therefore, different levels of resiliency to disruption between the sources and uses of U.S. energy. For example, transportation energy is overwhelmingly provided by petroleum products, while electricity is provided from a range of fuels.

The energy supply chain largely consists of the production and distribution of fuels and electricity, enabled via multiple and oftentimes interdependent infrastructure. Fuels for energy such as coal, natural gas and oil are extracted, and biomass relies on agricultural production. These fuels are often processed after extraction and then transported via rail and barge (coal, biomass, oil) or pipeline (natural gas and oil). Oil and biomass are then refined into liquid fuels and distributed by pipelines and trucks to end users, predominately in the transportation sector. Natural gas is distributed by pipeline to residential, commercial and industrial users for heating and industrial inputs. Coal and natural gas are delivered to electric power plants to create electricity, which is then delivered to customers through a vast electricity transmission and distribution network.

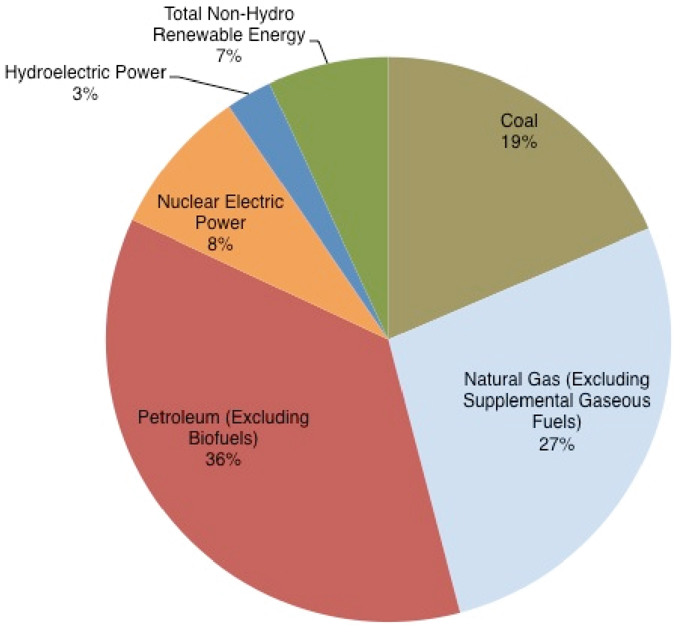


Figure 4.3: 2013 U.S. Primary Energy Consumption by Source.
Source: Data from EIA (2014).

Several different federal entities have oversight and regulatory authority over U.S. energy infrastructure, including the Department of Energy, the Environmental Protection Agency, the Federal Energy Regulatory Commission, the Nuclear Regulatory Commission, the North American Electric Reliability Commission, and the Department of Transportation (GAO, 2014). Other stakeholders include state and local regulatory bodies and private firms that design, construct, own, operate and maintain a large portion of the U.S. energy supply infrastructure. Table 4.1 highlights some of the major enabling infrastructure systems in the U.S. energy supply chain, many of which are traditionally associated with transportation infrastructure.

Principal climate change impacts and vulnerabilities. Across all regions and to varying degrees, the infrastructure supporting U.S. energy supply is currently impacted by climate change, and these impacts will amplify in the future. The Third National Climate Assessment of the U.S. Global Change Research Program state that: infrastructure is being damaged by sea-level rise, heavy downpours and extreme heat; damages are projected to increase with continued climate change, and; disruption in one infrastructure system can cascade to others (Melillo et al. 2014).

Under a changing climate, the frequency and intensity of some extreme weather events are expected to change, higher temperatures are expected increase electricity demands, water availability will constrain energy production, and sea level rise and storm surges can affect coastal energy infrastructure (Dell et al. 2014). The National Climate Assessment summarized some of the key regional climate indicators affecting the U.S. energy supply, shown in Table 4.2.

Table 4.1: Some of the Enabling Infrastructure for the U.S. Energy Supply Chain

Fuel Production	*Fuel Transportation*	*Fuel Refining and Distribution*	*Electricity Production*	*Electricity Transmission and Distribution*
Oil, gas and coal extraction, processing and storage Agricultural production of corn and other biomass	Oil, gas and liquids transmission pipelines Natural gas compression stations Bulk rail and barge transportation of coal, biomass and liquids Fuel commodity import and export terminals	Petroleum and biomass refineries Petroleum product storage Roadway network for fuel distribution City pipelines for natural gas distribution Liquid fuel terminals and points of sale	Thermal power plants for coal, natural gas, nuclear, geothermal, biomass, and solar thermal generation Dams and pumped hydroelectric generation Wind and solar photovoltaic plants Primary and emergency petroleum-fired generators	High voltage transmission lines Transmission level substations Distribution level substations Medium voltage feeder lines Residential, commercial and industrial voltage supply Load control, dispatch facilities, and metering Maintenance support facilities

Note: These are a sample of the main types of energy supply infrastructure; additional enabling infrastructure not listed.

Table 4.2: Projected U.S. Regional Indicators from the 2014 National Climate Assessment

Key Indicator	*Mean Annual Temperature (2071-2099 vs. 1971-2000)*	*Summer Precipitation (2071-2099 vs. 1971-2000)*	*Sea level Rise (2100)*	*Number of Days > 95 °F (2041-2070 vs. 1971-2000)*	*Number of Days < 10 °F (2041-2070 vs. 1971-2000)*
Northeast	+4°F to 9°F	-5% to +6%	1.6 – 3.9 feet (0.5 – 1.2 m)	+10 days	-12 days
Southeast	+3°F to 8°F	-22% to +10%		+23 days	-2 days
Midwest	+4°F to 10°F	-22% to +7%		+14 days	-14 days
Great Plains	+3°F to 9°F	-27% to +5%		+22 days	-4 days
Southwest	+4°F to 9°F	-13% to 3%		+20 days	-3 days
Northwest	+3°F to 8°F	-34% to -4%		+5 days	-7 days

Source: Adapted from Dell et al. (2014), Tables 4.1 and 4.3. This source excludes extreme weather events. Sea-level rise will vary by geography and does not apply to the Midwest. Alaska, Hawaii and Pacific Islands were not studied.

Impacts of increased frequency or severity of weather. Energy infrastructure will be affected by an increase in the frequency and severity of extreme weather events, which have begun to occur across most of the U.S. The projected changes could include more frequent and intense precipitation, wildfire and drought (Dell et al. 2014). Increased storm intensity, coupled with sea-level rise and storm surge, could affect coastal oil and gas extraction, as well as transport and storage infrastructure. Barges utilize inland waterways and rail transportation often follows riverbeds. Therefore, increased river flooding could disrupt the supply of coal, petroleum products and other liquids, or biomass transported by both train and barge (Dell et al. 2014; DOE, 2013). Increased storms and river flooding could also threaten inland thermoelectric and hydroelectric generation facilities by damaging structural components, sediment deposition and flooded facilities (DOE, 2013; Hauenstein, 2005).

Impacts of increased temperatures. As shown in Table 4.1, both the mean annual temperatures and the number of extreme heat days are expected to increase across all regions in the U.S. These increased temperatures will increase cooling needs in every region, while decreasing projected heating needs (Dell et al. 2014). This will increase the summer peak demands of the electricity system, as nearly all cooling energy is provided by electricity. A higher summer electricity peak will require increased usage of expensive and underutilized generation equipment and stress and reduce the capacity of transmission and distribution infrastructure (Sathaye et al. 2013). A regional reduction in heating needs can affect the amount of infrastructure required for fuel distribution and storage, as heating needs are supplied through electricity as well as natural gas, heating oil and other fuels. On the other hand, winter peak electricity needs would be reduced, further altering the need for natural gas and other fuels for electricity in the winter heating season.

Increased temperature could also affect energy generation infrastructure. Higher water temperatures could cause curtailments at thermoelectric plants using rivers for cooling in order to remain within thermal discharge limits. Hotter air and water temperatures will also reduce the efficiency of thermoelectric generation, requiring more fuel to produce similar amounts of electricity. Higher temperatures could also affect the available capacity of hydropower, solar PV, wind power and biofuel production, as well as threaten the stability of the Arctic oil and gas infrastructure located on permafrost (DOE, 2013). Given the very high likelihood of increased temperatures in the future (Dell et al. 2014), engineering decision making in the energy sector should recognize and plan for the potential impacts to long-term supply, distribution and demand.

Impacts of decreased water availability. Energy in the U.S. is enabled through water use. The production, transportation, refining and storage of fuels (e.g. oil and gas, coal, biomass), as well as power generation in coal, natural gas, nuclear, hydroelectric, biomass and solar thermal plants, require long-term access to water (DOE, 2013). Long-term precipitation changes, drought and reduced snowpack, coupled with increasing demands for water, are projected to alter water availability. The impacts will vary by region; longer dry spells are projected in the Northwest and seasonal water constraints are projected in the Southwest and Southeast (Dell et al. 2014). Reduced water flows and higher water temperatures limit the availability of river water use for thermoelectric power plant cooling, while reduced snowpack affects hydroelectric capacity.

Decreased water availability and prolonged droughts could affect oil and gas exploration, especially unconventional production relying on horizontal drilling and hydraulic fracturing. The costs and availability of conventional oil refining could also be affected, as the process requires between 0.5 and 2.5 gallons of water or more per gallon of gasoline equivalent (DOE, 2013). Reduced river water levels decrease the barge capacity of the inland water transportation system, which transports coal, oil and petroleum products. A one-inch drop in river capacity can reduce a barge tow's capacity by 255 tons on the upper Mississippi, Illinois and Ohio rivers, and by up to 765 tons on the lower Mississippi (DOE, 2013).

Impacts of sea-level rise, storm surge and subsidence. Sea levels have risen globally by about 8 inches since 1880 and are projected to rise 1 to 4 feet by 2100 (Dell et al. 2014). Sea-level rise amplifies the impacts of storm surges, and combined with local subsidence and high tides, can threaten coastal energy infrastructure. These include oil and gas infrastructure in the central Gulf Coast region and power plants and electricity infrastructure throughout the coastal United States (DOE, 2013; Dell et al. 2014). For coastal energy facilities to withstand future storm surges, the performance of existing structural measures should be reevaluated under future sea-level rise, storm surge and subsidence impacts (Brown et al. 2014). Similarly, a scale-up of future coastal thermoelectric power generation, including nuclear power, could face increased costs for hardening against sea-level rise and storm surge (Kopytko and Perkins, 2011).

Approaches for adaptation decision making with climate uncertainty. Infrastructure enabling the U.S. energy supply is designed for a useful life of several decades or more, and is expensive and time-consuming to construct and retrofit. Much of the existing coal and nuclear power plants in the U.S. were constructed during a building boom from the 1960s to the 1980s; decisions are currently being made about recapitalizing, retrofitting or retiring these and other existing energy assets. At the same time, new firms are deploying new infrastructure for renewables, natural gas power generation and unconventional hydrocarbon development. Infrastructure stakeholders in the private and public sectors need to design, construct and operate existing and future energy infrastructure to be resilient against climate change impacts. Energy infrastructure should be responsive to future energy demands as well as dramatically reduce associated greenhouse gas emissions, decrease air, water and waste impacts, and maintain competitive life cycle costs. This enormous challenge, coupled with the range of uncertainties regarding the timing, magnitude and location of climate change impacts, requires new approaches for engineering decision making for adaptation. These approaches must enable decisions in the face of uncertainty and should maximize low-regret alternatives, co-benefits of actions, and robustness under the range of future climate change impacts. Many of the elements of adaptation strategies for infrastructure can be based on existing knowledge (Wilbanks and Fernandez, 2013).

A near-term action is to conduct vulnerability assessments for new energy infrastructure and existing infrastructure with a high likelihood of impact risk (e.g., coastal power plants). Vulnerability assessments should inform the development of robust risk management strategies that iteratively incorporate observation, evaluation and learning (Wilbanks et al. 2013). The civil engineering community should also support data collection, monitoring and analysis of energy infrastructure to update these vulnerability assessments with empirical observations.

The next set of actions include those with low-regret—that is, those decisions that are likely to perform well in the face of climate uncertainty. Low-regret approaches include system designs and infrastructure to manage, store and shift electricity load in the transmission and distribution system, while dramatically reducing the greenhouse gas intensity of power generation. As specific energy infrastructure approaches the end of its service life, finding opportunities to reduce energy system sensitivities to water and temperature impacts could steadily recapitalize the system for resilience (Wilbanks et al. 2013). Other low-regret approaches could couple climate-resilient designs with other national priorities, such public health, economic growth, energy and national security (Bierbaum et al. 2014; DOE, 2013). Improving community resiliency and preparedness for disasters that disrupt energy services may create co-benefits across the planning for both climate and non-climate related disasters (DOE, 2013). Design standards for regional generation capacity reserve margins, power line capacity and distribution infrastructure could be established for performance in a set of expected future temperature, weather and demand conditions, which could be adjusted incrementally and holistically as new climate information becomes available (Dell et al. 2014). The World Bank (2011) described a set of structural, technological and behavioral adaptive measures for energy system infrastructure potentially affected by climate change, and the National Climate Assessment provided possible resilience measures for energy infrastructure. These actions are summarized in Table 4.3.

Finally, engineering stakeholders could transition to an integrated climate risk management framework to evaluate major infrastructure investments. This framework should include methods to introduce flexibility into infrastructure designs to manage uncertain future climate impacts and also uncertain future socioeconomic and policy trends (Wilbanks et al. 2013). In addition, these processes need to incorporate the values and goals of the stakeholders, the evolving scientific literature, the available information and the perception of risk (Moss et al. 2014; Chang et al. 2014). One applicable method is to use Robust Decision Making (RDM) (Lempert et al. 2006; Groves and Lempert, 2007), which is an iterative, quantitative approach designed for conditions of deep uncertainty, such as the timing and magnitude of climate change impacts. RDM has seen increasing application and success in areas focused on natural resources and water resources

Table 4.3: Examples of Adaptive Measures for Energy System Infrastructure

Energy System	*Structural Measures*	*Technological Measures*	*Behavioral and Siting Measures*
Mined Resources (oil and gas, thermal power, nuclear power)	• Improve robustness of infrastructure to withstand storms, flooding and drought • Build redundancy into facilities	• Replace cooling systems with air or dry cooling, or recirculating systems, or pre-cool water discharges • Improve gas turbine designs • Expand strategic fuel reserves • Consider underground transfers and transport structures • Use non-fresh water supplies	• (Re)locate in areas with lower risk of flooding or drought • Build dikes and reinforce walls to contain flooding • Evaluate and revise emergency and drought management planning • Evaluate flood planning and management of on-site drainage and runoff • Reduce and integrate water use • Adapt regulations
Hydropower	• Build de-silting gates • Increase dam height • Construct small dams in upper basins • Adapt capacity to flow regime	• Manage water reserves and reservoir • Use transmission connections to integrate regionally	• (Re)locate or adapt plant operations based on changes in flow regime • Complement with other energy sources
Wind		• Improve designs of turbine infrastructure to withstand higher wind speeds	• (Re)locate based on expected changes in wind speed, anticipated sea-level rise or flooding
Solar		• Improve technology designs to withstand extreme weather	• (Re)locate based on changes cloud cover • Ensure distributed solar energy can function after extreme events
Biomass	• Build dikes • Improve drainage • Expand/improve irrigation systems • Improve robustness of infrastructure to withstand extreme events	• Introduce new crops with higher heat and water tolerance • Substitute fuel sources	• Support early warning and emergency harvesting systems • Adjust crop management, rotations, planting, and harvesting regimes • Introduce soil moisture conservation practices
Transmission and Distribution	• Improve robustness of pipelines, power lines and infrastructure to extreme weather events • Install underground electrical infrastructure	• Improve reliability of grid systems through back-up power, storage, and intelligent controls • Increase transmission capacity within and across regions	• Create plans for emergencies • Implement regular inspection of vulnerable infrastructure (e.g. wooden utility poles and rights of way)
Demand	• Invest in high efficiency infrastructure • Invest in distributed generation	• Improve building energy management and demand response capabilities • Improve irrigation and water distribution efficiency	• Improve and promote efficiency of consumption • Promote peak shaving, peak shifting, and flexible work hours

Source: Adapted from The World Bank (2011) and Dell et al. (2014). For hurricane risk to offshore wind turbines, see Rose et al. (2012).

planning—in particular, flood risk (Fischbach et al. 2012; Lempert et al. 2013), water supply management (Groves, et al. 2008, 2013), and water quality decision making (Fischbach et al. forthcoming). RDM provides a means to incorporate both well established and imprecise data into the analysis, identify new strategies more robust than those previously considered, and help stakeholder groups with different interests and expectations participate more effectively in the analysis. Other methods, such as Capabilities-Based Planning (Samaras and Willis, 2013), Scenario Planning (Moss et al. 2014), and coupled energy-infrastructure-adaptation systems modeling (Schaeffer et al. 2012; Koch and Vögele, 2009) could be also used to characterize the choices that engineers and stakeholders face.

4.7 Cold regions

Implications of climate change. The cold regions of specific interest to the United States are generally recognized to be the northern states and Alaska. For both of these regions, the issues noted under the other infrastructure categories in this section of the report apply. In addition, for the northern states and Alaska, climate change issues are related to: the active layer (the zone at the ground surface that annually freezes and thaws); the timing and magnitude of precipitation in the form of snow; the gradual (permanent) warming of the air temperature (which, over time, will result in a warming of the ground temperature), and; an increase in the frequency of extreme events (for example, the occurrence of two successive, abnormally warm summers or an abnormally wet and heavy snowfall).

The climate change issues for the northern states projected under the IPCC Fourth Assessment (2007) would result in a reduction in the active layer and therefore a reduction in frost heave and thaw weakening in this layer. If the changes in precipitation in the form of snow for the northern tier states are accurate, there may be a reduction in snowfall and accumulation, with the exception of extreme event projections. Finally, there would be a reduction in river and lake ice formation, which would generally result in a reduction of this hazard. Thus, the projected climate change for the northern tier states may not be detrimental but, rather, beneficial.

For Alaska, the consequences of projected and observed climate change are much more complicated. In the northern states and south and central Alaska, the active layer is associated with the annual freezing of the ground surface in the winter and thawing in the spring as the ground at depth is unfrozen. In Arctic Alaska, the active layer is associated with the annual thawing of the ground surface in the summer and refreezing in the winter as the ground at depth is perennially frozen. The Arctic is underlain by permafrost, defined as any geologic material that remains at a temperature below 0° C for two or more years.

The IPCC Fourth Assessment Report projects a global warming of 0.2 °C per decade for the next two decades. Global temperature change at 2090-2099 relative to 1980-1999 is projected to be from 1.1 °C to 6.4 °C (IPCC, 2007). It is expected that the warming in the Arctic will be stronger than the global average.

Permafrost is widespread in the Arctic, Subarctic, ice-free areas in Antarctica and in high-mountain regions. Permafrost regions occupy approximately 23 million km^2 of land area in the Northern Hemisphere (Zhang et al. 1999). Hinzman et al. (2005) note "the dynamic nature of the Arctic is framed by extremes: very cold winter temperatures, highly skewed annual cycle of solar radiation input, dominance of snow cover, and relatively low rates of precipitation, all of which result from its geographic position. Many of the unique features of the Arctic terrestrial system arise from the extreme seasonality of the northern climate. There are essentially two seasons, one frozen and one thawed, with abrupt transitions between them. During the winter or frozen season, which lasts 7–10 months of the year, unfrozen surface water is rare, and a negative annual radiation balance is established (more radiation is lost to space as heat than comes in through solar heating). It is this negative radiation balance that creates the gradients that drive the Arctic climate."

Two types of permafrost have been identified as most vulnerable to surface thaw in a warming environment in the near future on the decadal scale: relatively warm, patchy and thin permafrost in the Subarctic and boreal regions, much of which is already in imbalance with climatic conditions in interior, western and southern Alaska and largely protected from thaw by vegetation and soil organic layers (Shur and Jorgenson, 2007), and; permafrost with high ground ice content (>20 % excess ice by volume) in near-surface layers and vulnerable to rapid thermokarst and erosion once the ice in these layers starts to melt (Kanevskiy et al. 2011). As of 2012, only 135,500 mi^2 (27 %) of the Alaska permafrost zone is classified as thaw-stable, defined as having low or no ground ice content. The remaining 73 % (about 370,000 mi^2) belongs to permafrost regions with variable-to-high ice content and clear indicators of past vulnerability to thaw, such as the presence of thermokarst lakes, thaw slumps, thaw pits and similar landforms (Jorgenson et al. 2008).

Permafrost temperatures have increased since the 1980s (IPCC, 2007b). Temperatures in the colder permafrost of northern Alaska, the Canadian Arctic and Russia have increased up to 3°C near the permafrost table and up to 1 to 2°C at depths of 10 to 20 meters since the late 1970s to early 1980s (Osterkamp, 2007; Romanovsky et al. 2010; Smith et al. 2009, 2010). Temperature increases have generally been less than 1°C in the warmer permafrost of the discontinuous permafrost zone of the polar regions (Osterkamp, 2007; Romanovsky et al. 2010; Smith et al. 2010) and also in the high-altitude permafrost of Mongolia and the Tibetan Plateau (Zhao et al. 2010). When the other conditions remain constant, active layer thickness in the Arctic is expected to increase in response to warming. Active layer thickness has increased by about 20 cm in the Russian Arctic between the early 1960s and 2000 (Zhang et al. 2005) and up to 1.0 m over the Qinghai-Tibetan Plateau since the early 1980s (Wu and Zhang, 2010), with no significant trend in the North American Arctic since the early 1990s (Shiklomanov et al. 2010). However, over extreme warm summers, active layer thickness may increase substantially (Smith et al. 2009).

Increases in air temperature are in part responsible for the observed increase in permafrost temperature over the Arctic and Subarctic, but changes in snow cover also play a critical role (Osterkamp, 2005; Zhang, 2005; Zhang et al. 2005; Smith et al. 2010). Trends toward earlier snowfall in autumn and thicker snow cover in winter have resulted in a stronger snow insulation effect, and as a result, a much warmer permafrost temperature than air temperature in the Arctic. On the other hand, permafrost temperature may decrease even if air temperature increases, if there is also a decrease in the duration and thickness of snow cover (Taylor et al. 2006). The lengthening of the thaw season and increases in summer air temperature have resulted in changes in active layer thickness.

In Barrow, Alaska, the annual end of snowmelt shows increased variability over the last sixty years and a trend toward a markedly earlier snow-free season. The snowmelt date relates to the day when the snow depth is less than 2.5 cm and continues to melt or, since radiometric data have become available, the day when the surface albedo falls below 0.30 and does not recover to sustained higher values. The earlier melt is consistent with May air temperatures on the Alaskan North Slope, which show an abrupt and rapid increase in variability since 1990. Also, total snow accumulation in winter has decreased and March and April temperatures have increased in recent decades. Stone et al. (2002) attribute these changes to synoptic circulation changes that have affected the climate of the entire North Slope.

Regression analysis indicates that the snowmelt date has advanced by about 10 days since 1941. Melting of massive ground ice and thawing of ice-rich permafrost can lead to subsidence of the ground surface and to the formation of uneven topography known as thermokarst, having implications for ecosystems, landscape stability and infrastructure performance (Walsh, 2005). As ice-rich permafrost warms, it becomes more susceptible to various forms of failure. Coastal erosion rates have doubled along the Beaufort Sea over the last two decades, while slope and riverbank failures have become more common.

Esch and Osterkamp (1990) summarized the following engineering concerns related to permafrost warming:

- warming of a permafrost body at depth
- increase in creep rate of existing piles and footings
- increased creep of embankment foundations
- eventual loss of adfreeze bond support for pilings.
- increased seasonal thaw depth (active layer)

- increased thaw settlement during seasonal thawing.
- increased frost-heave forces on pilings
- increased total and differential frost heave during winter
- development of residual thaw zones (taliks)
- decrease in effective length of piling located in permafrost
- progressive landslide movements
- progressive surface settlements

Furthermore, thermosyphons and thermopiles are ubiquitous in the Arctic and Subarctic. Under projected climate change, these devices will extract less heat and be less efficient during a warmer winter of shorter duration.

The Arctic Climate Impact Assessment (ACIA) (Instanes et al. 2005) discusses engineering challenges and typical engineering projects that are likely to be affected by climate change. For an engineering structure on permafrost, it is not just the change in air temperatures that is important, but also changes in precipitation, wind and solar radiation. It will not be as simple as assuming a trend line for warming in the Arctic based on one or an average projection from an ensemble of GCMs. The greatest threat to Arctic and Subarctic infrastructure may well be associated with an extreme event "upset condition," related to "two successive abnormally warm summers." This is the scenario used in the design of the Barrow Utilidor in an era prior to the concern expressed for climate change in the Arctic.

For certain extremes (e.g., precipitation-related extremes), the uncertainty in projected changes by the end of the 21st century is more the result of uncertainties in climate models rather than uncertainties in future emissions. For other extremes (in particular, temperature extremes at the global scale and in most regions), the emissions uncertainties are the main source of uncertainty in projections for the end of the 21st century (IPCC, 2012). For the Arctic and Subarctic, the natural variability of climate may create the greatest uncertainty. Professor S-I Akasofu (renowned Geophysicist at the University of Alaska Fairbanks), in his testimony before the U.S. Senate Subcommittee Hearing on Global Climate Change and Impacts (April 2006), stated: "Prominent climate change is in progress in the Arctic, compared with the rest of the world. However, Arctic climate change consists of *both* natural change and the greenhouse effect, and thus it is incorrect to conclude that the present warming in the Arctic is due entirely to the greenhouse effect caused by man. Therefore, it is important to find out the contribution of both natural and manmade components to the present climate change in the Arctic."

More recently, Akasofu (2010, 2013) noted that the rise in global average temperature over the last century has halted since about 2000, while the release of CO_2 into the atmosphere is still increasing. He suggests this interruption has been caused by the suspension of the near linear (+ 0.5° C per 100 years or 0.05° C per 10 years) temperature increase over the last two centuries, due to recovery from the Little Ice Age (LIA) by a superposed multi-decadal oscillation of a 0.2°C amplitude and a 50- to 60-year period, which reached its positive peak in about the year 2000.

Akasofu noted that the Earth experienced the LIA between from 1200-1400 and 1800-1850. The temperature during the LIA is believed to have been 1° C lower than the present temperature. As well, the solar irradiance was relatively low during the LIA. The gradual recovery from 1800-1850 was approximately linear and the recovery (warming) rate was about 0.5°C per 100 years. The same linear change continued from 1800-1850 to 2000. In this period, the solar irradiance began to recover from its low value during the LIA. Akasofu stated that the recovery from the LIA is still continuing today. The multi-decadal oscillation is superposed on the linear change. The multi-decadal oscillation peaked in about 1940 and also in 2000, causing the temporal halting of the recovery from the LIA. The negative trend after the peak in 1940 and 2000 overwhelmed the linear trend of the recovery, causing the cooling or the halting of warming. The view presented in Akasofu's recent papers predicts the temperature increase in 2100 to be 0.5°C ± 0.2 ° C, rather than the 4° C ± 2.0°C predicted by the IPCC (2007).

While there are differences and uncertainties in the various models representing regional climate impacts, all future GCM projections agree that global temperatures will increase over this century in response to increasing greenhouse gas emissions from human activities (Walsh et al. 2014). Understanding the potential regional Arctic impacts, and developing a risk-based framework for Arctic infrastructure development under uncertainty, is an important issue for the engineering and climate science communities that has been recognized by a number of authors (e.g, Instanes and Anisimov, 2008; Schaefer et al. 2012; Markon et al. 2012).

5 Research, Development, and Demonstration Needs

Research, development and demonstration (RDD) is needed to advance recommended civil engineering practices and standards in order to effectively address climate change impacts. Wilbanks et al. (2013) describe three types of information needed: action-oriented knowledge, fundamental knowledge and analytical tools. Civil engineers will especially require action-oriented climate change information that translates and characterizes climate projections on water, temperature, sea-level rise, storm surge and wind regimes over the next few decades. Research is needed to better understand the interdependencies within the various components of civil infrastructure, such as energy supply and demand, as well as the interdependencies between the various components of civil infrastructure, such as energy, water, transportation, agriculture, communication and other infrastructure (DOE, 2013). Understanding the relationship between the rate of change of climate impacts on infrastructure systems and the natural turnover of the infrastructure stock is also crucial for characterizing low-regret adaptive actions (Dowling, 2013).

The civil engineering community also needs fundamental knowledge for infrastructure designs. The potential impacts from climate change on infrastructure require a reexamination of many civil engineering design standards and performance metrics. For example:

- How do climate change impacts affect engineering factors of safety included in existing and proposed designs?
- What are the limits in current designs and materials for extreme loads due to wind, temperature, flooding and precipitation?
- How does the increased expected climate variability affect loads and performance?
- How do behavioral responses and changing demands for services provided by infrastructure affect near-term and long-term infrastructure vulnerabilities?
- What is the empirical experience with the cost and performance of adaptive designs, and what is the modeled life-cycle costs and performance?
- How do greenhouse mitigation efforts affect adaptation plans and requirements?

Finally, civil engineers need improved analytical tools and methods for decision making under uncertainty. A priority is the integration of variance, extremes and non-stationarity into engineering planning and design. In addition, infrastructure stakeholders must create commonly accepted methods and indicators to compare risks to the energy sector and measures of adaptation effectiveness. Finally, better characterization of the economic implications of infrastructure vulnerabilities and potential adaptation co-benefits would also inform infrastructure decision making regarding potential adaptive measures (e.g., DOE, 2013). All of these measures suggest the necessary inclusion of climate adaptation methods and risk management in civil engineering education and training programs.

6 Summary, Conclusions, and Recommendations

Civil engineers have responsibilities for the planning, design, construction, operation and maintenance of physical infrastructures. These infrastructures include all types of buildings, communication facilities, energy generation and distribution facilities, industrial facilities, transportation networks, water resource facilities and urban water systems. They are expected to remain functional, durable and safe for long service lives, typically 50 to more than 100 years. They are exposed to, and potentially vulnerable to, the effects and extremes of climate and weather such as droughts, floods, heat waves, high winds, storm surges, wildfire and accumulated ice and snow. Engineering practices and standards are intended to provide acceptably low risks of failures in functionality, durability and safety over the service lives of infrastructure systems and facilities.

There is increasing demand for engineers to incorporate projections of future climate into project design criteria. Climate scientists have reached near-unanimous consensus that climate has changed and will continue to change. The vast majority of climate scientists accept the following characteristics of future climate: substantial increases in temperature, related increases in atmospheric water vapor, and increases in extreme precipitation amounts and intensities in most areas.

Global climate models (GCMs) are the primary tools that climate scientists use to make quantitative projections of future global and regional climate. Climate models project systematic changes in climate and weather conditions. The current class of climate models consists of four main components: atmosphere, ocean, land surface and sea ice. GCMs solve equations of thermodynamics and fluid mechanics for variables of interest. Variables that describe the atmospheric state include temperature, pressure, humidity, winds, and water and ice condensate in clouds. Variables are defined on a large spatial grid. A typical GCM might have grid cells with a size of about 100 km (62 miles) on a side. Processes that occur on too small a spatial or time scale to resolve on the model grid are represented by average or typical tendencies rather than the full underlying atmospheric fluid mechanics.

Climate projections introduce additional climatic uncertainty beyond those that can be estimated from observations of the past. Uncertainty of the climate response is much larger on local and regional scales than on the global scale. There are three sources of uncertainty in climate model projections: internal uncertainty (i.e., natural variability of the climate), numerical model uncertainty (e.g., model parameters, model structure), and scenario uncertainty (e.g., projections of future emissions). Uncertainty in numerical models include the representation of physical processes, such as cloud formation and land cover effects, that occur at spatial scales smaller than the large spatial scale used in climate models. There is also uncertainty in the underlying climate science; that is, the physics of the atmosphere, ocean and land is not completely understood, resulting in limitations in the model. Models are not independent; uncertainties that are related to the underlying science will be similar in different models. Models use different parameterizations when a physical law is not completely understood. For example, moist convection causes the release of latent heat and is important to the Earth's energy budget. However, convection and clouds occur on too small a scale to be resolved by climate models and, hence, must be parameterized. Weather and climate are inherently variable. The additional uncertainty that climate projections bring up is whether or not variability may change – for example, whether a greater part of the precipitation may fall in heavy and extreme events, or whether El Niño southern oscillation may change its magnitude or character. Finally, the changes and scale of future anthropogenic greenhouse gas emissions introduce scenario uncertainty into projecting future climate impacts. Civil engineers need to design long-lived infrastructure that could be affected differently in a low-emissions future versus one with business-as-usual projections.

The extreme amount of computational resources required for GCMs results in their being limited to larger spatial and temporal scales. Consequently, they tend to underestimate the variance and serial persistence in observed climate, which implies that GCMs may not do well modeling the extremes of natural climate variability. Engineering design is primarily concerned with the extremes. For example, a 40-50 year hourly precipitation time series is often used to generate runoff and obtain historical storm event statistics useful for BMP design. Also, engineering practices have been based on assumed stationarity of extremes of climate and weather; however, the frequencies and intensities of extremes observed in the past may not adequately represent those that will occur in the future.

GCMs perform better at larger spatial and temporal scales. Downscaling techniques are used to obtain higher-resolution regional and local projections. Downscaling creates local and regional information, but it will not reduce the uncertainty in the information. Downscaling actually increases the uncertainty when it captures a larger variance. The site-specific nature of most engineering projects contributes to the challenge of using GCM output or any downscaled result for design. Describing the possible evolution of the mean and extremes of key environmental factors over a region may be possible, but is probably not achievable at a scale of relevance to engineering practice.

Engineering practice has always recognized that there are uncertainties in future conditions and has developed methods to account for this uncertainty. These methods include designing for a future flood or wind velocity with a specific magnitude, using freeboard or safety factors, employing probabilistic methods as well as observational and risk-based methods.

Risk analysis and management is the primary approach engineers take to deal with future uncertainty. Uncertainty about the future climate can mean increased risk and can motivate action. Planning for increased climate risk will likely come at a cost.

Risk is commonly measured in simple terms as the probability of occurrence of an event and the outcomes or consequences associated with occurrence of an event. Risk assessment is primarily concerned with three questions: (1) What can happen? (i.e., what can go wrong?) (2) How likely is it to happen? (3) If it does happen, what are its consequences? Risk assessment is a systematic process to identify potential uncertain events (or hazards), determine the consequences if the event occurs, and estimate its likelihood of occurrence.

A risk management framework should ensure that a system can be updated over time as conditions change. Such a framework would include a monitoring program to evaluate system performance over time and the flexibility needed to make changes. A climate change risk management program can be incorporated into an organization's strategic and systematic process of operating, maintaining, upgrading and expanding physical assets effectively throughout their life cycle. Performance data collected over the life cycle of a system can be used to evaluate the system's performance under changing conditions, and also inform other stakeholders who are evaluating decisions for similar infrastructure. A risk management framework is rooted in the observational method of engineering practice proposed and employed in the field of geotechnical engineering over 50 years ago.

Decision methods that account for this uncertainty may be employed, such as low-regret decision making. With low-regret decision making, robust alternatives are often chosen that would do well across a range of possible future conditions. Robustness should be adopted as an important performance metric when evaluating project designs and management plans. A decision scaling approach to project planning may help to identify robust alternatives. For example, the case study on Lake Superior presented herein used robustness as a decision criterion in choosing regulatory rules.

The uncertainty associated with future climate is not completely quantifiable and, therefore, it will require engineering judgment if it is to be considered. A better and more transparent understanding of the methods of climate modeling and of quantifying uncertainty about future climate is needed to help engineers incorporate this new information into their practice.

Considering the above summary and the information presented in this report the following conclusions are appropriate:

- Climate is changing, but there is significant uncertainty regarding the magnitude of the change over the design life of the systems and elements of our built environment. It will be difficult to reliably estimate the change that will occur over several decades, long after the infrastructure is built and the financing and governance have been established.
- The prediction of future extreme events with associated parameters and their frequency of occurrence have even greater uncertainty and less reliability than projections of long-term

trends in temperature or precipitation. Downscaling does not reduce the uncertainty inherent in GCM projections and most likely would increase the uncertainty.
- Probabilistic methods often have relied on the assumption of stationarity, which implies the statistical properties of variables in future time periods will be similar to past time periods. The use of this assumption has been challenged recently because future climate, weather and their extremes are expected to be statistically different than in the past.
- Because the uncertainty associated with future climate is not completely quantifiable, it may not be possible to employ a probabilistic risk-based approach and, therefore, if projections of future climate are to be considered in engineering practice it will require considerable engineering judgment.

Engineers build long-lived infrastructure. The right-of-ways and footprints of the infrastructure have even longer-term influences. These facts suggest that the planning and design of new infrastructure should account for the climate of the future. Considering the impacts of climate change in engineering practice is analogous to including forecasts of long-term demands for infrastructure use as a factor in design. However, even though the scientific community agrees that climate is changing, there is significant uncertainty about the spatial and temporal distributions of the changes over the lifetime of infrastructure designs and plans. The requirement that engineering infrastructure meets future needs while taking into account the uncertainty of future climate, and at the scale of the majority of engineering projects, leads to a dilemma for practicing engineers. The dilemma is a gap between climate science and engineering practice that must be bridged.

Infrastructure designs and plans, as well as institutions, regulations and standards to which they must adhere, will need to accommodate a range of future climate conditions. Secondary effects from a changing climate such as changes in land cover and land use, resource availability and demographics in population will be similarly uncertain and will require flexibility in infrastructure location and design. The standards, codes, regulations, zoning laws, etc., which govern infrastructure are often finely negotiated or delicately balanced legally, which often makes them slower to adapt. In addition, different stakeholders may exploit the uncertainties associated with climate change to argue for positions they prefer.

Considering the above information, the following recommendations are appropriate:

- Engineers should engage in cooperative research involving climate, weather, and life scientists to gain an adequate, probabilistic understanding of the magnitudes and consequences of future extremes. Doing so will improve the relevance of modeling and observations for use in the planning, design, operation, maintenance and renewal of the built and natural environment. It is only when engineers work closely with scientists that: the needs of the engineering community become fully understood, the limitations of the scientific knowledge become more transparent to engineers, and the uncertainties of the projections of future climate effects become fully recognized for engineering design purposes.

- Practicing engineers, project stakeholders, policy makers and decision makers should be informed about the uncertainty in projecting future climate and the reasons for the uncertainty, as elucidated by the climate science community. Because the uncertainty associated with future climate is not completely quantifiable, if projections of future climate are to be used in engineering practice it will require considerable engineering judgment to balance the costs of mitigating risk through adaptation against the potential consequences of failure.
- Engineers should develop a new paradigm for engineering practice in a world in which climate is changing, but cannot be projected with a high degree of certainty. When it is not possible to fully define and estimate the risks and potential costs of a project and reduce the uncertainty in the timeframe in which action should be taken, engineers should use low-regret, adaptive strategies such as the observational method to make a project more resilient to future climate and weather extremes. Engineers should also seek alternatives that do well across a range of possible future conditions.
- Critical infrastructure that is most threatened by changing climate in a given region should be identified, and decision makers and the public should be made aware of this assessment. An engineering-economic evaluation of the costs and benefits of strategies for resilience of critical infrastructure at national, state and local levels should be undertaken.

The goal of ASCE CACC to bridge the gap between climate science and civil engineering practice is shared by many professionals representing all of the specialties of civil engineering. However, it will be very challenging to translate this goal into project-specific design criteria, standards and regulations. Civil engineers can use the observational method and work with infrastructure owners, users, funders and other stakeholders to make adaptive design decisions under uncertainty, to maximize infrastructure performance and resilience, and minimize life cycle costs under a changing climate.

Appendix A: Lake Superior Regulation: Addressing Uncertainty in Upper Great Lakes Water Levels

Overview. The International Upper Great Study (IUGLS) recommended an improved regulation plan for outflows from Lake Superior to the International Joint Commission. The new plan, *Lake Superior Regulation Plan 2012*, is more robust than the existing plan, both for historical climate and future climate states, and provides important benefits, especially for the environment. The Study employed over 100 experts and scientists from many of the top research centers in Canada and the U.S. The recommendations from the Study Board on climate-related issues of uncertainty are among the highlights of their final, peer-reviewed report to the International Joint Commission (IJC), marking the end of the $15 million five-year study (2007-2012). The Study was conducted under traditional water resources planning guidelines that included a comprehendsive consideration of all the water-using sectors (municipal and industrial water supply, irrigation, hydropower) and those affected by varying lake levels (ecosystems, navigation, riparian homeowners, recreation industry). The full report can be seen at: http://www.iugls.org/files/tinymce/uploaded/content_pdfs/Lake_Superior_Regulation_Full_Report.pdf

In view of the uncertainty emerging from early results of climate change research, the IUGLS Board decided to undertake a broader exploration and evaluation of how the results of that research could be best used and how decisions should be made. The result was the development of a fairly straightforward but relatively innovative process for using various sources of climate information to inform the evaluation of alternative regulation options and decision making. Their approach was to first characterize the sensitivity of a decision to changes in climate conditions, and then evaluate the impacts of such changes based on a variety of climate information sources and their relative credibility as assessed by expert judgment – i.e. the independent Study Board that reported to the IJC.

From its outset, adaptation to climate change was one of the principal goals of the Study. The title of the Final Report, *Lake Superior Regulation: Addressing Uncertainty in Upper Great Lakes Water Levels,* conveys the principal thrust of the evaluation, and that is dealing with uncertainties. The Study was the third comprehensive assessment in the last 40 years to address a recurring challenge in the upper Great Lakes system; how to manage fluctuating lake levels in the face of uncertainty over future water supplies to the basin, while seeking to balance the needs of those interests served by the system. The Study Board developed several planning objectives that guided the formulation of scores of alternative options and the fundamental evaluation criteria. However, it is one thing to conduct scientific climate assessments based on numerous climate scenarios that are linked to hypothetical vulnerability assessments, as was done for hundreds of generic assessments as part of the IPCC process. It is quite another thing to use highly uncertain information for making actual decisions today that anticipate unknown events far into the future.

The IUGLS Study took the approach that there were many sources of information, each with their own associated uncertainties. Rather than simply relying on downscaling a suite of climate change projections ("top-down" approach), they undertook a decision-scaling approach (Brown, et al, 2011), asking a series of fundamental questions associated with existing operation of the system: Under what climate circumstances would the system fail? What does failure mean for each of the water-using and dependent entities? What are the options for mitigating service delivery failure? In other words, it was a more conventional "bottom-up" engineering perspective, reflecting a logical evaluation process of defining the conditions for system operation and failure points, and then looking through various sources of information (Stakhiv, 2011). The Study Board included traditional hydrologic analyses, stochastic analysis, paleo-climatic evidence and GCM model scenarios to determine where there was a confluence of data and evidence to provide a higher degree of confidence in the final choice of robust options.

Study findings. Undertaking an analysis of future climate-related impacts on the upper Great Lakes required the development of cutting-edge scientific information and methods for analysis. In particular, the Study found that changes in lake levels might not be as extreme over the next 30 years as previous studies have predicted. This finding reflects a trend of increasing evaporation, likely due to lack of ice cover, and increasing water temperatures and wind speeds, with the resulting reduction in water supplies largely offset by increased precipitation. Projections suggest that lake levels will remain within a relatively narrow historical range, with lower levels likely, although higher levels are possible at times.

A new regulation plan must be robust. Limitations in model projections of future hydroclimate conditions resulted in significant uncertainty beyond the next 30 years. While lower lake levels were considered likely, the possibility of higher levels could not be dismissed. Both possibilities were considered in the development of a new regulation plan. Therefore, in terms of water management and lake regulation, the best approach is to make decisions in such a way as to not overly rely on assumptions of particular future climatic and lake-level conditions or specific model projections. *Robustness,* the capacity to meet regulation objectives under a broad range of possible future water-level conditions, was one major objective of any new regulation plan. As a result, the Study Board considered four broad conditions that subsumed 13 scenarios encompassing the widest range of plausible futures. Each was based on a different hypothesis regarding the impact of varying climate and was represented by a subset of net basin supply (NBS) data series from different models selected to test plans under each scenario. In order for the Study Board to endorse a plan, the selected plan had to perform as well as any other plan for all four of the scenarios.

The process used robustness as the tie-breaking decision criterion when comparing options that were nearly equal in their economic, environmental and social performance indicators for the historical sequence of hydrology. Robustness was defined as performing well over a wide variety of projected future climate conditions. Other possible decision criteria, such as overall optimal performance in the most likely future ("maxi-max" approach) or maximization of the expected value based on probabilities of the future, were deemed inappropriate under the circumstances. While selecting an optimal plan for the most likely future is a well-accepted decision rule, the great range of uncertainty associated with climate change on the Great Lakes precludes such an approach. If it were possible to select a most likely future, it would be only slightly more likely than many others. Maximization of the expected value of regulation plan performance was also rejected because of the insurmountable difficulty in estimating the probabilities of future climate on which such a calculation relies. Thus, the analysis focused on assessing the range of climate conditions over which acceptable performance was possible, and applying this analysis for each candidate regulation plan.

The role of climate science. A major goal of the Study was to bring the best possible hydroclimatic science to bear on selecting a robust regulation plan. In working towards that objective, the Study included state-of-the-science climate projections from one of the largest ensembles of GCM runs ever assembled for a regional study, regional climate modeling from two separate national modeling centers, a variety of statistical modeling approaches and innovations in modeling of the lake system's responses to climate. Climate research showed that changes in lake levels in the near-term future might not be as extreme as previous studies have predicted. For example, comparing the results of statistically down-scaled GCMs with results of dynamical down-scaled GCM projections, the Study found that predicted changes in net basin supplies (NBS) for the design period of year 2040 varied considerably, with both drier or wetter conditions predicted depending on the models used and their resolution (See Figure A.1). The Study's hydroclimate findings represent major steps forward in improving understanding of the largest regulated freshwater system in the world.

Despite best efforts, in terms of understanding the lakes system relative to lake levels, the unavoidable conclusion from the Study was that the Great Lakes are a complex system whose dynamics are only partially understood, and this current state of understanding has its limitations for deriving projections of the future. Furthermore, at present there is no evidence that the statistics of the historical record are not valid for projecting future climate. The current record of Great Lakes NBS appears continually stationary, marked by strong interannual and decadal variability, and showing no response that may be attributable to climate change. During the planning period (i.e., 30 years), "natural variability" is likely to mask any forcing due to greenhouse gas emissions. Lake levels are likely to continue to fluctuate, but still remain within a relatively narrow historical range. While lower levels are likely, the possibility of higher levels cannot be dismissed but rather must be considered in the development of a new regulation plan.

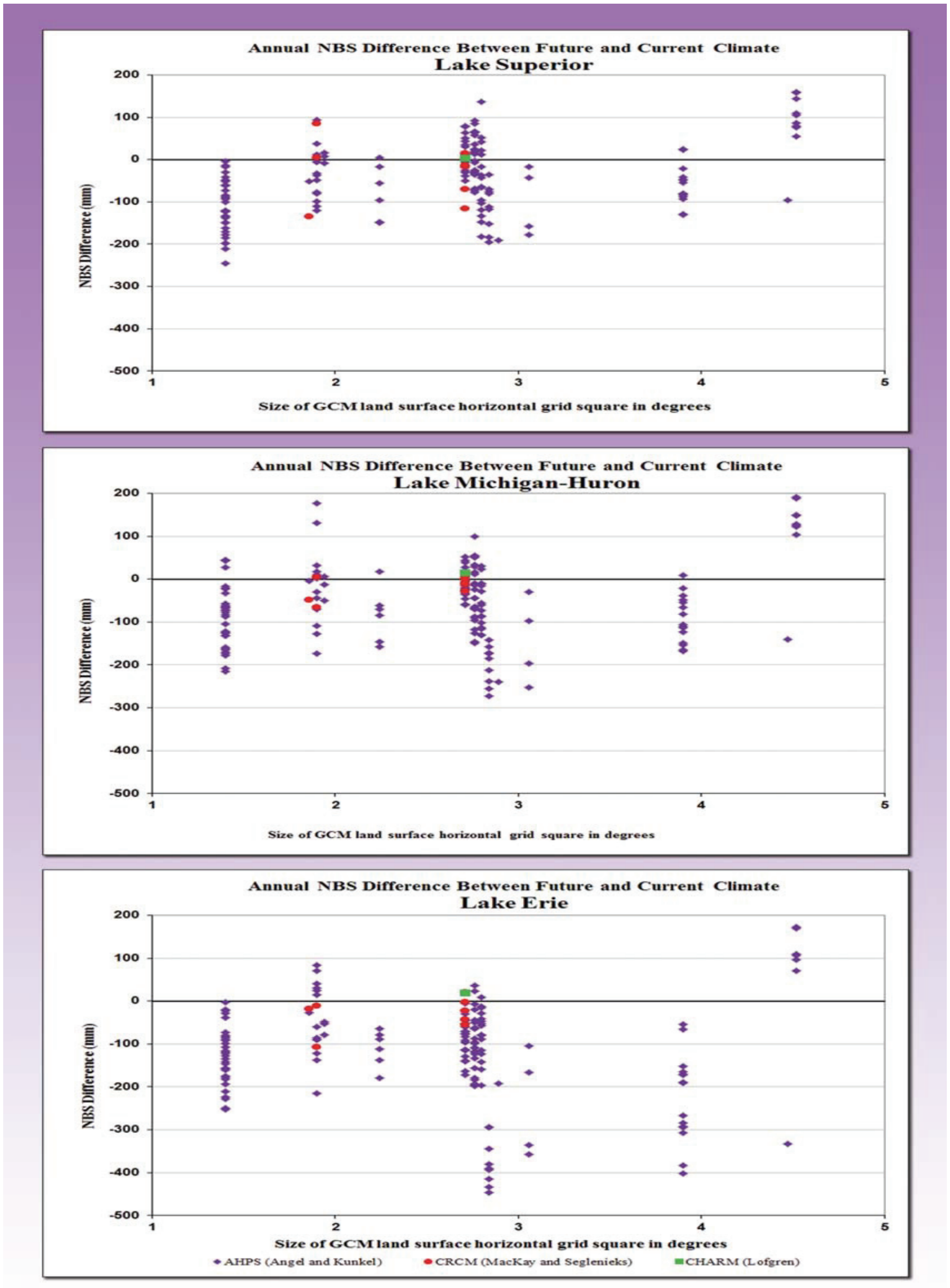


Figure A.1. The annual difference in Net Basin Supply (NBS) between the future and current time slices for each GCM using different downscaling methods. The x-axis groups the results for each GCM with the highest resolution GCMs on the left and the lowest resolution on the right. Downscaling methods: AHPS - Advanced Hydrological Prediction System; CRCM - Canadian Regional Climate Model; CHARM - Coupled Hydrologic Atmospheric Research Model

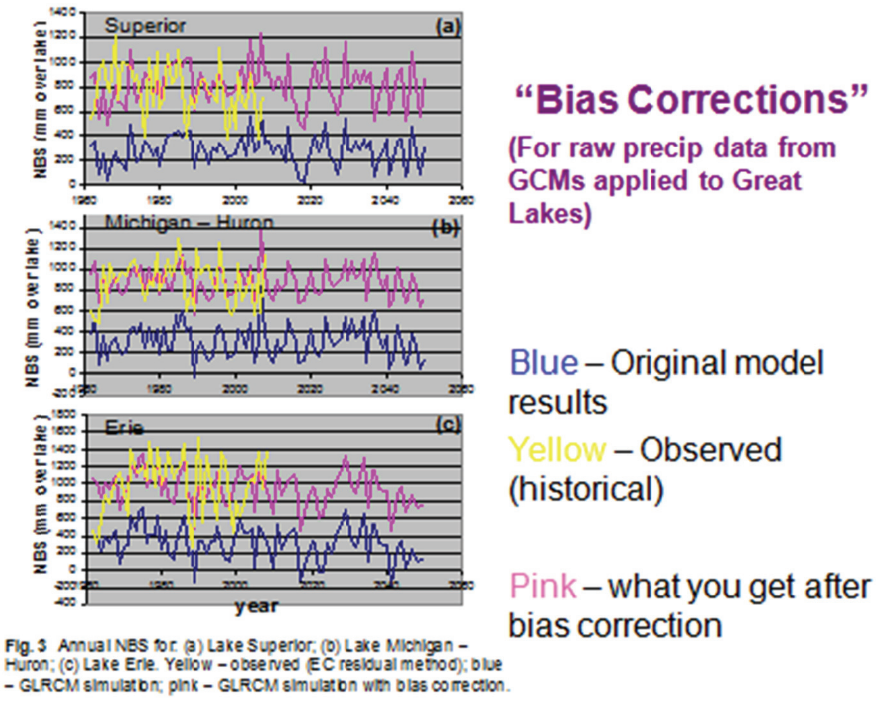
Source: Figures 4.4-1, 4.4-2, and 4.4-3 in IUGLS (n.d.).

Therefore, the best approach to making decisions is to not greatly rely on uncertain assumptions of the future.

Evaluating the myriad of alternative plans. A series of Shared Vision Models (SVMs) were created to model and evaluate the impacts of different regulation plans under different climate scenarios. A SVM dynamically links water management decisions to impacts and is trusted and understood well enough to minimize conflicts over facts. Model design was driven by the IUGLS Study Board criteria for selecting a new regulation plan, using information available during the IUGLS. The evolution of the SVM was dynamically linked to both the Study Board's criteria and their research agenda, each of the three elements influencing the others. The first SVM was created before information was available in order to shape the debate around what criteria to use and whether the research agenda would develop the information required for the Study Board to make its decision.

The Study's innovations in decision making under uncertainty. The main innovation was the application of an evaluation process termed *decision scaling* that inherently dealt with the basic decision making dilemmas associated with many sources of uncertainties–in particular, the concatenation of uncertainties engendered by a suite of interrelated sources of hydroclimatological data and modeling. Even though the Great Lakes are a relatively well-studied system, many unforeseen uncertainties emerged in much of the data and modeling that is routinely used for hydrologic and hydraulic analysis. A great deal of effort and resources were expended on upgrading the information base and all of the principal models that had been used for decision making. This was further exacerbated by the much larger uncertainties associated with GCMs–first in the bias corrections, and then in downscaling information to the region (See Figure A-2). Yet, decisions about the relative robustness and effectiveness of alternative regulation plans had to be made by the Board.

Climate modeling. To fully encompass estimates of the future climate of the Great Lakes, the Study first evaluated output of 565 model runs from 23 GCMs compiled by Angel and Kunkel (2010). The model runs utilized future emission scenarios B1, A1B and A2, representing relatively low, moderate and high emissions, respectively. Scenario A2 corresponds most closely to recent experience and International Energy Agency projections (International Energy Agency, 2007). The Study considered both the validity of the model runs and the applicability of utilizing the entire data set or a subset of the runs. The analysis used the Great Lakes Environmental Research Laboratory (GLERL) model to calculate NBS and lake levels for the current climate (covering 1970 to1999), using the input variables of maximum, minimum, and mean temperature, precipitation, humidity, wind speed and solar radiation. For each of the GCM runs, change functions expressed as the difference between the current climate and each of the future time slices (2005-2034, 2035-2064, 2065-2094) were calculated.



"Bias Corrections"

(For raw precip data from GCMs applied to Great Lakes)

Blue – Original model results

Yellow – Observed (historical)

Pink – what you get after bias correction

Fig. 3 Annual NBS for: (a) Lake Superior; (b) Lake Michigan – Huron; (c) Lake Erie. Yellow – observed (EC residual method); blue – GLRCM simulation; pink – GLRCM simulation with bias correction.

Figure A.2. Annual Net Basin Supply for (a) Lake Superior; (b) Lake Michigan – Huron; and (c) Lake Erie. Yellow – observed (EC residual method); blue – Great Lakes Regional Climate Model (GLCRM) simulation; pink – GLRCM simulation with bias correction.
Source: Figure 3 in IUGLS (n.d.).

In addition, it was noted that the results of the simulations varied widely for a single model, depending on the starting boundary conditions. Only a small number of models were run successively to determine the sensitivity and internal variability of model runs on initial conditions. Finally, in order to convert the precipitation forecasts for each model, a considerable degree of bias correction was needed, often by a factor of five or six, to convert the projections to current values. The bias-corrected precipitation then had to be routed through the GLERL model and then the coordinated Great Lakes routing model.

As well, two regional climate models (RCM) were utilized to downscale possible global climate scenarios and derive and assess current and possible future water supply sequences. The method used to accomplish this was a standard nested modeling approach, forcing the established United States and Canadian regional climate models, Coupled Hydrologic Atmospheric Research Model (CHARM) and the Canadian Regional Climate Model (CRCM), respectively, by using several GCMs to provide boundary conditions. In this way, the interaction between the lakes and the atmosphere can be taken into account in interpolating the results from the GCMs, as opposed to using statistical methods to derive important climate forcing that will impact the water cycle. A set of possible future states of the climate system was derived using these methods.

The traditional approach—that of perturbing observed sequences of climate variables with fixed ratios or differences derived directly from GCMs for conceptual runoff and evaporation modeling—may not capture important land surface-atmosphere feedback processes. This is particularly problematic for large bodies of water such as the Great Lakes (Mackay and Seglenieks, 2011). The Study evaluated dynamical downscaling using series GCMs boundary conditions with the Canadian RCM (CRCM) nested within these GCMs. The CRCM runs consisted of two different approaches: a multi-model, multi-member "ensemble" approach based on data from eight simulations of the CRCM driven by three different GCMs, and a high-resolution approach in which one of the eight simulations was further downscaled using a variant of the CRCM known locally as the Great Lakes Canadian Regional Climate Model (GL-CRCM), developed for the Study.

Dealing with irreducible uncertainties. The Study developed an *Adaptive Management Strategy* for dealing with extreme water levels associated with climate uncertainties that would be outside of our ability to regulate lake levels (see Figure A.3). By its nature, lake regulation is highly flexible and is compatible with adaptive management principles in that operating rules can be relatively easily adjusted as climate variables change and better information becomes available. This adaptive management strategy can help decision makers anticipate and respond to future extreme water levels.

Figure A.3. Elements of an Adaptive Management Strategy
Source: Figure 9.6 in IUGLS (2012).

Adaptive management is a planning process that provides a structured, iterative approach for improving actions through long-term monitoring, modeling and assessment. It allows decisions to be reviewed, adjusted and revised as new information and knowledge becomes available or as conditions change.

Recommendations. The following are six core initiatives for a long-term adaptive management strategy proposed by the Study Board to address future extreme water levels in the Great Lakes-St. Lawrence River basin:

- strengthen hydroclimatic monitoring and modeling
- conduct ongoing risk assessment
- ensure more comprehensive information management and outreach
- improve tools and processes for decision-makers to evaluate their actions
- establish a collaborative regional adaptive management study to address water-level extremes
- promote the integration of water quality and quantity modeling and activities.

Appendix B: Exploring Flood Nonstationarity in the Southeast and Mid-Atlantic Regions of the United States

Flood Frequency Analysis (FFA) provides important guidance for infrastructure planning and design, as well as for disaster preparedness. Conventional estimation methods assume that annual peak flows remain stationary, even as nonstationarity has long been recognized (Barros and Evans, 1997; Milly et al. 2008). Another constraint in FFA is the lack of sufficiently long observational records and the intermittency in the spatial and temporal configuration of the observing system of stream gauges over time. According to the USGS (United States Geological Survey) database, the Southeast United States has only 47 stations with more than 100 years of record, while 7,000 stations have fewer than 25 years of record. In addition to climate, flood risk is strongly linked to land-use and land-cover (LULC) patterns (Hollis, 1975; Villarini et al. 2009; Gilroy et al. 2012). Large contrasts in LULC and landscape geomorphology result in large spatial nonstationarity. For example, Brun and Barros (2013) showed strong differences between flood climatology associated with the passage of hurricanes and tropical storms in rural and suburban watersheds in the Piedmont (return periods on the order 2–5 years), contrasting with large response in urban areas and mountain catchments (equivalent return periods greater than 20 and up to 60 years).

To illustrate various aspects of nonstationarity from the perspective of an engineering practitioner, four network configurations that remain fixed over a specific period of time in the Southeastern United States were used as reference networks (1990-2000, 1920-2010, 1950-2010, 1980-2010). Figure B.1 shows regional scale statistics for the 10-year event (Q10). Similar results could be shown for other return periods. For each reference network, there is an increase in the number of outliers with time. The increase in the numbers of outliers for the more recent reference networks is caused by increased urbanization and by the fact that new stream gauges (post-1950) are installed in rapidly urbanizing areas (on the outskirts of large cities) or where large infrastructure is being built—such as along highways similar to the clustering of early network outliers in the east-coast metropolitan corridor from New York to Washington D.C. in the beginning of the 20th century, and more recently, along the I-85 corridor as well as around Houston, Texas, among others (Figure B.2). The spatial distribution of outliers does not change over time, but there is local decadal variability consistent with population density and sometimes time-varying changes in LULC and local regulations independent of population increases.

The effect of record length and flow regulation on the estimation of the 100-year event (Q100) is illustrated in Figure B.3 for two very distinct locations: Mississippi River at St. Louis, and the Congaree River at Columbia in South Carolina. The FFA at St. Louis shows the high inter-decadal variability in the Q100 estimates as a function of record length: the longer the record length, the less variable the estimate as a function of time, and; the variability is larger with a

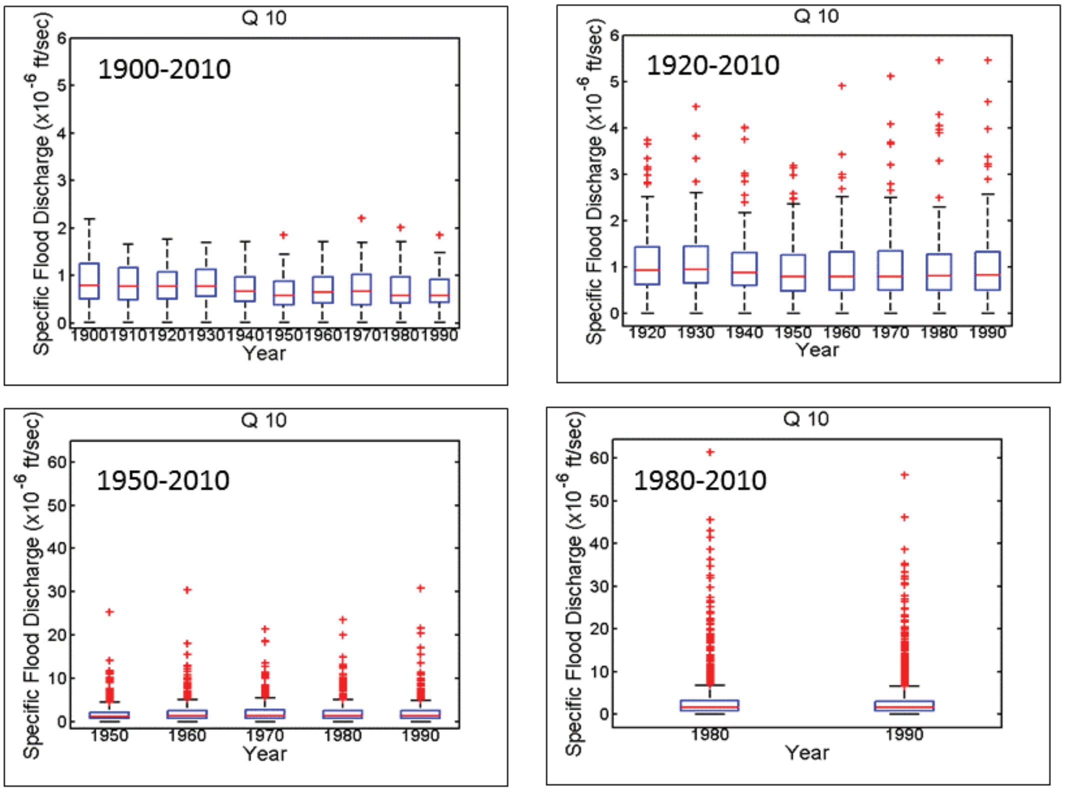


Figure B.1: Statistical characteristics of the Q10 event estimates (10-year return period) for each of the four reference networks. Note the change in scale by one order of magnitude between the two top and the two bottom panels.

Source: Figure 3 in Barros et al. (2014)

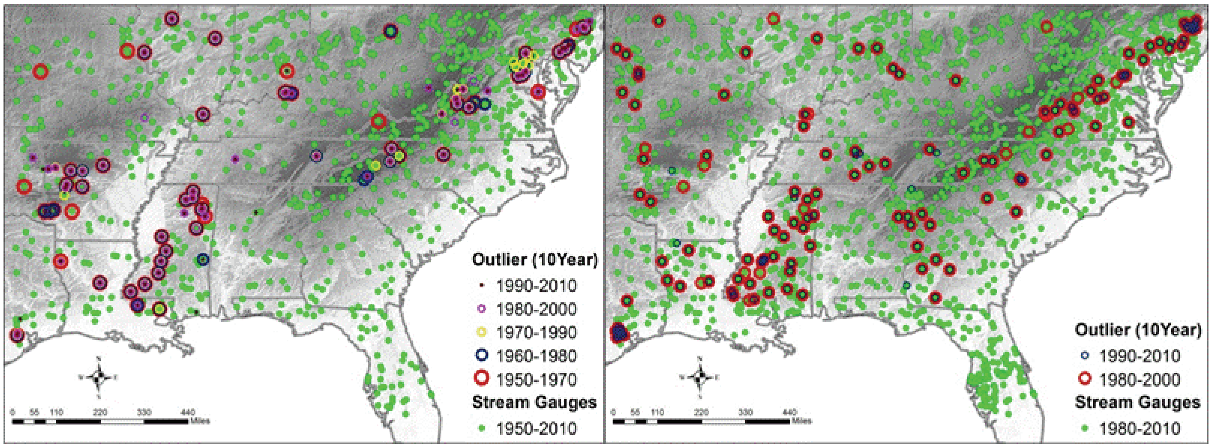


Figure B.2: Spatial variability of the outliers of the spatial distributions of Q10 for the 1950-2010 (left panel) and 1980-2010 (right panel) network configurations using an 20-year moving window.

Source: Adapted from Figure 5 in Barros et al. (2014).

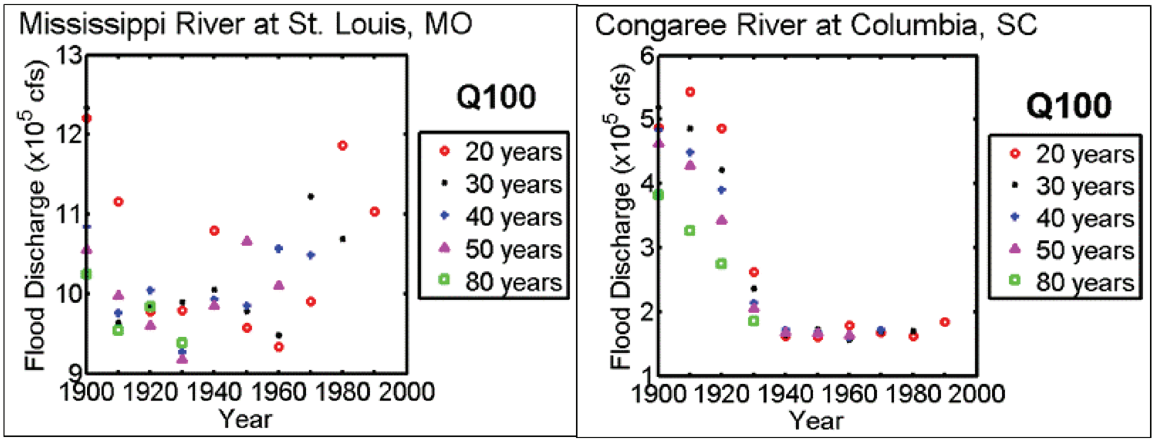


Figure B.3: Comparison of the sensitivity to record length (legend) and decadal variability of the estimates of Q100 at two locations without (left) and with (right) the effect of dam regulation for the 1900-2012 reference network.

Source: Adapted from Figure 9 in Barros et al. (2014).

positive trend after 1950 for all record lengths. By contrast, the Congaree FFA clearly shows the regulating effect of the upstream dam after 1940 and thus, fairly constant estimates of floods that do not depend on record length or decadal climate variability. A two-tail Mann-Kendall test was applied to characterize the trends in the annual stream-flow time series at the 98% confidence level (level of significance, α =0.02) shows generally no trend (not shown). This lack of trends in annual stream flow is consistent with results from Douglas and Barros (2003) for extreme precipitation that only showed significant trends in rainfall in coastal areas and occasionally in the mountains associated with the passage of tropical cyclones. Recently, Li et al. (2013) showed multi-decadal nonstationarity in the 2-4-year variability in warm season rainfall in the southeast U.S., which should have implications for the magnitude of bankfull events and urban flooding. Further research is necessary to attribute and distinguish specific quantitative changes in stream flow statistics due to climate forcing and also LULC change, and to infer their trends in the future.

For More Information

An extended version of Appendix B was published in the *Journal of Hydrologic Engineering* as Barros, A.P., Duan, Y., Brun, J., Medina, M.A., 2014: Flood Nonstationarity in the SE and Mid-Atlantic Regions of the United States. http://dx.doi.org/10.1061/(ASCE)HE.1943-5584.0000955.

Appendix C: U.S. Department of Transportation Gulf Coast Study, Phase 2

Project Background. The U.S. Department of Transportation (U.S. DOT) is conducting a comprehensive, multi-phase study of the Central Gulf Coast region to better understand climate change impacts on transportation infrastructure and to identify potential adaptation strategies. This region is home to a complex multimodal network of transportation infrastructure and several large population centers, and it plays a critical economic role in the import and export of oil and gas, agricultural products and other goods. Completed in 2008, Phase 1 of the Gulf Coast Study examined the impacts of climate change on transportation infrastructure at a regional scale.

Phase 2 (to be completed in 2014) focuses on a smaller region, enhancing regional decision makers' ability to understand potential impacts on specific critical components of infrastructure and to evaluate adaptation options. An important goal of Phase 2 is to develop methodologies that could be used by other transportation agencies to evaluate vulnerability and adaption measures. With that goal in mind, novel methodologies were developed and pilot tested on the transportation system in Mobile, Alabama.

This study evaluated the impacts on six transportation modes (highways, ports, airports, rail, transit and pipelines) from projected changes in temperature and precipitation, sea-level rise, and the storm surges and winds associated with more intense storms. Important products of this study include findings on Mobile's transportation vulnerability, approaches for evaluating vulnerability and adaptation options, and tools and resources that will assist other transportation agencies in conducting similar work.

Project highlights. Phase 2 of the Gulf Coast Study is notable for its development of the following:

- lessons learned about developing and using detailed, downscaled climate projection information
- methodologies to screen transportation assets for criticality and vulnerability
- approaches for conducting detailed engineering analyses on specific assets for a range of modes and climate stressors to better understand their specific vulnerabilities and options for adaptation
- tools to assist other transportation agencies in conducting similar assessments (The tools include: a web-based framework for evaluating vulnerability, with various videos, reports, and other resources to assist transportation practitioners at each stage of their assessments; an Excel-based Vulnerability Assessment Scoring Tool (VAST) to simplify

vulnerability assessments, and; a CMIP Data Processing Tool to "translate" projected changes in local temperature and precipitation into terms that are relevant to transportation stakeholders.)

*Approach to determine criticality***.** A single transportation system is comprised of many individual assets, which can number in the hundreds or thousands, depending on how those assets are defined. Because conducting a vulnerability assessment on such a large number of assets is not feasible, the study first identified which assets are considered highly critical. To determine vulnerability, the project team developed a scoring system that ranked each asset's criticality as high, medium or low. To do so, a set of criteria for evaluating criticality was developed. The specific criteria varied for each mode, but all criteria related to socioeconomic importance, use and operational characteristics, or the health and safety role in the community. These criteria were scored using methods ranging from statistics on use (such as volume of cargo throughput at a port), to traffic modeling to determine impact on the system if a particular segment becomes inaccessible, to expert judgment. The scores were then averaged to determine an overall criticality score.

Approach to develop climate information. It is important to understand how the climate may change before evaluating vulnerability or adaptation. Therefore, the project developed climate information to characterize plausible future climate scenarios in Mobile. Table C.1 summarizes the climate variables, scenarios and timeframes used for projecting future climate conditions in Mobile.

A key feature of the approach for temperature and precipitation was data presentation in terms of the short-term extreme events that are more relevant to transportation practitioners than longer-term averages. For example, the amount of rain falling within a 24-hour period during a 100-year event is more likely to indicate potential impacts to transportation infrastructure than seasonal or monthly precipitation averages.

Approach to screen critical assets for vulnerability. Several hundred assets were considered to be highly critical, and detailed vulnerability assessments could not be conducted on each asset. Therefore, this study identified appropriate "indicators" of the three components of vulnerability: exposure, sensitivity and adaptive capacity. These indicators are characteristics of an asset that may suggest the asset would be or would not be exposed, be or not be sensitive or have or not have adaptive capacity to the projected changes in climate. Indicators were scored on a scale of 1 to 4, and then a composite vulnerability score was calculated for each asset (see Figure C.1).

Conduct engineering assessments of selected vulnerable assets. The project team then took a closer look at a small subset of the transportation assets thought likely to be vulnerable. Zeroing in on a specific feature of the asset (such as the embankment of a roadway) and a particular climate stressor (such as storm surge), these detailed analyses considered the engineering design specifications and evaluated how the asset might be vulnerable to the climate stressor. Evaluations of specific potential adaptation options were also conducted. This work represents some of the most detailed assessments to date of transportation vulnerability and adaptation for a wide range of transportation assets. Each of these analyses comprises an individual case study based on unique methodologies and results.

Table C.1: Summary of Projected Climate Information Developed Under Phase 2 of the Gulf Coast Study

Climate Variable	Scenarios	Timeframes	Approach
Temperature	B1, A2, and A1Fi emissions scenarios	2010-2039 (near-term) 2040-2069 (mid-term) 2070-2099 (end-of-century)	Projections statistically downscaled from a variety of global climate model outputs, and compared to the current baseline to estimate change. Results were conveyed in terms that represent shorter-term extremes, such as number of days above 95 degrees instead of average seasonal temperature.
Precipitation & Runoff	B1, A2, and A1Fi emissions scenarios	2010-2039 (near-term) 2040-2069 (mid-term) 2070-2099 (end-of-century)	Precipitation projections calculated using the same approach for temperature. Monthly stream flow projections were developed using a monthly water balance model (WBM) driven by Mobile-specific information and using the projected precipitation values.
Sea Level Rise	30 cm (1 ft) of global sea level rise by 2050, and 75 cm (2.5 ft) and 200 cm (6.6 ft) of global sea-level rise by 2100		Global sea-level rise values were adjusted based on local subsidence and uplift of land.
Storm Surge and Wind	Two historical storms (Katrina and Georges) modeled with different trajectories, intensities and sea level	Not applicable	11 scenarios were developed using Hurricane Georges and Hurricane Katrina as base storms, and then certain characteristics of the storm parameters were adjusted to simulate what could happen under alternate conditions. Using these storm scenarios, storm surge was modeled using the ADvanced CIRculation model (ADCIRC). ADCIRC also provided estimates of wind speeds. Wave characteristics were simulated using the STeady State spectral WAVE (STWAVE) model.

Source: Table from FHWA (2014).

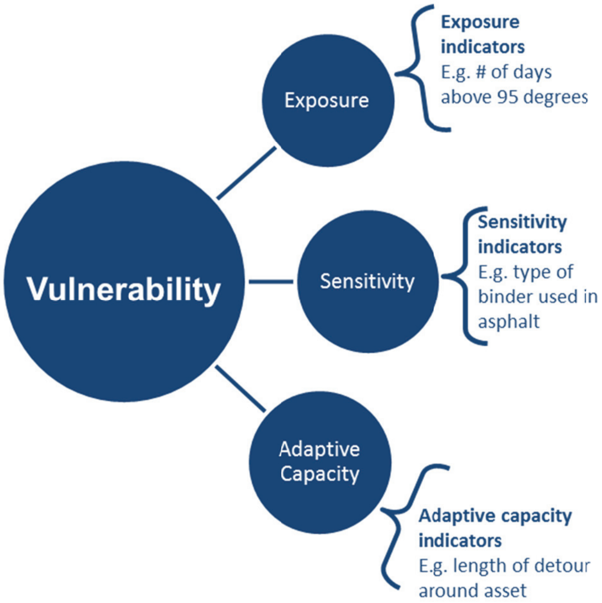


Figure C.1: Using Indicators to Assess the Three Components of Vulnerability
Source: Figure 2 in FHWA (2014).

Key findings of Mobile's transportation vulnerability to climate change. The vulnerability analysis found that storm surge and sea-level rise appear to pose the greatest threat to Mobile's transportation system (see Figure C.2 as an example). Overall, vulnerabilities tended to be greatest near the coast, due in part to the role of sea-level rise and storm surge in overall transportation system vulnerabilities, the fact that a lot of transportation infrastructure is concentrated near the Bay and Mobile River, and the fact that the coastal areas tended to be more low-lying and thus more vulnerable to not only sea-level rise and storm surge but also precipitation.

The following are specific findings for each of the transportation modes:

- **Highways** appear to be particularly vulnerable to storm surge and sea-level rise, due in part to the fact that a lot of critical highways would be exposed and sensitive to storm surge and sea-level rise.
- The **port and marine waterway system** in Mobile is highly vulnerable to storm surge and moderately vulnerable to sea-level rise and increases in precipitation.
- A**irports** appear to be particularly vulnerable to temperature, due to sensitivity of runways and taxiways to damage from heat. The Mobile Regional Airport is too far inland to be exposed to sea-level rise and storm surge; meanwhile, although the Downtown Airport is located directly on the coast, its high elevation prevents it from being exposed to sea-level rise and most storm surges.
- **Rail lines** in Mobile appear to be especially vulnerable to sea-level rise and storm surge.

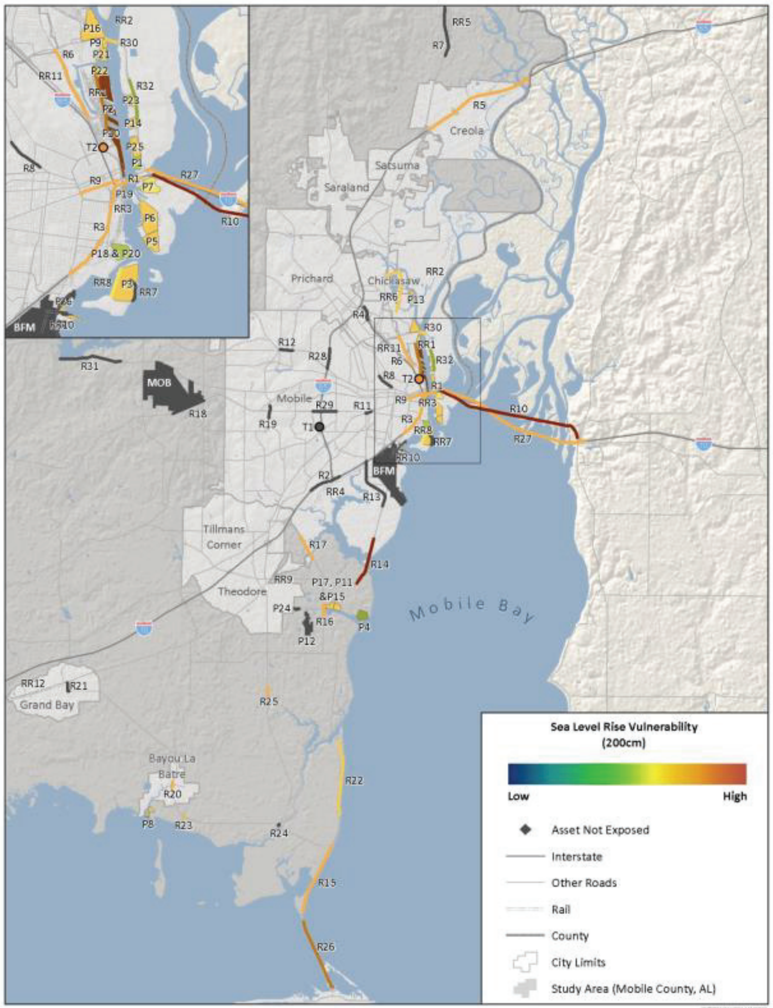


Figure C.2: Geographic Distribution of Vulnerabilities of Representative Assets to Sea Level Rise of 2.0 meters (6.6 feet), All Modes
Source: Figure 3 in FHWA (2014).

- For **transit**, only one of the critical facilities (the GM&O facility) was exposed to sea-level rise and storm surge, and it was highly vulnerable to those climate stressors. Meanwhile, the Beltline facility, which is situated inland, is particularly vulnerable to wind damage during major storms.

Example opportunities for adaptation. The engineering assessments evaluated different adaptation options. The following are examples:

- For a culvert on Airport Boulevard that would not meet ALDOT design standards under future precipitation levels, adding one cell on each side of the existing crossing would be the most cost-effective way to bring the culvert into compliance with ALDOT standards.

- The Cochrane Bridge is high enough that sea-level rise would not overtop the bridge or its approaches, but sea-level rise could reduce the vertical clearance over the river enough that larger ships may not be able to pass under it. Structural solutions to deal with this challenge include raising the bridge deck or retrofitting it to have moveable spans. The impacts of sea-level rise are far enough into the future that it would be reasonable to wait until major rehabilitation of the bridge is warranted for other reasons, rather than making costly retrofits now. A non-structural approach would be to undertake community-planning actions to prepare for a future where large ships could not navigate the Mobile River past the Cochrane Bridge.
- In the case of at least one bridge, the bridge abutments themselves were not designed to withstand modeled storm surge and waves, but the protection offered by their riprap, bulkhead and willow mattresses should make them sufficiently able to withstand modeled surges. Thus, it is important that maintenance of these protective structures is given as much attention as maintenance of the structures themselves.

Lessons learned. Throughout the study, important methodology lessons were learned, including: Stakeholder input is essential for identifying assets that are culturally important to the community. A quantitative criticality assessment that focuses on use, role in the economy, access to medical or job facilities, and other highly specific factors may undervalue assets that are important to the community for less tangible and quantifiable reasons. Similarly, it is important to ground-truth any desk study with the transportation officials who manage the assets. Short-term, extreme events (such as short periods of intense rain) are usually more applicable to transportation managers than longer-term averages (such as average seasonal rainfall). Even then, it is challenging to put climate projections into terms that resonate with engineers. For example, engineers might consider precipitation values over a 30-minute timeframe, but climate projections cannot be developed with that precision.

Additional guidance is needed for incorporating climate projection data into engineering design. Engineering design can be greatly influenced by the assumed values of future climate data, so the uncertainty surrounding plausible future climate data ranges is challenging for engineers to reconcile. Furthermore, climate projection data is often expressed in terms that are different than terms used by transportation engineers. For example, storm surges are expressed in terms of feet or meters and no probability is assigned, but engineers design for recurrence probability of storm events (e.g. the 20-year storm or the 100-year storm).

While it is important to understand how the climate may change in the future, it is not necessarily essential to have comprehensive data sets of climate projections to complete a vulnerability assessment. Attempting to articulate climate projections from multiple emissions, sea-level rise or storm scenarios, or for multiple timeframes and using multiple models, can result in an extremely large dataset. Furthermore, each of these data points is as likely as the others to accurately portray what really happens in the future. It is therefore important to be able to concisely convey projected changes in climate in terms that are understandable to transportation practitioners, but that are also grounded in good science. Using climate narratives to bound the range of plausible changes in climate, and focusing on a small number of climate exposure indicators, is sufficient for conducting a vulnerability assessment. The use of indicators can provide a good starting point for screening assets. Indicators can draw on existing data that is well known to planners and decision makers. Quantitative scoring systems are useful for screening assets, but care needs to be taken to ensure that the scoring system does not skew results toward or away from certain types of assets. For example:

- Some criteria (e.g., designated evacuation routes) should automatically trigger a "highly critical" designation for an asset. The criticality of these assets could be unduly diluted when considering other criticality factors as well.
- Cost information can be informative regarding the adaptive capacity of assets, but can skew results toward expensive assets.
- Some indicators may be more important than others, and some may be very similar to other indicators. Careful consideration needs to be given to ensure indicators are evenly weighted.

Risk management tools and resources. Tools, case studies, videos, background information and other resources to assist transportation agencies in conducting similar assessments and in managing their identified risks were developed. They are available at http://www.fhwa.dot.gov/environment/climate_change/adaptation/ . This web-based portal houses a multitude of resources (including the ones mentioned below) for transportation practitioners wishing to conduct vulnerability assessments and conduction adaptation planning activities.

Resources include:

- *Vulnerability Assessment Scoring Tool (VAST):* An Excel-based tool that serves as a framework for conducting a quantitative, indicator-based vulnerability screen. The tool is intended for state DOTs and MPOs interested in assessing how components of their transportation system may be vulnerable to climate stressors–including, but not limited to, changes in temperature, changes in heavy precipitation, sea-level rise and severe storms.
- *Sensitivity Matrix:* Information on the sensitivity of transportation infrastructure components to different climate effects, built into an easy-to-use Excel interface.
- *CMIP Climate Data Processing Tool:* An Excel-based tool that pulls the best available climate model information and translates outputs into terms that are relevant to decision makers (e.g., frequencies of extremes).

For More Information

Gulf Coast Study:
http://www.fhwa.dot.gov/environment/climate_change/adaptation/ongoing_and_current_research/gulf_coast_study/

Contacts:
Robert Hyman
Sustainable Transport and Climate Change Team
Federal Highway Administration
robert.hyman@dot.gov, 202-366-5843

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