Water: The Potential Consequences of Climate Variability and Change for the Water Resources of the United States

The Report of the Water Sector Assessment Team
of the National Assessment of the Potential Consequences of
Climate Variability and Change

For the U.S. Global Change Research Program

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About the National Assessment

The Earth's climate is intrinsic to everything important to society – the production of food and energy, human and ecosystem health, the functioning and characteristics of the hydrologic cycle, and much more. Natural and human-induced changes in the Earth's climate will thus have widespread implications for society. The National Assessment of Potential Consequences of Climate Variability and Change for the United States ("the National Assessment") was designed to begin the complex process of assessing how to respond and adapt to an uncertain and changing climate. The National Assessment was called for by the 1990 Global Change Research Act (Public Law 101-606) and has been conducted under a plan approved by the National Science and Technology Council – the cabinet-level body of agencies responsible for scientific research in the U.S. government.

The Global Change Research Act gave voice to early scientific findings that human activities were starting to change the global climate:

> "(1) Industrial, agricultural, and other human activities, coupled with an expanding world population, are contributing to processes of global change that may significantly alter the Earth habitat within a few generations; (2) Such human-induced changes, in conjunction with natural fluctuations, may lead to significant global warming and thus alter world climate patterns and increase global sea levels. Over the next century, these consequences could adversely affect world agricultural and marine production, coastal habitability, biological diversity, human health, and global economic and social well-being."

To address these issues, Congress established the U.S. Global Change Research Program (USGCRP) and instructed Federal research agencies to cooperate in developing and coordinating a "comprehensive and integrated United States research program which will assist the Nation and the world to understand, assess, predict, and respond to human-induced and natural processes of global change." Further, the Congress mandated that the USGCRP

> "shall prepare and submit to the President and the Congress an assessment which
>
> > 1) integrates, evaluates, and interprets the findings of the Program and discusses the scientific uncertainties associated with such findings;
> > 2) analyzes the effects of global change on the natural environment, agriculture, energy production and use, land and water resources, transportation, human health and welfare, human social systems, and biological diversity; and

> 3) analyzes current trends in global change, both human-induced and natural, and projects major trends for the subsequent 25 to 100 years."

The USGCRP's National Assessment of the Potential Consequences of Climate Variability and Change is being conducted under the provisions of this Act.

The overall goal of the National Assessment is to analyze and evaluate what is known about the potential consequences of climate variability and change for the Nation in the context of other pressures on the public, the environment, and the Nation's resources. It is also addressing the question about why we should care about, and how we might effectively prepare for, climate variability and change. The National Assessment process has been broadly inclusive, drawing on inputs from academia, government, the public and private sectors, and interested citizens. Starting with public concerns about the environment, the Assessment is exploring the degree to which existing and future variations and changes in climate might affect issues that people care about. A short list of questions has guided the process as the Assessment has focused closely on regional concerns around the U.S. and national concerns for particular sectors:

- What are the current environmental stresses and issues that form the backdrop for potential additional impacts of climate change?

- How might climate variability and change exacerbate or ameliorate existing problems? What new problems and issues might arise?

- What are the priority research and information needs that can better prepare the public and policymakers for reaching informed decisions related to climate variability and change? What research is most important to complete over the short term? Over the long term?

- What coping options exist that can build resilience to current environmental stresses, and also possibly lessen the impacts of climate change?

The National Assessment has three major components:

1. Regional analysis: Regional workshops and assessments are characterizing the potential consequences of climate variability and change in regions spanning the United States. A total of 20 workshops were held around the country, with the Native Peoples/Native Homelands workshops being national in scope rather than regional. Based on the issues identified, 16 of these groups have been supported to prepare assessment reports. The reports from these activities address the issues of most interest to those in the particular regions by focusing on the regional patterns and texture of changes where people live. Most workshop reports are already available (see http://www.nacc.usgcrp.gov).

2. Sectoral analysis: Workshops and assessments are also being carried out to characterize the potential consequences of climate variability and change for major sectors that cut across environmental, economic, and societal interest. The sectoral studies analyze how the consequences in each region affect the nation, making these reports national

in scope and of interest to everyone. The sectors being focused on in this first phase of the ongoing National Assessment include Agriculture, Forests, Human Health, Coastal Areas and Marine Resources, and in this report, Water. Final sector assessment reports are now starting to become available.

3. National overview: The National Assessment Synthesis Team has responsibility for providing a national perspective that summarizes and integrates the findings emerging from the regional and sectoral studies and that then draws conclusions about the importance of the consequences of climate change and variability for the United States. The draft synthesis report was released for public comment in June 2000 and the final will be published in the Fall 2000.

Each of the regional, sectoral, and synthesis activities is being led by a team comprised of experts from both the public and private sectors, from universities and government, and from the spectrum of stakeholder communities. All of the reports are going through an extensive review process involving experts and other interested stakeholders. The assessment process is supported in a shared manner by the set of USGCRP agencies, including the departments of Agriculture, Commerce (National Oceanic and Atmospheric Administration), Energy, Health and Human Services, and Interior, plus the Environmental Protection Agency, National Aeronautics and Space Administration, and the National Science Foundation. Through this involvement, the USGCRP is hopeful that broad understanding of the issue and its importance for the nation will be gained and that the full range of perspectives about how best to respond will be aired.

Extensive information about the National Assessment, names of participants on the various assessment teams and groups, and links to the activities of the various regions and sectors are available over the Web at http://www.nacc.usgcrp.gov or by inquiry to the Global Change Research Information Office, PO Box 1000, 61 Route 9W, Palisades, New York 10964.

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Executive Summary of the
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Introduction

The water resources of the United States of America, like the water anywhere on the planet, are an integral part of the global hydrologic cycle. Precipitation originates as evaporation from land and the oceans. Soil moisture is used by plants, which return more moisture to the atmosphere. Water that does not evaporate or transpire or seep into aquifers runs off to form the nation's streams and rivers. Snow stored in winter in the mountains provides water for rivers and deltas in the spring and summer. Storms bring extra moisture; droughts arise from protracted periods of low rainfall – all as part of our natural climate.

Over the past century, the United States has built a vast and complex infrastructure to provide clean water for drinking and for industry, dispose of wastes, facilitate transportation, generate electricity, irrigate crops, and reduce the risks of floods and droughts. This infrastructure has brought tremendous benefits, albeit at a substantial economic and environmental cost. To the average citizen, the nation's dams, aqueducts, reservoirs, treatment plants, and pipes are largely invisible and taken for granted. Yet they help insulate us from wet and dry years and moderate other aspects of our naturally variable climate. Indeed they have permitted us to almost forget about our complex dependences on climate. We can no longer ignore these close connections.

The scientific evidence that humans are changing the climate is increasingly compelling. Complex impacts affecting every sector of society, including, especially, the nation's water resources, now seem unavoidable.

This report summarizes the conclusions of the substantial body of literature on the implications of both existing climate variability and future climate change for U.S. water resources. We have identified nearly 1,000 relevant peer-reviewed studies, and that number grows larger every day. As a result, this report must be considered just a snapshot in time, a summary of what we think we know, do not know, and would like to know at the beginning of the 21st century. In the coming years, we hope and expect that our understanding of the impacts of climate changes for U.S. water resources will improve, as will our understanding of the ability of existing and new technologies, policies, economic tools, and institutions to help us mitigate and adapt to those impacts.

Many uncertainties remain; indeed, we expect that uncertainties will always remain. The nature and intensity of future greenhouse gas emissions depend upon future decisions of governments and individuals, the speed of deployment of alternative energy systems, population sizes and affluence, and many more factors. The models that simulate the role of these gases in our atmosphere are imperfect. There are significant limitations in the ability of climate models to incorporate and reproduce important aspects of the hydrologic cycle. Many fundamental hydrologic processes, such as the formation and distribution of clouds and precipitation, occur on a spatial scale smaller than most climate models are able to resolve. Regional data on water availability and use are often poor. Tools for quantifying many impacts are imperfect, at best. We thus know much less about how the water cycle will change than we would like in order to make appropriate decisions about how to plan, manage, and operate water systems.

At the same time, not everything is uncertain. The research done to date tells us many things, both positive and negative, about how hydrology and U.S. water resources could be affected by climate variability and changes. We have learned important things about the vulnerability and sensitivity of water systems and management rules, and we are exploring the strengths and weaknesses of technologies and policies that might help us cope with adverse impacts and take advantage of possible beneficial effects.

In many cases and in many locations, there is compelling scientific evidence that climate changes will pose serious challenges to our water systems. The good news is that where climate changes are minor or where other factors dominate, the impacts on U.S. water resources may be low. In some regions and for some issues, climate changes may even reduce the risks and stresses imposed by growing populations, industrialization, and land-use changes. The bad news is that a growing body of evidence suggests that certain aspects of our water resources are very sensitive to both climate and to how we choose to manage our complex water systems. Making changes in management of these systems requires understanding what changes would be most effective and then applying the will and direction of those responsible. Coping or mitigating other kinds of impacts, even if possible, may prove very costly in dollars, environmental health, and even human lives.

We also note that most impacts studies have been done using information from global climate models that evaluate the effects of increases in greenhouse gas concentrations up to particular levels. At this point in time, there is no reason to believe that increasing concentrations will stop at these levels. Greater and greater impacts would be expected to result from ever increasing levels of climate change.

It is vital that uncertainties not be used to delay or avoid taking certain kinds of action now. Prudent planning requires that a strong national climate and water research program be maintained, that decisions about future water planning and management be flexible, and that the risks and benefits of climate change be incorporated into all long-term water planning. Rigid, expensive, and irreversible actions in climate-sensitive areas can increase vulnerability and long-term costs. Water managers and policymakers must start considering climate change as a factor in all decisions about water investments and the operation of existing facilities and systems.

A continued reliance solely on current engineering practice may lead us to make incorrect – and potentially dangerous or expensive – decisions. The United States has hundreds of billions of dollars invested in dams, reservoirs, aqueducts, water-treatment facilities, and other concrete structures. These systems were designed and for the most part are operated assuming that future climatic and hydrologic conditions will look like past conditions. We now know this is no longer true. Accordingly, two of the most important coping strategies must be to try to understand what the consequences of climate change will be for water resources and to begin planning for and adapting to those changes.

Conclusions

More than two decades of research into the implications of climate change for water resources have improved our understanding of possible impacts and points of vulnerability. Many critical issues and some clear and consistent results have been identified. Taken together, the current state-of-the-science suggests a wide range of concerns that should be addressed by national and local water managers and planners, climatologists, hydrologists, policymakers, and the public. Many climate changes are expected. We summarize below some of those with the greatest implications for the hydrologic cycle and U.S. water resources, using a consistent set of terms to denote levels of confidence. Sidebar ES-1 lists the common terms of uncertainty used here.

The Nature of Expected Climate Changes

- Global-average and U.S.-average surface temperatures will continue to increase above recent historical levels unless there are substantial changes in both U.S. and international energy and land-use patterns (very high confidence). As greenhouse-gas emissions continue into the future, the size of these temperature increases will become larger over time.

Sidebar ES-1:
Measuring and Reporting Uncertainties

There are many different ways of assessing, defining, and describing uncertainties. Below we list two quantitative approaches and two qualitative approaches that have helped guide this assessment. The terms used in the text were adopted from these scales, but we note that much more work is needed to both reduce the overall uncertainties about the effects of climate change as well as to better describe the uncertainties that will inevitably remain.

Quantitative Scales for Assessing Uncertainties

IPCC Confidence Terms	Probability or Confidence Limit
Very High Confidence	1.00 to 0.95
High Confidence	0.95 to 0.67
Medium Confidence	0.67 to 0.33
Low Confidence	0.33 to 0.05
Very Low Confidence	0.05 to 0.00

Source: Moss and Schneider (1999).

Common Language Terms	Probability or Confidence Limit
Very likely or very probable	>90%
Likely or probable	67 to 90%
Possible	34 to 66%
Unlikely or some chance	10 to 33%
Little chance or very unlikely	< 10%

Source: USGCRP (2000).

Qualitative Scales for Assessing Uncertainties

Qualitative Terms (three levels)	
High Confidence	Wide agreement, multiple findings, high degree of consensus, considerable evidence
Medium Confidence	Consensus, fair amount of information, other hypotheses cannot be ruled out conclusively
Low Confidence	Lack of consensus, serious competing ideas, limited evidence in support

Source: IPCC (1996b).

Qualitative Terms (four levels)	
Well established	Multiple lines of evidence, models consistent with observations
Established but incomplete	Models incorporate most known processes, one or more lines of evidence, observations somewhat consistent but incomplete
Competing explanations	Different models produce different results or incorporate different key processes
Speculative	Conceptually plausible ideas that have received little attention, or that are laced with difficult-to-reduce uncertainties

Source: Moss and Schneider (1999).

- The regional and seasonal pattern of temperature increases across the U.S. will vary (very high confidence). Researchers have low confidence in estimates of detailed regional departures from these larger-scale changes.

- As atmospheric greenhouse-gas concentrations continue to rise, global average precipitation will increase (very high confidence).

- There will be changes in the timing and regional patterns of precipitation (very high confidence). Researchers have low confidence in projections for specific regions because different models produce different detailed regional results.

- Temperature increases in mountainous areas with seasonal snowpack will lead to increases in the ratio of rain to snow and decreases in the length of the snow storage season (very high confidence). It is likely that reductions in snowfall and earlier snowmelt and runoff would increase the probability of flooding early in the year and reduce the runoff of water during late spring and summer. Basins in the western United States are particularly vulnerable to such shifts.

- Average precipitation will increase in higher latitudes, particularly in winter (high confidence). Models are inconsistent in other estimates of how the seasonality of precipitation will change.

- Increases in annual average runoff in the high latitudes caused by higher precipitation are likely to occur (high confidence).

- Research results suggest that flood frequencies in some areas are likely to change. In northern latitudes and snowmelt-driven basins, research results suggest with medium confidence that flood frequencies will increase, although the amount of increase for any given climate scenario is uncertain and impacts will vary among basins.

- Research results suggest that drought frequencies in some areas are likely to change. The net risks to society from such changes have not been evaluated and specific projections of where such changes will occur are speculative. Models project that the frequency and severity of droughts in some areas could increase as a result of regional decreases in total rainfall, more frequent dry spells, and higher evaporation. Models suggest with equal confidence that the frequency and severity of droughts in some regions would decrease as a result of regional increases in total rainfall and less frequent dry spells.

- Higher sea levels associated with thermal expansion of the oceans and increased melting of glaciers will push salt water further inland in rivers, deltas, and coastal aquifers (very high confidence). It is well understood that such advances would adversely affect the quality and quantity of freshwater supplies in many coastal areas.

- Water-quality problems will worsen where rising temperatures are the predominant climate change (high confidence). Where there are changes in flow, complex positive and negative changes in water quality will occur. Specific regional projections are not well-established at this time because of uncertainties in how regional flows will change.

- Increased atmospheric carbon dioxide will affect the use of water by vegetation (high confidence), but hydrologists have low confidence in the net effects of this and other competing influences. Increasing CO_2 concentrations in some circumstances can reduce the rate of transpiration from certain plants. This in turn would tend to increase runoff since less water is returned directly to the atmosphere by such vegetation, allowing a greater share of precipitation to reach streams or aquifers. Rising CO_2 concentrations can also increase plant growth, leading to a larger area of transpiring tissue and a corresponding increase in transpiration.

- The southern boundary of continuous permafrost is projected to shift north by 500 kilometers over the next 50 years due to warming projected by GCMs. A 5° C warming in Alaska would eventually melt virtually all of the subarctic permafrost in Alaska (medium confidence), which would affect more wetland area than currently found in the rest of the United States.

- While we note that some climate scenarios can produce conditions that might reduce stresses on certain ecosystems, experience with ecosystem dynamics strongly suggests that perturbing ecosystems in any direction away from the conditions under which they developed and thrive will have adverse impacts on the health of that system. Aquatic ecosystems can be highly sensitive to hydroclimatic factors, particularly water temperature, water quality, the probability of extreme events, and flow volumes, rates, and timing. Determining the impacts on particular species or ecosystems will require additional region-specific, and ecosystem-specific, research.

- Ecologists have high confidence that climate warming will produce a shift in species distributions northward, with extinctions and extirpations of temperate or cold-water species at lower latitudes, and range expansion of warm-water and cool-water species into higher latitudes.

- A growing number of studies suggest that climate changes will increase the frequency and intensity of the heaviest precipitation events, but there is little agreement on detailed regional changes in storminess that might occur in a warmed world.

- Contradictory results from models support the need for more research, especially to address the mismatch between the resolution of models and the scales at which extreme events can occur. This issue should be regularly revisited in later assessments.

What are the Major Impacts of Climate Variability and Change on U.S. Water Resources?

The current state-of-the-science suggests that plausible climate changes, projected by general circulation models, raise a wide range of concerns that should be addressed by national and local water managers and planners, climatologists, hydrologists, policymakers, and the public.

- Detailed estimates of changes in runoff due to climate change have been produced for the United States using regional hydrologic models of many specific river basins. In spite of many remaining uncertainties, model results suggest that some significant changes in the timing and amount of runoff will result from plausible changes in climatic variables (high confidence).

- With few exceptions, we have low confidence that we can determine specific changes for specific regions. In the arid and semi-arid western United States, it is well established that relatively modest changes in precipitation can have proportionally large impacts on runoff.

- Research indicates that U.S. watersheds with a substantial snowpack in winter will experience major changes in the timing and intensity of runoff as average temperatures rise (very high confidence). Reductions in spring and summer runoff, increases in winter runoff, and earlier peak runoff are all common responses to rising temperatures. The ability of existing systems and operating rules to manage these changes has not been adequately assessed.

- Research to date suggests that there is a risk of increased flooding in parts of the U.S. that experience large increases in precipitation (medium confidence). The Intergovernmental Panel on Climate Change concluded in 1996, and we concur, that: "the flood related consequences of climate change may be as serious and widely distributed as the adverse impacts of droughts" and "there is more evidence now that flooding is likely to become a larger problem in many temperate regions, requiring adaptations not only to droughts and chronic water shortages, but also to floods and associated damages, raising concerns about dam and levee failure."

- Non-linear or threshold events are likely to occur, but are difficult to project. Examples include a fall in lake level that cuts off outflows or separates a lake into two separate parts, an increase in flood intensity that passes specific damage thresholds, and exceedance of water-quality limits.

- Relative sea-level rise adversely affects groundwater aquifers and freshwater coastal ecosystems (high confidence). Rising sea level causes an increase in the intrusion of salt water into coastal aquifers. Shallow island aquifers (such as those found in Hawaii, Nantucket, Martha's Vineyard, and along the southeastern seaboard) together with coastal aquifers supporting large amounts of human use (such as those in Long Island, New York, and central coastal California) are at greatest risk. Other impacts of sea-level rise are likely to include changes in salinity distribution in estuaries, altered coastal circulation patterns, destruction of transportation infrastructure in low-lying areas, and increased pressure on coastal levee systems.

- Climate changes have the potential to alter water quality significantly by changing temperatures, flows, runoff rates and timing, and the ability of watersheds to assimilate wastes and pollutants. Global and regional increases in air temperature, and the associated increases in water temperature, are likely to lead to adverse changes in water quality, even in the absence of changes in precipitation. Changes in precipitation can lead to both positive and negative impacts on water quality. The net effect on water quality for rivers, lakes, and groundwater in the future depends not just on how climate might change but also on a wide range of other human actions.

- Lakes are known to be sensitive to a wide array of changes in climate. Even small changes in climate can produce large changes in lake levels and salinity. As air temperatures increase, fewer lakes and streams in high-latitude areas will freeze to the bottom and the number of ice-free days will increase, leading to increases in nutrient cycling and productivity. Other effects of increased temperature on lakes could include higher thermal stress for cold-water fish, improved habitat for warm-water fish, increased productivity and lower dissolved oxygen, and degraded water quality.

- The direct effects of climate change on freshwater ecosystems will be complex, depending on the nature of the change, the system affected, and the nature and scope of intentional interventions by humans. Work across the United States suggests a wide range of serious concerns for ecosystems, with changes in vegetation patterns, possible extinction of endemic fish species already close to their thermal limits, declining area of wetlands with reductions in waterfowl populations, concerns about stream health, and major habitat loss.

- Researchers express concern for the limited ability of natural ecosystems to adapt or cope with climate changes that occur over a short time frame. This limited ability to adapt to rapid changes may lead to irreversible impacts, such as extinctions. While some research has been done on these issues, far more is needed.

- Little work has been done on the impacts of climate change for specific groundwater basins, or for general groundwater recharge characteristics or water quality. Some studies suggest that some regional groundwater storage volumes are very sensitive to even modest changes in available recharge.

What are the Major Impacts of Climate Variability and Change on Managed U.S. Water Systems?

Climate change will affect the availability of water in the United States, as well as its quality, distribution, and form. Climate change will also affect the complex infrastructure and systems in place to manage the nation's water and existing climate variability. There is a growing literature about how different climate changes may affect the infrastructure and complex systems built to manage U.S. water resources (http://www.pacinst.org/CCBib.html). Research has been conducted on potential impacts over a wide range of water-system characteristics, including reservoir operations, hydroelectric generation, navigation, and other concerns. At the same time, significant knowledge gaps remain and far more research is needed. Priorities and directions for future work should come from water managers and planners as well as from the more traditional academic and scientific research community.

- Large changes in the reliability of water yields from reservoirs could result from small changes in inflows (high confidence).
- In some watersheds, long-term demand growth will have a greater impact on system performance than climate changes. Uncertainties in projecting future water demands complicate evaluating the relative effects of these two forces. Overall regional impacts will further depend upon the economic, institutional, and structural conditions in any region.
- Variability in climate already causes fluctuations in hydroelectric generation. Climate changes that reduce overall water availability will reduce the productivity of U.S. hydroelectric facilities. Reliable increases in average flows would increase hydropower production. Changes in the timing of hydroelectric generation can affect the value of the energy produced. Specific regional impacts are not well-established.
- Dynamic management strategies can be effective in mitigating the adverse impacts of climate change, but such policies need to be implemented before such changes occur to maximize their effectiveness.
- Climate change will play a role in power production from conventional fossil fuel and nuclear power plants by raising cooling water temperatures and reducing plant efficiencies (medium confidence). In some circumstances, higher water temperatures will constrain plant operations.
- Water-borne shipping and navigation are sensitive to changes in flows, water depth, ice formation, and other climatic factors. A warming would increase the potential length of the shipping season on some northern lakes and rivers that typically freeze in winter. Decreases in river flows could reduce the periods when navigation is possible, increase transportation costs, or increase the conflicts over water allocated for other purposes. Changes in storm frequency or intensity would affect Great Lakes navigation. Research done to date suggests that the net effects of climate change may be to increase shipping and navigation costs in the Great Lakes region (medium confidence).
- Research in specific watersheds has shown that some major U.S. river basins are so heavily developed, with such complicated overlapping management layers, that their ability to adapt to changes in climate may be compromised.

All of the physical and ecological impacts of climate change will entail social and economic costs and benefits. On top of the uncertainties in evaluating both climate change and potential impacts, evaluating the economic implications of the diverse impacts is fraught with additional difficulties, and few efforts to quantify them have been made. Ultimately, however, comprehensive efforts to evaluate costs will be necessary in order to assist policymakers and the public in understanding the implications of both taking and not taking actions to reduce or adapt to the impacts of climate change.

The socioeconomic impacts of a greenhouse warming look very different depending on which climate projections are used, and on the methods and assumptions adopted by the researchers. The results published to date are a valuable guide for future assessments but policymakers should have low confidence in specific quantitative estimates. Some results are described below:

- Even given the uncertainties, research indicates that the possible economic impacts of reductions in flow could be very large and that some U.S. water systems are highly sensitive to climate. Under some climate scenarios, the additional costs imposed by climate changes are considerably larger than the additional costs imposed by future population growth, industrial changes, and changing agricultural water demands.

- The contrasting hydrologic implications of the two climate models used for the National Assessment indicate that the direction and size of many socioeconomic impacts are uncertain and likely to vary among regions.

- The upper end of the costs on U.S. water resources imposed by climate changes described in some studies is on the order of 0.5 percent of the nation's total gross domestic product.

- There are many opportunities to adapt to changing hydrologic conditions, and the net costs are sensitive to the institutions that determine how water is managed and allocated among users.

Is Climate Change Already Affecting the Nation's Water Resources?

There is a very high degree of confidence in the scientific community that unchecked increases in atmospheric greenhouse-gas concentrations will eventually lead to changes in the Earth's climate, including the variability of that climate. Despite gaps in data, inadequate and uneven climate and hydrologic monitoring, short collection periods, and biases in instrumental records, there is an increasing amount of evidence that indicates some changes are already occurring.

The evidence that humans are changing the water cycle of the United States is increasingly compelling. Some of the observed changes with the most relevance for U.S. hydrology and water resources are summarized here:

- The United States has, on average, warmed by two-thirds of a degree C since 1900 (very high confidence).

- Permafrost in the Alaskan arctic is beginning to thaw (very high confidence).

- Mean sea level has risen between 10 and 20 centimeters since the 1890s (very high confidence).

- Mountain glaciers are melting at rates unprecedented in recorded history (high confidence).

- Arctic ice thickness has declined significantly from levels recorded in the mid-20th century (high confidence). A comparison of these trends with model estimates reveals that the observed decreases are similar to model projections and that both trends are much larger than would be expected from natural climate variability.

- Vegetation is blooming earlier in spring and summer and continuing to photosynthesize longer in the fall (medium confidence).

- Snow and ice cover are decreasing and melting earlier, on average, while total annual snowfall in the far northern latitudes is increasing (medium confidence). Field surveys show that snow cover over the Northern Hemisphere land surface since 1988 has been consistently below averages over the last quarter century, with an annual mean decrease in snow cover of about 10% over North America. These changes have been linked to the observed increases in temperature.

- There is evidence of historical trends of both increasing and decreasing precipitation in different parts of North America since 1900.

Average precipitation over the contiguous U.S. has increased by about 10% since 1910. The intensity of precipitation has increased for very heavy and extreme precipitation days. There is medium confidence in average U.S. results but low confidence in any particular regional changes.

- The timing of runoff in snowmelt-dominated rivers in the western U.S. appears to be changing (medium confidence), with a decrease in spring runoff and an increase in winter runoff. The causes of these changes are not completely understood.

Effects on Other Sectors

Five separate sectoral reports have been prepared for the National Assessment. In addition to this one on water, work is available on agriculture, human health, coastal ecosystems, and forests (see http://www.nacc.usgcrp.gov). None of the indicated impacts on these sectors is independent of what happens to U.S. water resources and water systems. Yet truly integrated analysis of possible impacts has not yet been done. We urge further work on the combined synergistic effects of climate change on the United States and we offer below a few comments on some critical issues.

Human Health

There are direct and indirect links between water availability and quality and human health. Changes in climate will affect the viability of disease vectors like mosquitoes that carry malaria or dengue fever. The transport of water-borne pathogens such as *Cryptosporidium* is known to be affected by changes in precipitation and runoff intensities and by land-use practices. The distribution of *Vibrio cholerae*, the bacteria responsible for cholera, is affected by climate, including El Niño frequency and intensity, temperature, and ocean salinity.

No clear evidence is available yet to conclude how climate change will ultimately affect these factors or to suggest any climate-related change in the incidences of these kinds of diseases in the United States, but we urge more research and careful monitoring of water-related disease vectors and data.

Agriculture

Recent studies of U.S. agriculture suggest that overall production of food may not be seriously threatened by climate changes as currently projected by GCMs. Indeed, in the climate scenarios evaluated for the National Assessment the net economic effects of changes in agriculture were generally positive, although there were substantial regional differences and some regions suffered production declines. The overall results showed a decline in water demand for irrigation, largely because of the differential effects of climate change on productivity of irrigated versus non-irrigated crops, and the assumed positive effects on plants of higher levels of CO_2. At the same time, there are serious caveats that accompany the research done to date, including some related to water availability and quality. Reliable information on changes in storm frequency and intensity is not yet available. Integration of indirect effects of climate change on hydrology and water into agroclimatic models has not yet been widely done, particularly effects of pests, soil conditions, disease vectors, and socioeconomic factors. Even less work has evaluated the impacts of changes in climate variability for agriculture. Integrating these and other links between water and food should remain a high priority for researchers.

Forests

Research suggests that climate change can lead to dramatic long-term changes in forest health and distribution. These factors depend partly on how precipitation and runoff patterns will change. But changes in forest conditions will, in turn, have locally and regionally important effects on runoff, soil erosion, soil salinization, groundwater quality, and more. These effects have not been adequately assessed.

Coastal Ecosystems

Impacts of climate change on water resources will have a wide range of consequences for coastal ecosystems. Ecosystem health will be affected by changes in the quality and quantity of freshwater runoff into coastal wetlands, higher water temperatures, extreme runoff rates or altered timing, and the ability of watersheds to assimilate wastes and pollutants. The net effect on coastal systems depends not just on how climate might change but also on a wide range of other human actions, including construction and operation of dams that trap sediments and nutrients, water withdrawal rates and volumes, disposal of wastes, and more.

Higher average or a greater range of flows of water could reduce pollutant concentrations or increase erosion of land surfaces and stream channels, leading to more sediment and greater chemical and nutrient loads in rivers and coastal deltas. Lower average flows could reduce dissolved oxygen concentrations, reduce the dilution of pollutants, reduce erosion, and increase zones with high temperatures. For almost every source or water body, land use and agricultural practices have a significant impact on water quality. Changes in these practices, together with technical and regulatory actions to protect water quality, can be critical to future water conditions.

Other Impacts

The impacts of climate change on U.S. water resources have the potential to affect international relations at the nation's northern and southern borders, where shared watersheds can lead to local and international political disputes. International agreements covering these shared waters do not include provisions for explicitly addressing the risks of climate-induced changes in water availability or quality.

A change in flood risks is one of the potential effects of climate change with the greatest implications for human well-being. Few studies have looked explicitly at the implications of climate change for flood frequency, in large part because of the lack of detailed regional precipitation information from climate models and because of the substantial influence of both human settlement patterns and water-management choices on overall flood risk.

Climate change is just one of a number of factors influencing the hydrological system and water resources of the United States. Population growth, changes in land use, restructuring of the industrial sector, and demands for ecosystem protection and restoration are all occurring simultaneously. Current laws and policies affecting water use, management, and development are often contradictory, inefficient, or unresponsive to changing conditions. In the absence of explicit efforts to address these issues, the societal costs of water problems are likely to rise as competition for water grows and supply and demand conditions change.

Recommendations

Coping and Adaptation

There are many opportunities to reduce the risks of climate variability and change for U.S. water resources. The nation's water systems are highly developed and water managers have a long history of adapting to changes in supply and demand. Past efforts have been focused on minimizing the risks of natural variability and maximizing system reliability. Many of the approaches for effectively dealing with climate change are little different than the approaches already available to manage risks associated with existing variability. Tools for reducing these risks have traditionally included supply-side options such as new dams, reservoirs, and pipelines, and more recently, demand-management options, such as improving efficiency, modifying demand, altering water-use processes, and changing land-use patterns in floodplains. This work is going on largely independently of the issue of climate change, but it will have important implications for the ultimate severity of climate impacts.

Sole reliance on traditional management responses is a mistake: first, climate changes are likely to produce

– in some places and at some times – hydrologic conditions and extremes of a *different nature* than current systems were designed to manage; second, climate changes may produce similar kinds of variability but *outside of the range* for which current infrastructure was designed and built; third, relying solely on traditional methods assumes that sufficient time and information will be available before the onset of large or irreversible climate impacts to permit managers to respond appropriately; and fourth, this approach assumes that no special efforts or plans are required to protect against surprises or uncertainties.

The first situation could require that completely new approaches or technologies be developed. The second could require that efforts above and beyond those currently planned or anticipated be taken early. Complacency on the part of water managers, represented by the third and fourth assumptions, may lead to severe impacts that could have be mitigated or prevented by cost-effective actions taken now.

As a result, we make the following observations and recommendations:

- *Prudent planning requires that a strong national climate and water monitoring and research program should be maintained, that decisions about future water planning and management be flexible, and that expensive and irreversible actions be avoided in climate-sensitive areas.*

- *Better methods of planning under climate uncertainty should be developed and applied.*

- *Governments at all levels should re-evaluate legal, technical, and economic approaches for managing water resources in the light of potential climate changes.* The federal government should require all federally owned and operated water systems to begin assessing both climate impacts and the effectiveness of different operation and management options.

- *Improvements in the efficiency of end uses and the intentional management of water demands must now be considered major tools for meeting future water needs, particularly in water-scarce regions where extensive infrastructure already exists.* We note the IPCC conclusion that "water demand management and institutional adaptation are the primary components for increasing system flexibility to meet uncertainties of climate change."

- *Water managers should begin a systematic reexamination of engineering designs, operating rules, contingency plans, and water allocation policies under a wider range of climate conditions and extremes than has been used traditionally.* For example, the standard engineering practice of designing for the worst case in the historical observational record may no longer be adequate.

- *Cooperation between water agencies and leading scientific organizations can facilitate the exchange of information on the state-of-the-art thinking about climate change and impacts on water resources.*

- *The timely flows of information among the scientific global change community, the public, and the water-management community are valuable.* Such lines of communication need to be developed and expanded.

- *Traditional and alternative forms of new supply, already being considered by many water districts, can play a role in addressing changes in both demands and supplies caused by climate changes and variability.* Options to be considered include wastewater reclamation and reuse, water marketing and transfers, and even limited desalination where less costly alternatives are not available and where water prices are high. None of these alternatives, however, is likely to alter the trend toward higher water costs.

- *Prices and markets are increasingly important for balancing supply and demand.* Because new construction and new concrete projects can be expensive, environmentally damaging, and politically controversial, the proper application of economics and water management can provide incentives to use less and produce more. Among the new tools being successfully explored are tiered rates, water banking, and conjunctive use of groundwater.

- *Even without climate change, efforts are needed to update and improve legal tools for managing and allocating water resources.* Water is managed in different ways in different places around the country, leading to complex and often conflicting water laws.

Research Needs

Records of past climate and hydrological conditions are no longer considered to be reliable guides to the future. The design and management of both structural and non-structural water-resource systems should allow for the possible effects of climate change, but little professional guidance is available in this area. Further research by hydrologists, civil engineers, water planners, and water managers is needed to fill this gap, as is broader training of scientists in the universities.

- More work is needed to improve the ability of global climate models to provide information on water-resources availability, to evaluate overall hydrologic impacts, and to identify regional impacts.
- Substantial improvements in methods to downscale climate information are needed to improve our understanding of regional and small-scale processes that affect water resources and water systems.
- Information about how storm frequency and intensity have changed and will change is vitally important for determining impacts on water and water systems, yet such information is not reliably available. More research on how the severity of storms and other extreme hydrologic events might change is necessary.
- Increased and widespread hydrologic monitoring systems are needed. The current trend in the reduction of monitoring networks is disturbing.
- There should be a systematic reexamination of engineering design criteria and operating rules of existing dams and reservoirs under conditions of climate change.
- Information on economic sectors most susceptible to climate change is extremely weak, as is information on the socioeconomic costs of both impacts and responses in the water sector.
- More work is needed to evaluate the relative costs and benefits of non-structural management options, such as demand management and water-use efficiency, or prohibition on new floodplain development, in the context of a changing climate.
- Research is needed on the implications of climate change for international water law, U.S. treaties and agreements with Mexico and Canada, and international trade in water. Can “privatization” affect vulnerability of water systems to climate change?
- Little information is available on how climate changes might affect groundwater aquifers, including quality, recharge rates, and flow dynamics. New studies on these issues are needed.
- The legal allocation of water rights should be reviewed, even in the absence of climate change, to address inequities, environmental justice concerns, and inefficient use of water. The risks of climate change make such a review even more urgent.

Key Messages for Water Managers, Planners, and Interested Members of the Public

Climate is not static and assumptions made about the future based on the climate of the past may be inappropriate. Assumptions about the probability, frequency, and severity of extreme events used for planning should be carefully re-evaluated.

Climate changes will be imposed on top of current and future non-climate stresses. In some cases, these changes will be larger than those expected from population growth, land-use changes, economic growth, and other non-climate factors.

Certain threshold events may become more probable and non-linear changes and surprises should be anticipated, even if they cannot be predicted.

The time lags between identifying the nature of the problems, understanding them, prescribing remedies, and implementing them are long. Waiting for relative certainty about the nature of climate change before taking actions to reduce climate-change related risks may prove far more costly than taking certain pro-active management and planning steps now. Methods must be used that explicitly incorporate uncertainty into the decision process.

While some kinds of actions should be taken now, expensive and long-lived new infrastructure should be postponed until adequate information on future climate is available. If postponement is not possible, a wider range of climate variability than provided by the historical record should be factored into infrastructure design.

Water: The Potential Consequences of Climate Variability and Change for the Water Resources of the United States

The Report of the Water Sector Assessment Team
of the National Assessment of the Potential Consequences of
Climate Variability and Change

Overview

Introduction

Clean and adequate fresh water is critical to the welfare of the United States. It is a fundamental component of the natural ecosystems upon which we all depend, vital for human health and industrial production, used directly and indirectly to generate energy, an important part of our transportation system, the basis for extensive outdoor recreation, and a medium for disposing of wastes. The natural variability of the hydrologic cycle is also important to society: large socioeconomic costs are associated with both too much and too little water. The nation's water resources, in turn, are dependent on the climate.

As a nation, the United States is relatively water rich. Total precipitation averages nearly 750 millimeters per year over the surface of the country. Much of this precipitation quickly evaporates back into the atmosphere, but the remainder provides a renewable supply of surface water and groundwater that is nearly twenty times larger than current consumptive use (Shiklomanov 2000). The vast amounts of water stored in lakes, reservoirs, and groundwater aquifers provide reliable, high-quality supplies for much of the nation's population.

However, a fundamental characteristic of the natural water cycle is that average figures hide important regional and temporal variations. We get water in places and at times it is not needed, while other regions may need water and not get it. Despite its average abundance and renewability, fresh water can be a scarce resource almost anywhere in the United States, particularly west of the 100th meridian. It can also be present in too much abundance, causing floods that kill or injure large numbers of people and destroy property. The last drought in the northeastern U.S., followed by the worst flooding ever seen along portions of the eastern seaboard, associated with the 1999 hurricane season, are just recent manifestations of how variability in existing climate conditions affects both our water systems and society as a whole.

The major concerns of water managers and planners in the past have been how to meet the demands of a growing and increasingly affluent population and how to handle both floods and droughts. Over the past few decades, these concerns have been further complicated by the growing understanding that human water use must be balanced with the need to sustain a healthy natural environment and restore ecosystems degraded or destroyed by past water policy decisions. Even more recently, the scientific community has become aware of the likelihood that human-induced climate changes will occur, with a wide variety of implications for human-built and natural water systems.

Experience with historical climatological and hydrological conditions plays a major role in determining current water-use patterns and the infrastructure and institutions we have put in place to regulate and allocate supplies. Even today, the design and evaluation of alternative water investments and management strategies assume that future precipitation and runoff can be adequately described by assuming the future will continue to look like the past. The increasing likelihood that a human-induced greenhouse warming will affect the variability and availability of water quality and supplies as well as the demand for water raises doubts about this assumption and about the most appropriate water policies for the future.

The Water Sector report addresses the impacts of climate changes and variability for the water resources and water systems of the United States. It also begins to explore impacts on water-management infrastructure, the nature of water supply and demand, and the technical, economical, and institutional mechanisms for adapting to climate variability and changes that may occur. Despite many remaining uncertainties, no one can claim that this subject is unexplored. As early as 1975, the U.S. National Academy of Sciences (NAS) published a Program for Action, acknowledging the possibility that humans could influence global climate and calling for a strong national research program (National Academy of Sciences 1975). In 1979, the United States Senate held a symposium on climate change, which included discussions of possible impacts on the nation (U.S. Senate 1979). In 1983, the NAS published a report on climate change with an overview of issues related to water resources in the western United States (Revelle and Waggoner 1983).

Since then, our understanding has expanded enormously. As part of the National Assessment Water Sector efforts, a comprehensive bibliography about the impacts of climate change on U.S. water resources was prepared. This bibliography now contains over 920 papers and more are being added regularly. The bibliography itself is available online in a searchable form and is updated regularly (http://www.pacinst.org/CCBib.html).

Assessing the impacts of climate changes cannot be a static activity – new information is constantly being made available, new methods and models are being developed and tested, and policies related to water management and planning are dynamic and changing. This report must therefore be considered a snapshot in time, a summary of what we think we know, do not know, and would like to know about climate and water at the very beginning of the 21st century. In the coming years, we hope and expect that our understanding of the implications of climate changes for U.S. water resources, as well as our possible responses to those impacts, will improve and advance.

Uncertainties

Making accurate projections of the future is fraught with problems and difficulties. Uncertainties pervade all levels of climate impact assessment. Compounding the vast uncertainties associated with naturally stochastic systems like the Earth's atmosphere and hydrologic cycle are complicating human factors ranging from rates of population growth to the speed and scope of technological innovation and the flexibility and changeability of human institutions and policies. Trying to project the future behavior of the Earth's climate as greenhouse gas concentrations in the atmosphere increase imposes even more complexities and uncertainties.

One of the major challenges of every aspect of the National Assessment is to present balanced and up-to-date information on the impacts of climate change and response options, while the extent of our knowledge is continuously evolving. Decision-makers must weigh their potential actions and responses to the risks of climate change before all the uncertainties can be resolved

– indeed, all the uncertainties will never be resolved because of the nature of the problem. As a result, imperfect information must be synthesized, evaluated, and presented in a transparent and appropriate way.

There are many possible ways of describing the state of the science, but there are no universally accepted standards for defining uncertainties in the many different stages of climate impact assessment. A few documents offering guidance are available (see, for example, Carter et al. 1994, IPCC 1996a, Moss and Schneider 1997, 1999, USGCRP 2000). Uncertainty can range from a lack of absolute sureness to speculation or informed guesses. Some forms can be quantified; others must remain qualitative. Such uncertainties are not unique to the problem of climate change. Scientists doing fieldwork or working in laboratories must deal with natural variability, statistical variation, measurement error, and subjective judgment. The science of climate change involves even worse complexities having to do with the global and regional scales of impacts, the long time periods involved, and the impossibility of reproducing large-scale climate conditions in a testable, laboratory situation. Yet the issue of climate change is not a purely scientific one: it also involves socioeconomic factors and public policy questions that further complicate assessment.

Once any given climate scenario is developed, translating climate conditions into hydrological conditions can be done using a variety of methods, each with advantages and disadvantages. Hydrologic modelers have developed a wide range of computer models at many different spatial and temporal scales capable of using climate data to project runoff, water conditions, reservoir behavior, or other variables of interest. Translating new hydrologic conditions into impacts also entails uncertainties. These tend to result from assumptions used, data limitations, and socioeconomic factors, though there are also problems with water-management and operations models themselves. Finally, additional important uncertainties are imposed by the inability to know how future demographics, economics, and social preferences will change over the coming decades, or how water managers might respond to those changes. Because of all of these factors, it is unlikely that we will ever be able to foresee all of the kinds of impacts likely to result before they actually occur, and it is unlikely that all of our best estimates will be accurate.

Acknowledging the many uncertainties involved is vital. At the same time, we note that not everything is uncertain: indeed, our understanding of the nature and magnitude of the potential impacts of climate change on U.S. water resources is improving every day. It is vital, therefore, that uncertainties not be used as an excuse to delay or avoid taking certain kinds of action now. Prudent planning requires that a strong national climate and water research program be maintained, that decisions about future water planning and management be flexible, and that the risks and benefits of climate change be incorporated into all long-term water planning. Rigid, expensive, and irreversible actions in climate-sensitive areas can increase vulnerability and long-term costs. More than two decades of serious research into the implications of climate change for water resources has improved our understanding of possible impacts, points of vulnerability, and critical issues, and some clear and consistent results have been identified. Taken all together, the current state-of-the-science suggests a wide range of concerns that should be addressed by national and local water managers and planners, climatologists, hydrologists, policymakers, and the public.

Sidebar 1 summarizes some of the uncertainties associated with each stage in the Water Sector assessment. The greatest uncertainties generally arise in the initial climate scenarios because of the difficulty of knowing how the driving forces affecting the global climate system will change.

Sidebar 1:
Important Uncertainties and Complexities in the Climate Research Process

A wide range of uncertainties result from the difficulty of forecasting the future rates of greenhouse gas emissions and interested readers should look at IPCC (1996a) and the background documents for the National Assessment (http://www.usgcrp.gov/nacc).

- Most research on the hydrologic implication of the greenhouse effect begins with estimations of regional atmospheric or surface variables such as temperature and precipitation derived from a long-term general circulation model (GCM) simulation. Large uncertainties result from estimates of how increased greenhouse gas concentrations will affect the climate. GCMs generally do a better job of representing large-scale atmospheric dynamics than temperature and precipitation and they are run at spatial scales far coarser than hydrologists would like. Biases of several degrees C are not uncommon in attempts to reproduce seasonal temperature variations and there is considerable variation among GCM estimates of the future direction, magnitude, and timing of changes in precipitation. Detailed information on the promise and limitations of GCMs can be found in IPCC (1996a).

- The next step in the research sequence involves going from the large scale of the GCMs, which often have grid cell areas of about 40,000 km^2, to the river-basin scale. “Downscaling” introduces new uncertainties about the relationships between large-scale climate data and smaller-scale dynamics of the atmosphere, how those dynamics affect the hydrology of a watershed, and the proper translation of coarse hydrologic data to finer resolution.

- Climate information is then fed into hydrologic models calibrated and tested with observed streamflow and meteorological data at the river-basin level. These models produce estimates of runoff, soil moisture, and other water conditions under a range of climate scenarios. The hydrologic modeling errors introduced at this point are relatively modest compared to those introduced by the GCM simulations and downscaling.

- The resulting hydrological data can then be used with models of water-management systems to evaluate the differences in system performance under different climate scenarios. Applying the climate-adjusted hydrology to water-resource system models calibrated and designed to operate with historical streamflows introduces additional uncertainties. Few models exist to quantify the effects of different water-management strategies on aquatic ecosystems and their ability to continue to provide essential ecological goods and services in a changing climate. Quantitative models are lacking that link changes in hydrology with ecosystem processes (such as productivity, nutrient dynamics, and food web interactions), ecological interactions (such as predation and species invasions), and water quality.

- Finally, the impacts of future climate changes on water resources in the U.S. will depend on many non-scientific factors, including regional demographic factors, water policies, prices, and rules for operating complex systems. Such changes can help systems cope with possible climate changes or they can make the system more vulnerable to such changes. Because we cannot know how water managers will react in advance, or even if they will, the ultimate impacts of climate change will depend on choices and value judgments as well as scientific information and data.

(Gleick 1989, IPCC 1996a, IPCC 1996b, Wood et al. 1997, Frederick et al. 1997).

For example, the nature and intensity of future greenhouse gas emissions depend upon future decisions of governments and individuals, the development of alternative energy technologies, population sizes, the distribution of wealth, and many more factors. Even if we could reliably determine atmospheric gas concentrations over time, converting these conditions into climate changes involves modeling some of the most complex geophysical behaviors on Earth. Additional uncertainties appear in each subsequent stage as well.

We note when findings in this report depend on a particular climate scenario. Confidence in such findings is evaluated assuming that the hypothesized change in climate actually occurs. Interested readers are directed to the comprehensive discussions of these issues in the IPCC reports (IPCC 1996a,b,c) and in the other reports of the National Assessment.

In order to be as explicit as possible about uncertainties, efforts have been made to clarify and define terms. Carter et al. (1994) recommends the use of confidence limits where possible, including upper and lower estimates of an outcome with a mean or median outcome used as a "best" or " central" estimate. They also note, however, the difficulty of quantifying most kinds of uncertainty in impacts assessments. The National Assessment Synthesis Team adopted some common language terms and applied them to quantitative ranges of probability of impacts (USGCRP 2000). A comparable set of terms and quantitative ranges from the IPCC are available (IPCCa) (These terms are shown in Tables 1 and 2.) When only qualitative measures are available we refer to two sets of terms used by the IPCC (IPCC 1996b, Moss and Schneider 1997, 1999). These sets, using slightly different language and probabilities, are presented in Tables 3 and 4 (IPCC 1996a, Moss and Schneider 1999). Both qualitative scales, which rely on expert judgment, are used here when deemed appropriate by the authors.

For the major findings described in this study we have tried to identify the most important factors and uncertainties likely to affect the conclusions. When quantitative measures of precision are available, we try to note them. When quantitative measures are not available, a qualitative approach is applied similar to that adopted by Working Group II (Impacts) of the Intergovernmental Panel on Climate Change. In this summary the terms "will," "would," and "likely" are used to characterize consequences of climate change when findings are well-established or established but incomplete. When consequences are not well-established, speculative, or subject to competing explanations, we try to use the terms "could," "may," or "might." Readers of this report will note that detailed information on uncertainties becomes less frequent in the later sections. This kind of information is often not provided for the more science-based analyses and it is even harder to find measures of uncertainty for socioeconomic or ecological assessments.

More work defining "uncertainty" would help future assessments. For example, a form of uncertainty assessment and risk analysis – decision analysis – can be used to evaluate the value of different water-management response strategies to climate change. Decision analysis assigns likelihoods to different scenarios, identifying those responses that would provide the least-cost flexibility needed to reduce the anticipated range of impacts (see, for example, Fiering and Rogers 1989, Haimes and Li 1991, Carter et al. 1994). These and other approaches are worthy of more discussion and analysis.

Table 1:
Quantitative Scale for Assessing Uncertainties

Scale	Confidence Level
1.00 - 0.95	“Very High Confidence”
0.95 - 0.67	“High Confidence
0.67 - 0.33	“Medium Confidence”
0.33 - 0.05	“Low Confidence”
0.05 - 0.00	“Very Low Confidence”

Source: Moss and Schneider (1999).

Table 2:
Quantitative Scale for Assessing Uncertainties

Probability Range	Common Language
< 10 percent confidence	Little chance or very unlikely
10 to 33 percent confidence	Unlikely or some chance
34 to 66 percent confidence	Possible
67 to 90 percent confidence	Likely or probable
> 90 percent confidence	Very likely or very probable

Source: USGCRP (2000).

Table 3:
A Three-Tier Qualitative Scale for Assessing Uncertainties

High Confidence: This category denotes wide agreement, based on multiple findings through multiple lines of investigation. In other words, there is a high degree of consensus among the authors based on the existence of substantial evidence in support of the conclusion.

Medium Confidence: This category indicates that there is a consensus, but not a strong one, in support of the conclusion. This ranking could be applied to a situation in which an hypothesis or conclusion is supported by a fair amount of information, but not a sufficient amount to convince all participating authors, or where other less plausible hypotheses cannot yet be completely ruled out.

Low Confidence: This category is reserved for cases when lead authors are highly uncertain about a particular conclusion. This uncertainty could be a reflection of a lack of consensus or the existence of serious competing hypotheses, each with adherents and evidence to support their positions. Alternatively, this ranking could result from the existence of extremely limited information to support an initial plausible idea or hypothesis.

Source: IPCC (1996b).

Table 4:
A Four-Tier Qualitative Scale for Assessing Uncertainties

Well-established: models incorporate known processes; models consistent with observations; or multiple lines of evidence support the finding.

Established but Incomplete: models incorporate most known processes, although some parameterizations may not be well tested; observations are somewhat consistent but incomplete; current empirical estimates are well founded, but the possibility of changes in governing processes over time is considerable; or only one or a few lines of evidence support the finding.

Competing Explanations: different model representations account for different aspects of observations or evidence, or incorporate different aspects of key processes, leading to competing explanations.

Speculative: conceptually plausible ideas that haven’t received much attention in the literature or that are laced with difficult-to-reduce uncertainties.

Source: Moss and Schneider (1999).

Water Use in the United States

Water Use in the 20th Century

The implications of climate changes for water resources in the United States depend not only on the behavior of the climate but on the characteristics of U.S. demand for water and the technologies, policies, and strategies chosen to meet and constrain those demands. The use of water to meet human and environmental needs can be "consumptive" and "non-consumptive." It can also involve withdrawing water for uses such as irrigation and drinking or leaving it in a stream or lake for uses such as fish and wildlife habitat and navigation. Sidebar 2 defines some of these terms.

Water withdrawals in the U.S. consistently grew faster than population during the first three-quarters of this century (Solley et al. 1998, Brown 1999). Volumes of water taken from rivers, lakes, and groundwater increased more than tenfold from 1900 to 1975, driven largely by population and economic growth. Since the mid-1970s, withdrawals have been constrained by high costs, environmental concerns, regulatory actions, and in a few cases, actual scarcity. Combinations of price incentives, water transfers, new technology, and regulations have eliminated some inefficient and low-value water withdrawals and encouraged the development and adoption of more water-efficient practices. These changes are reflected in national water-use trends – total withdrawals in the United States are no longer increasing and regional shifts in demands are occurring as urban populations grow and industrial and agricultural sectors evolve.

Figure 1 shows total and per-capita water withdrawals for the United States from 1900 to 1995 (Solley et al. 1998). Total withdrawals in 1995 were approximately 550 cubic kilometers and per-capita withdrawals were around 2,100 cubic meters per person per year. After peaking in the late 1970s and early 1980s, total water withdrawals have now decreased substantially, with declines in all sectors except public supply. Per-capita freshwater withdrawals peaked in 1980 and have declined 22% since then (Solley et al. 1998).

In 1995, water withdrawals in the U.S. were used primarily for cooling thermoelectric power plants and for agricultural irrigation. The vast majority of power-plant cooling water is not consumed and is returned to the originating source unless cooling towers are used. The vast majority of irrigation water is consumed through evapotranspiration. Figure 2 shows the breakdown of U.S. water withdrawals by sector over time up to 1995 (Solley et al. 1998).

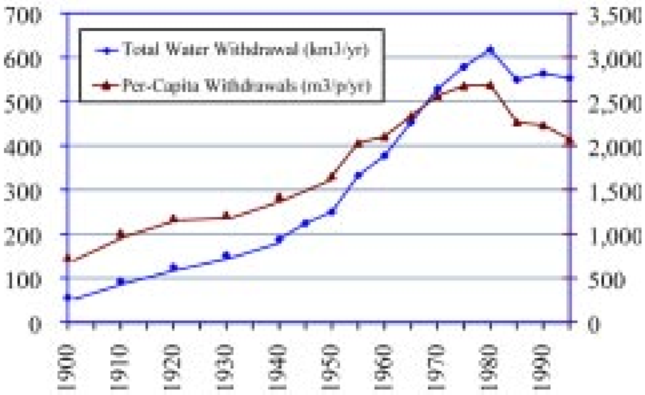
Changes in U.S. water withdrawals are due in part to the high costs and limited opportunities for further increasing offstream water use. Dams and reservoirs designed to transform unreliable streams into controlled and reliable sources of supply were the principal means of increasing agricultural and urban water supplies until about 1970. Since then, the pace of new dam and reservoir construction has fallen sharply (Frederick 1991, U.S. Army Corps of Engineers 1996). Figure 3 shows the cumulative number of large dams built in the U.S. between 1961 and 1995 and the slowdown in construction

Sidebar 2:
Water "Use, Withdrawal, Consumption"

Care should be taken when using – or reading – terms that describe different uses of water, since these terms are often used inconsistently and misleadingly in the water literature. The term "water use" itself encompasses many different ideas. Among other things it has been used to mean the withdrawal of water, gross water use, and the consumptive use of water. It is also vital to note that not all water "used" is actually ever withdrawn. Fish and wildlife habitat and navigation have substantial water needs, but no actual "withdrawals" are usually measured. The term "withdrawal" should refer to the act of taking water from a source for storage or use. Not all water withdrawn is necessarily consumed. For many processes, water is often withdrawn and then returned directly to the original source after use, such as water used for cooling thermoelectric power plants. "Gross water use" is distinguished from water withdrawal by the inclusion of recirculated or reused water. Thus for many industrial processes, far more water is required than is actually withdrawn for use, but that water may be recirculated and reused many times. Water "consumption" or "consumptive use" should refer to the use of water in a manner that prevents its immediate reuse, such as through evaporation, plant transpiration, contamination, or incorporation into a finished product. Water for cooling power plants, for example, may be withdrawn from a river or lake, used once or more than once, and then returned to the original source. This should not be considered a "consumptive use" unless it is evaporated, or contaminated and made unfit for further uses downstream. Water withdrawn for agriculture has both consumptive and non-consumptive components, as part of the water is transpired into the atmosphere or incorporated into plant material, while the remainder may return to groundwater or the surface source from which it originated.

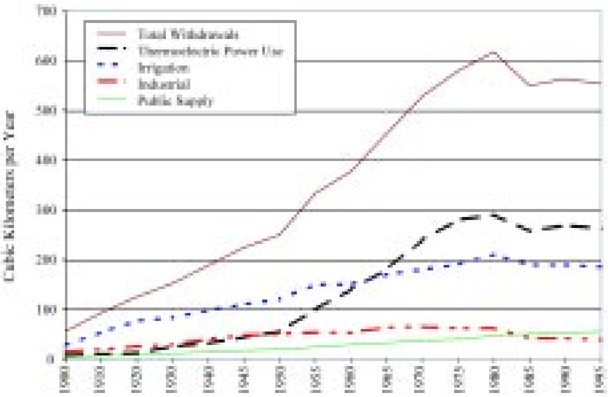
Source: Gleick 1998a.

Figure 1:
U.S. Total and Per-Capita
Water Withdrawals



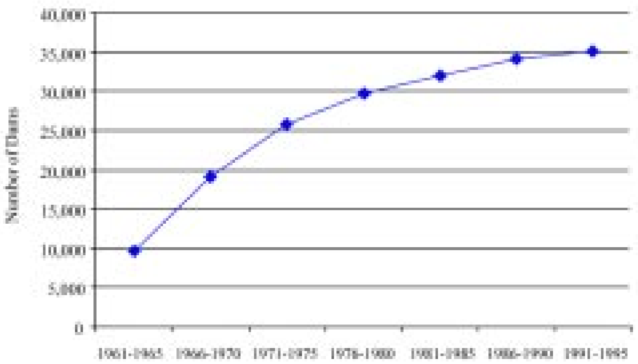
Source: Gleick (1998).

Figure 2:
Water Withdrawals in the
United States, 1900-1995



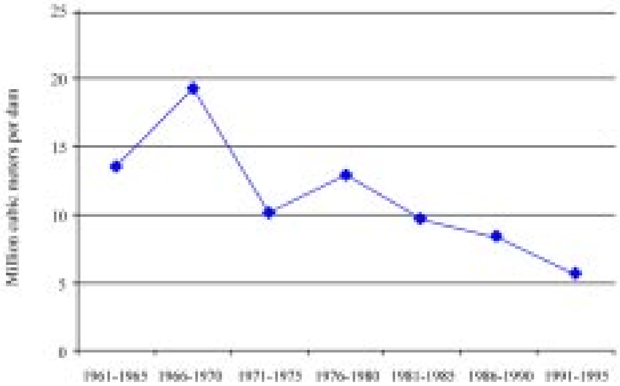
Source: Gleick (1998).

Figure 3:
Cumulative Number of Large Dams Built in the United States, 1961-1995



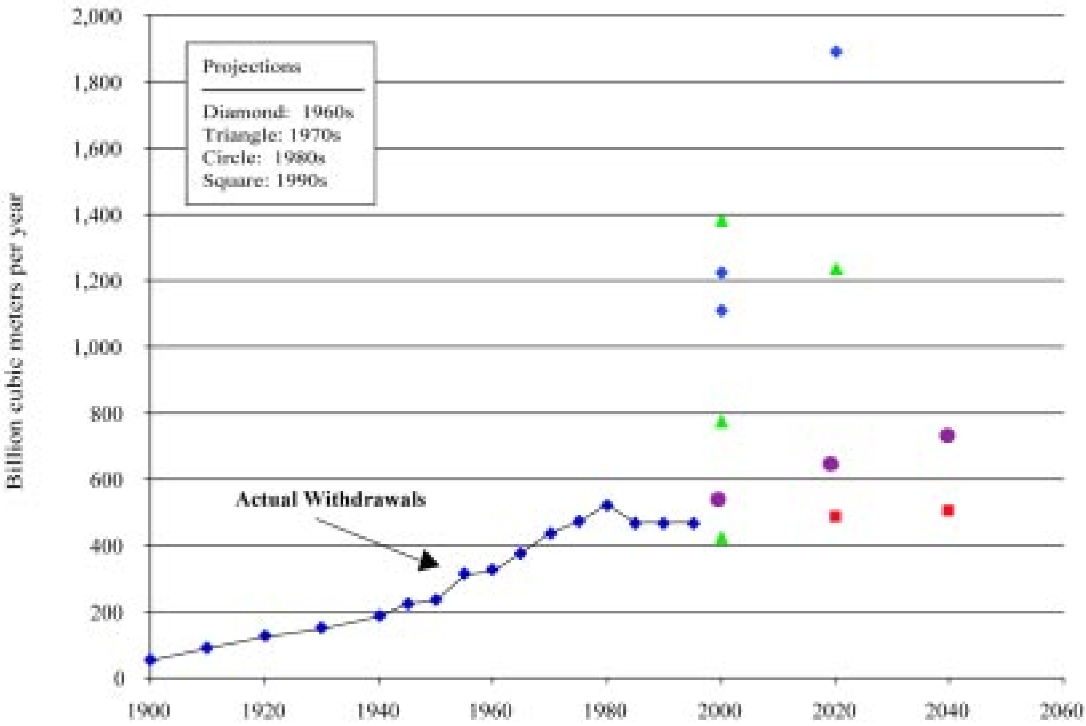
Total cumulative number of large dams built in the United States between 1961 and 1995. Note that the rate of additions to the nation's dams has greatly slowed in recent years. Source: US Army Corps of Engineers (1996).

Figure 4:
Average Volume of U.S. Reservoirs Built in Each Five-Year Period, 1961-1995



The average volume of resevoirs built in each five-year period between 1961 and 1965. New dams are still being added, but their average storage volumes are decreasing. Source: US Army Corps of Engineers (1996).

Figure 5:
U.S. Water Projections and Actual Withdrawals



Many projections of future U.S. water withdrawals have been made over the years. This graph shows projections made for the years 2000, 2020 and 2040 by various water planners. The decade the projections were made is indicated by the color and shape of the mark: Blue/diamonds were made in the 1960s, green/triangles in the 1970s, purple/circles in the 1980s, and red/squares in the 1990s. Actual total U.S. withdrawals are also show from 1900 to 1995. Source: Gleick (2000).

in recent decades. Figure 4 shows the decline in the average volume of reservoirs built in each five-year period since 1960 (U.S. Army Corps of Engineers 1996).

Proposed large new dam projects are often characterized by high economic costs, diminishing returns in their ability to increase the amount of water a system can reliably provide, and serious environmental and social concerns. These obstacles to dam construction are likely to mount in the future for several reasons. Since the best sites for storing water within a basin are typically the first to be developed, subsequent increases in storage require ever-larger investments of resources. There are also diminishing returns in the additional water that can be produced by successive increases in reservoir capacity within a basin. The social and ecological costs of storing and diverting water increase as the number of free-flowing streams declines and society attaches more value to water left in a stream (Frederick 1991, 1993, Gleick 1998b).

Future Water Use in the United States

A variety of projections of future water withdrawals in the United States (and worldwide) have been made over the past 50 years. With very few exceptions, these projections have overestimated, often substantially, the rates of increase in water withdrawals that eventually occurred. Figure 5 shows 12 such projections made for the years 2000, 2020, and 2040. Prior to 1980, when U.S. water withdrawals began suddenly to level off and even decline, projections assumed continued exponential increases in water withdrawals. Even after 1980, as population projections dropped and per-capita use declined, straight-line or exponential increases were often forecast for the future. Yet current water withdrawals are now one-half or even one-third of what they were expected to be using traditional forecasting approaches.

As part of the U.S. Forest Service's periodic assessment of long-term resource supply and demand conditions, Brown (1999) has made a new set of water-use projections out to the year 2040 for the 20 U.S. water-resource regions and for six water-use categories – livestock; domestic and public; industrial, commercial, and mining; thermoelectric power; irrigation; and hydroelectric power. Brown's projections are based on estimates of future population and income provided by the Bureau of the Census and Bureau of Economic Analysis and on assumptions about rates of change in other factors affecting water use. The projections reflect regional variations in water scarcity in the absence of climate change and some anticipated improvements in water-use efficiency encouraged by rising water costs. Under the middle population growth projection, total water withdrawals increase only seven percent by the year 2040 despite a 41% increase in population. The implied reduction in per-capita withdrawals is largely attributable to three factors: continued improvements in water-use efficiency in municipal, industrial, and thermoelectric uses; small increases in overall irrigated area; and a relative geographic shift in irrigation from the western to eastern U.S. where less water is applied per acre (Brown 1999). Even these relatively modest increases in withdrawals imply growing pressures on instream flows, especially if current groundwater overpumping is reduced to sustainable levels.

Making projections is inherently difficult, but in some regions the trend toward greater efficiency, wastewater reuse, and shifting industrial structure may reduce expected stresses from non-climate factors. In these regions the impacts of climate changes may be proportionally larger than impacts due to demographic and economics.

Climate Change and Impacts on U.S. Water Resources

Introduction

This section summarizes more than two decades of research on the effects of climate changes on fundamental water-resource variables such as temperature, precipitation, evaporation, runoff, soil moisture, and storms. Any such summary will necessarily be incomplete. Interested readers are strongly encouraged to explore the original citations for more detail about assumptions and methods. The starting point for much of this research is estimating how increasing concentrations of greenhouse gases in the atmosphere will affect large-scale climate conditions and, particularly, the hydrologic cycle. Many such studies have used scenarios of future climate derived from global climate simulations or general circulation models (GCMs) to evaluate changes in hydrologic conditions. Some studies have explored past climate conditions (both paleoclimates and climates of recent decades) as analogues for the future. A smaller effort has looked at specific impacts on the operations or management of water systems, or on impacts to ecosystems, navigation, recreation, or other water-related activities. Even fewer studies have considered the complex socioeconomic costs of climate impacts or the costs and benefits of adaptation and coping strategies. These "costs" include all private and social impacts, typically expressed in dollars, although we note that not all such costs are yet quantified, or even quantifiable.

Large-scale climate information is often linked with more regional or realistic hydrologic models either directly or through a variety of "downscaling" techniques. "Downscaling" refers to attempts to address the scale mismatch between global climate models and watershed models. Methods for downscaling range from simple interpolation of climate model outputs to the use of regional climate models nested within larger-scale simulations. Some methods use statistical representations and interpolations; some use dynamic approaches. All of these methods depend on the quality of the initial simulation and few standardized techniques have been widely accepted (Hostetler 1994, Miller et al. 1999). Wilby et al. (2000) suggest that even when fine-scale regional climate models are nested directly into GCMs, problems with model dynamics still occur and statistical approaches can still produce better results. Because of the importance of regional and small-scale processes in determining impacts on water resources and water systems, substantial improvements in methods to downscale climate information continue to be needed (Crane and Hewitson 1998).

Improvements continue to be made in the hydrologic representations of the GCMs themselves, and spatial resolutions are slowly increasing. There have also been considerable advances in the past several years in the understanding of hydrological processes both at the land surface and in the atmosphere. These have come about through ongoing field data collection, modeling projects, and hydrologic coordination activities such as HAPEX, GEWEX/GCIP, FIFE, BOREAS, and other efforts (see http://www.wmo.ch/web/wcrp/wcrp-home.html for more information on the World Climate Research Program). We urge these efforts to continue.

Impacts of Climate Changes on Large-Area Water Balances

The hydrologic cycle is an integrated and dynamic component of the Earth's geophysical system and both affects and is affected by climate conditions. Changes in the Earth's radiation balance affect winds, temperatures, atmospheric energy and water transport, cloud dynamics and more. Changes in temperature affect evapotranspiration rates, cloud characteristics and extent, soil moisture, and snowfall and snowmelt regimes. Changes in precipitation affect the timing and magnitude of floods and droughts, shift runoff regimes, and alter groundwater recharge characteristics. Synergistic effects will alter cloud formation, vegetation patterns and growth rates, and soil conditions. At a larger scale, climate changes can affect major regional atmospheric circulation patterns and storm frequencies and intensities. All of these factors are, in turn, very important for decisions about water and land-use planning and management.

General circulation models are limited in their ability to reproduce important aspects of the hydrologic cycle. Most information available from GCMs focuses on how climate changes will affect the water balance, notably precipitation, evaporation, and runoff. Many fundamental hydrologic processes, such as the formation and distribution of clouds and rain-generating storms or watershed soil-moisture dynamics, occur on spatial scales smaller than most GCMs are able to resolve. We thus know less about how the water cycle will change than we would like to know in order to make decisions about how to plan, manage, and operate water systems. But we do know some things about how hydrology and water-management systems will be affected by climate changes and how we might strive to cope with those changes (Frederick et al. 1997, Frederick and Major 1997, AWWA 1997, Steiner 1998, Frederick 1998, Major 1998, Boland 1998, Gleick 1998b, Stakhiv and Schilling 1998).

The National Assessment reviewed several current general circulation models and information from these models was used in a variety of research studies. Two models – the Canadian Global Coupled Model ("Canadian" or "CGCM") and the British Hadley Center Coupled Model (version 2) ("Hadley" or "HadCM2") model – were picked for the Assessment. Both the Canadian and Hadley "business as usual" scenarios assumed a one-percent-per-year increase in carbon dioxide equivalence and a doubling of sulfur emissions by 2100 – assumptions taken from the Intergovernmental Panel on Climate Change (IPCC 1996a). During the latter part of the Assessment, additional information was gathered from a third GCM – the National Center for Atmospheric Research model (NCAR CSM "stabilization run") – and other research studies have used GCM output from other modeling groups and different versions of the models. No single model can be taken as correct; each version has strengths and weaknesses depending on focus, design, and approach. As a result, modelers do not recommend that GCM outputs be used as predictions, but rather as sensitivity studies or scenarios of possible future climates. A detailed discussion of the strengths and limitations of GCMs, particularly the Canadian and the Hadley models, is available in other documents prepared for the National Assessment (see, for example, http://www.nacc.usgcrp.gov/scenarios/ and http://www.gcrio.org/nationalassessment/pdf/Chapter1.pdf, and Doherty and Mearns 1999).

The broad effects of a greenhouse warming on water systems will vary in both space and time. Many climate changes and impacts are expected. Considerable effort has gone into evaluating these impacts and both general and specific conclusions can be drawn. Some of the conclusions with the greatest implications for hydrology and water resources are summaried below, based on earlier research, the first two reports of the IPCC (IPCC 1990, 1996a, 1996b), and the research done for the National Assessment.

- Human activities are increasing atmospheric concentrations of greenhouse gases and aerosols. The net effect of greenhouse gases is to warm the troposphere and cool the stratosphere; the net effect of tropospheric aerosols is to cool the troposphere (very high confidence).

- Without substantial changes in U.S. and international energy and land-use patterns, emissions of greenhouse gases will continue to increase above current levels and lead to higher concentrations of such gases than experienced in hundreds of thousands of years (very high confidence).

- As atmospheric greenhouse-gas concentrations continue to rise, global average precipitation will increase (very high confidence).

- Increases in global-average and U.S.-average surface temperatures will result from higher concentrations of greenhouse gases. As greenhouse-gas emissions continue into the future, the magnitude of these temperature increases will become larger over time (very high confidence). It is well established that the regional and seasonal pattern of these temperature increases across the U.S. will vary, but researchers have low confidence in most estimates of detailed regional increases.

- GCMs indicate that there will be some changes in the timing and regional patterns of precipitation (very high confidence), but researchers have low confidence in projections for specific regions because different models produce different detailed regional changes.

- GCMs consistently show that average precipitation will increase in higher latitudes, particularly in winter (high confidence). Models are inconsistent in other estimates of how the seasonality of precipitation will change.

- Research results consistently show that temperature increases in mountainous areas with seasonal snowpack will lead to increases in the ratio of rain to snow and decreases in the length of the snow storage season (very high confidence). It is likely that reductions in snowfall and earlier snowmelt and runoff would increase the probability of flooding early in the year and reduce the runoff of water during late spring and summer. Basins in the western United States are particularly vulnerable to such shifts.

- Increases in annual average runoff in the high latitudes caused by higher precipitation are likely to occur (high confidence).

- Research results suggest that flood frequencies in some areas are likely to change. In northern latitudes and snowmelt-driven basins, research results suggest that flood frequencies will increase (medium confidence), although the amount of increase for any given climate scenario is uncertain and impacts will vary among basins.

- Research results suggest that drought frequencies in some areas are likely to change. The net risks to society from such changes have not been evaluated and specific projections of where such changes will occur are speculative. Models project that the frequency and severity of droughts in some areas could increase as a result of regional decreases in total rainfall, more frequent dry spells, and higher evaporation (medium confidence). Models suggest with equal confidence that the frequency and severity of droughts in some regions would decrease as a result of regional increases in total rainfall and less frequent dry spells.

- Higher sea levels associated with thermal expansion of the oceans and increased melting of glaciers will push salt water further inland in rivers, deltas, and coastal aquifers (very high confidence). It is well understood that such advances would adversely affect the quality and quantity of freshwater supplies in many coastal areas.

- Water-quality problems will worsen where rising temperatures are the predominant climate change (high confidence). Where there are changes in flow, complex positive and negative changes in water quality will occur. Water quality may improve if higher flows are available for diluting contaminants. Specific regional projections are not well established at this time because of uncertainties in how regional flows will change.

- Ecologists project that climate warming will produce a shift in species distributions northward, with extinctions and extirpations of temperate or cold-water species at lower latitudes, and range expansion of warm-water and cool-water species into higher latitudes (high confidence).

- Increased atmospheric carbon dioxide will affect the use of water by vegetation (high confidence), but hydrologists have low confidence in the net effects of this and other competing influences. Increasing CO_2 concentrations in some circumstances can reduce the rate of transpiration from certain plants. This in turn would tend to increase runoff since less water is returned directly to the atmosphere by such vegetation, allowing a greater share of precipitation to reach streams or aquifers. Rising CO_2 concentrations can also increase plant growth, leading to a larger area of transpiring tissue and a corresponding increase in transpiration. More work is needed on the roles of vegetation type and other interacting factors such as soil conditions and groundwater interactions.

- A growing number of studies suggest that climate changes will increases the frequency and intensity of the heaviest precipitation events, but there is little agreement on detailed regional changes in storminess that might occur in a warmed world. Contradictory results from models support the need for more research, especially to address the mismatch between the resolution of models and the scales at which extreme events can occur. This issue should be regularly revisited in later assessments.

- The southern boundary of continuous permafrost is projected to shift north by 500 kilometers over the next 50 years due to warming projected by GCMs. A 5^o C warming in Alaska would eventually melt virtually all of the subarctic permafrost in Alaska (medium confidence), which would affect more wetland area than currently found in the rest of the United States.

- While we note that some climate scenarios can produce conditions that might reduce stresses on certain ecosystems, experience with ecosystem dynamics strongly suggests that perturbing ecosystems in any direction away from the conditions under which they developed and thrive will have adverse impacts on the health of that system. Aquatic ecosystems can be highly sensitive to hydroclimatic factors, particularly water temperature, water quality, the probability of extreme events, and flow volumes, rates, and timing. Determining the impacts on particular species or ecosystems will require additional region-specific, and ecosystem-specific, research.

Temperature

For the continental United States, the Canadian and Hadley climate models show annual average warming by around 2090 of between 3 and 6° C over the North American continent. Much of Canada and the U.S. show strong winter warming above 9° C in the Canadian model. Winter temperature increases in the Hadley model are more modest but still reach 1 to 5° C over the U.S. in all seasons (Doherty and Mearns 1999). Table 5 and Figures 6 and 7 show the changes in mean annual temperature for the two models for 2030 and 2095 compared to current average temperature. Researchers have a very high degree of confidence that temperatures will rise, but only low confidence in specific regional projections from climate models. We also note here that changes in means can hide more significant changes in regional or seasonal values. In addition, whether there is a difference in day-time versus night-time warming will have important impacts on the hydrologic cycle. Research results have consistently shown that changes in temperature of the magnitude found in these and comparable climate models would have dramatic consequences for snowfall and snowmelt conditions, evaporation regimes, runoff patterns, and water-system operation and management.

Table 5:
Changes in Annual Mean Temperature, Hadley and Canadian Climate Models (Degrees Celsius)

	Canadian 2030	Hadley 2030	Canadian 2095	Hadley 2095
Northwest	1.8	1.7	4.9	4.1
Southwest/California/Rockies	2.0	1.8	5.5	4.0
Great Plains	2.2	1.6	6.3	3.6
Great Lakes/Midwest	2.4	1.1	6.1	2.7
Southeast	1.8	1.0	5.5	2.3
Northeast	1.8	1.0	5.6	2.7
United States	2.1	1.4	5.8	3.3

Note: The use of mean values often hides informative temporal or spatial values. Full details on temperature changes can be found in the original source. Source: B. Felzer, www.cgd.ucar.edu/naco/vemap/annual.html

Figure 6A:
CGCM2 Mean Surface Temperature
Delta 2030 (Annual)

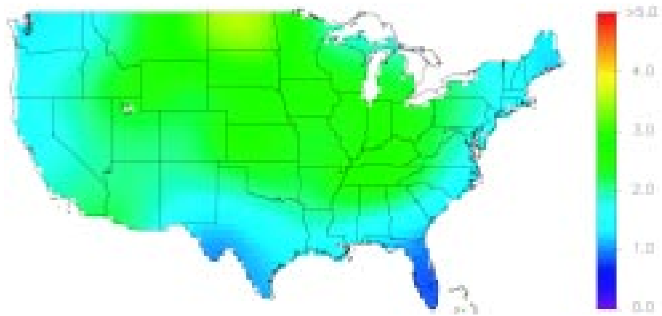


Figure 6B:
CGCM2 Mean Surface Temperature
Delta 2095 (Annual)

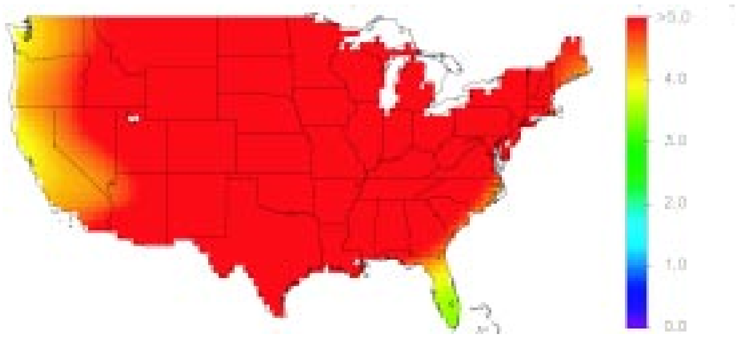


Figure 7A:
HadCM2 Mean Surface Temperature
Delta 2030 (Annual)

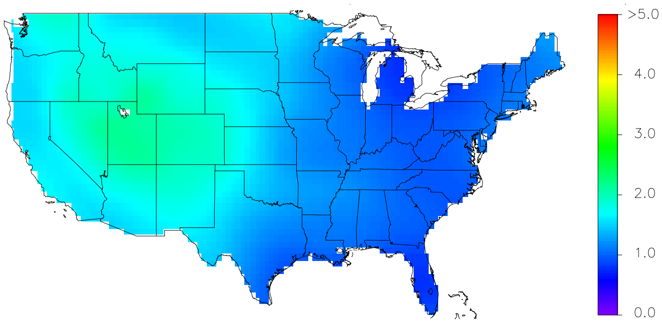
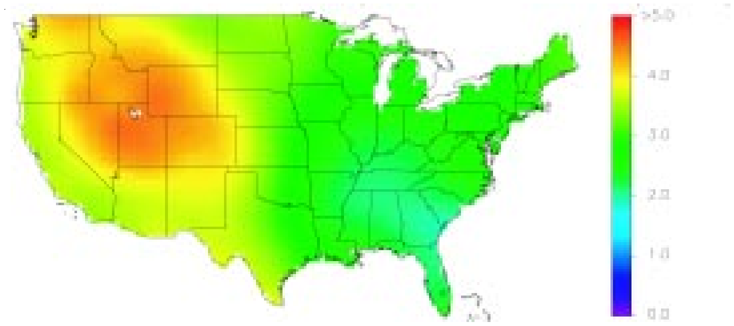


Figure 7B:
HadCM2 Mean Surface Temperature
Delta 2095 (Annual)



These figures show the average change in surface temperature (°C) projected for the Canadian (Figure 6) and Hadley (Figure 7) GCMs. Shown are differences between model projections for 2030 or 2095 and present day. Source: B. Felzer, NCAR, personal communication.

Figure 8A:
CGCM2 Precipitation Ratio
2030 (Annual)

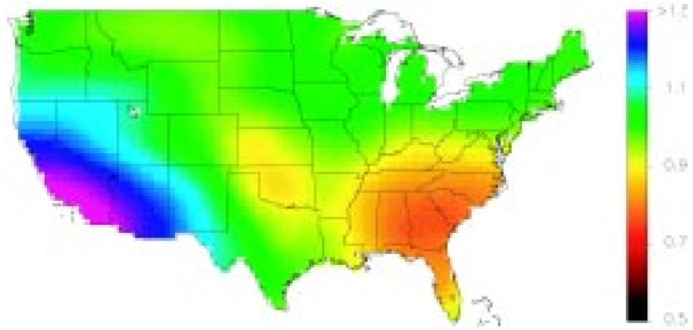


Figure 8B:
CGCM2 Precipitation Ratio
2095 (Annual)

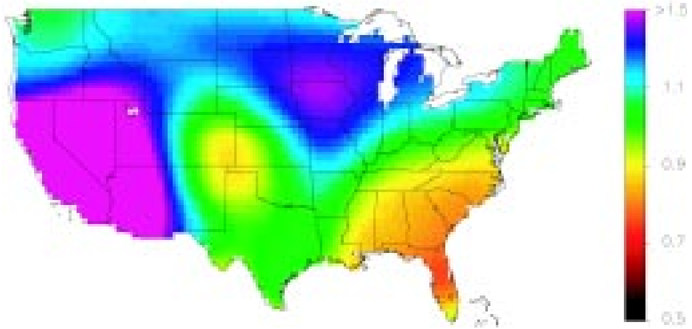


Figure 9A:
HadCM2 Precipitation Ratio
2030 (Annual)

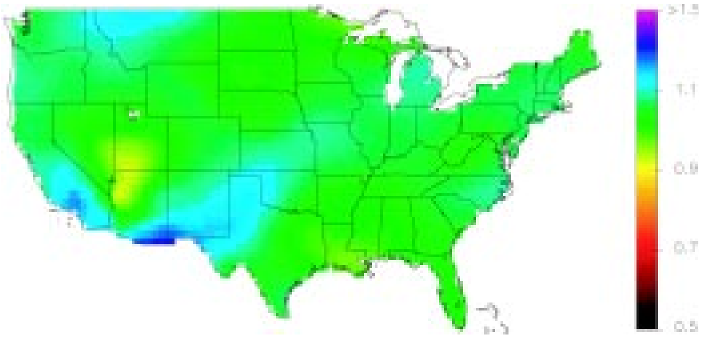
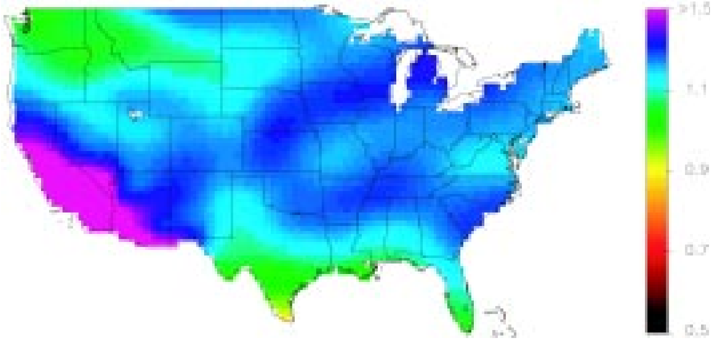


Figure 9B:
HadCM2 Precipitation Ratio
2095 (Annual)



These figures show the ratio of annual preciptation projected for the Canadian (Figure 8) and Hadley (Figure 9) GCMs compared to current precipitation. Source: B. Felzer, NCAR, personal communication.

Precipitation

There is a very high degree of confidence among climatologists and modelers that global climate change will, on average, result in a wetter world. Climate models consistently project an increase in global mean precipitation of between three and 15% for a temperature increase of 1.5 to 3.5° C (Schneider et al. 1990, IPCC 1996a,b). The global average, however, hides significant differences in regional precipitation patterns, with some regions showing increases, some decreases, and considerable interannual variability. Models indicate that increases in precipitation are likely to occur more consistently and intensely throughout the year at middle to high latitudes. In many model estimates, summer rainfall decreases slightly over much of the northern mid-latitude continents while winter precipitation increases. Other projections of precipitation changes in mid-latitudes remain highly variable and uncertain.

General circulation models poorly reproduce detailed precipitation patterns. Precipitation relies on meteorological conditions that often occur at scales smaller than GCMs currently resolve. As a result, accurate regional precipitation projections require GCM models with higher resolution and accuracy than current models provide. Doherty and Mearns (1999) show that both GCMs used in the National Assessment have similar biases (they are too wet over the intermountain West and the northeastern U.S. in spring and summer and too dry over the southeast and lower Mississippi region in winter and summer). When run with climate-change scenarios, the Canadian model shows precipitation declines by 2030 while the Hadley model shows precipitation increases. By 2095, both models show increases in precipitation of between 17 and 23% over the U.S. The largest percentage increases are in the southwestern U.S., California, and the Rocky Mountain region, and during winter months (Felzer and Heard 1999). Hadley shows the southeastern U.S. becoming wetter, while the Canadian model shows the same area becoming drier. Table 6 and Figures 8 and 9 show changes in precipitation for 2030 and 2095 for these two different models.

Table 6:
Changes in Annual Mean Precipitation, Hadley and Canadian Climate Models

	Ratio Canadian 2030	Ratio Hadley 2030	Ratio Canadian 2095	Ratio Hadley 2095
Northwest	1.08	1.11	1.31	1.13
Southwest/California/Rockies	1.16	1.08	1.67	1.27
Great Plains	0.98	1.06	1.13	1.16
Great Lakes/Midwest	0.98	1.09	1.20	1.27
Southeast	0.81	1.03	0.87	1.22
Northeast	0.94	1.08	1.00	1.24
United States	0.96	1.06	1.17	1.23

Note: The precipitation ratio is the ratio of precipitation in the year 2030 or 2095 compared to current average model precipitation. These averages hide regional discrepancies. Some large areas with increases or decreases in precipitation may have areas where precipitation changes in the opposite direction. Source: B. Felzer, www.cgd.ucar.edu/naco/vemap/annual.html

Because of the differences between these and other model results, researchers have little confidence in specific regional projections of precipitation.

Potential changes in rainfall intensity and variability are difficult to evaluate because intense convective storms tend to occur over smaller regions than global models are able to resolve. In the mid-latitudes, changes in precipitation must be carefully evaluated with changes in evaporation from higher temperatures, and few consistent results have been reported from GCMs. Changes in seasonal precipitation are even more variable over different regions.

Evaporation and Transpiration

Water is returned to the atmosphere through evaporation from land and water surfaces and transpiration from plants. Evaporation of water into the atmosphere is a function of many things, including climate and landscape conditions, such as humidity, wind speed, the availability of water and energy, and vegetation and soil characteristics. It is well established that as temperatures rise, the energy available for evaporation increases and the atmospheric demand for water from land and water surfaces increases. A warmer atmosphere can hold more water, but actual changes in both potential and actual evapotranspiration will depend on many factors, including the ability of the atmosphere to hold water (the humidity), changes in the movements of air (wind patterns), changes in net radiation (which can increase or decrease due to cloud cover), and available soil moisture.

The rate of evaporation is critical to a region's hydrologic balance. Increasing average temperatures generally lead to an increase in the potential for evaporation, though lower radiation and increased atmospheric water vapor content can reduce evaporative demands. Evaporation is driven by the availability of energy, but actual evaporation rates are constrained by the actual water availability on land and vegetation surfaces and in the soils. In temperate zones, atmospheric moisture content can limit evaporation rates, so changes in humidity are relatively important. Vegetative cover is also important because plants intercept precipitation and transpire water back to the atmosphere. Different vegetation types play different roles in evaporation, so evaluating the overall hydrologic impacts of climate change in a region requires having some understanding of the ways in which vegetation patterns may change.

Transpiration is also affected by a wide range of factors, including plant type and cover, root depth, stomatal behavior, and the concentration of carbon dioxide in the atmosphere. Some laboratory and field studies have shown that certain plants will decrease water use when exposed to higher carbon dioxide levels. Other studies suggest that much of this improvement can be lost if plants grow more and the increased leaf area offsets increased water-use efficiency (Field et al. 1995, Korner 1996, Rötter and Van de Geijn 1999). Evidence also suggests that some plants acclimatize to increased CO_2 levels, limiting improvements in water-use efficiency, and that nutrients other than water sometimes limit growth. One study suggests that water resources in the Delaware River Basin are sufficiently sensitive to changes in stomatal resistance that increased water-use efficiency by plants could offset to some extent the effects of higher temperatures and lower precipitation (Lins et al. 1997). Real-world effects make laboratory findings hard to reproduce in the field or inappropriate to generalize to large catchments. These issues continue to be major concerns for hydrologists, soil scientists, and plant physiologists (further details on this issue can be found in the Agricultural Sector report). Climate models have consistently projected that global average evaporation would increase in the range of three to 15% for an equivalent doubling of atmospheric carbon dioxide concentration. The greater the warming, the larger these increases. Moreover, regional increases in potential evaporation could be as high as 40% in humid temperate regions (IPCC 1996c). There is a significant difference between the actual and potential rates of evaporation in a basin. Higher temperatures will lead to an increase in potential evaporation, but could result in lower actual evaporation if water availability decreases due to soil-moisture drying or lower precipitation.

Variability, Storms, and Extreme Events

Climates vary naturally on all time-scales. These variations are caused by processes internal (such as ocean dynamics) and external (such as solar variability) to the climate system. These processes will continue to exert an important influence on the climate system even as changes induced by rising concentrations of greenhouse gases begin to be felt. Natural variations in climate complicate unambiguous detection of the human-induced greenhouse effect and are also a reason why future climate projections will never be perfect.

Existing variability of climate has profound impacts on humans, primarily through the costs of flood and drought events or through the cost of implementing options and building infrastructure to prevent them. Storms also help renew beaches or flush coastal ecosystems, and intense storms in some regions provide important water supplies. In recent years there have been new efforts to understand how natural patterns of variability, such as hurricanes, intense rainstorms, and El Niño/La Niña events, affect U.S. water resources (McCabe 1996, Vogel et al. 1997, Piechota et al. 1997). This research consistently notes that the hydrological “baseline” used by water planners and systems designers cannot be assumed to be constant, even without climate changes. It also helps to identify vulnerabilities of existing systems to hydrologic extremes and provides information that should be useful to those interested in the issue of adaptation and coping.

As CO_2 and other trace-gas levels change and circulation of the atmosphere adjusts, storm frequency and intensity may change as well. An important question, therefore, is what global climate changes may do to the frequency and intensity of weather events and systems, such as precipitation or temperature extremes, cyclones, hurricanes, and longer duration circulation phenomena like El Niño. The connection between elevated greenhouse gas concentrations and these extreme events has been inadequately studied and there is low confidence in the few available results.

Only in the past few years have models improved enough to begin to look at higher-order features such as extreme events in more detail. This is a product of the rapid development of climate modeling capabilities in concert with increased computer resources. Current global coupled climate models have improved resolution, more detailed and accurate land-surface simulations, and dynamical sea-ice formulations. Some have even higher resolution in the ocean near the equator (leading to improved simulations of El Niño and La Niña events). Techniques for studying climate processes at smaller regional scales from GCM results have also improved, through either embedding high-resolution regional models (with grid points every 50 km or so) in the global models or using statistical downscaling techniques. Despite these improvements, the models still have limitations in terms of spatial resolution, simulation errors, and parameterizations of processes that cannot yet be included explicitly in the models, such as those dealing with clouds and small-scale precipitation. As a result, researchers have varying degrees of confidence in many of the quantitative aspects of the model simulations (Meehl et al. 2000).

A growing number of model studies suggest that the variability (as measured, for example, by the interannual standard deviation) of the hydrologic cycle increases when mean precipitation increases and vice-versa. In one model study looking at convective systems, the total area over which precipitation fell decreased, even though global mean precipitation increased (Noda and Tokioka 1989), implying more intense local storms and, perhaps, increased runoff as well. Increased precipitation intensity (with widely varying regional changes) in a future climate with increased greenhouse gases was seen in early model results and this result also appears in improved, more detailed models (Kothavala 1997; Hennessy et al. 1997).

Increases in extreme precipitation events recently have been projected in nested regional models over the United States (Giorgi et al. 1998), and in a high-resolution nested hurricane model over the north-west tropical Pacific (Knutson and Tuleya 1999). In a recent global model simulation with doubled CO_2, precipitation extremes increased more than the mean (the mean increase was 4%; 20-yr extreme precipitation event return values increased 11%) with a decrease in the return period of 20-yr extreme precipitation events to 10 years over North America (Zwiers and Kharin 1998).

Another long-standing model result points to an increase in drought, represented by a general drying of mid-continental areas during summer with increasing CO_2 (e.g. Rind et al. 1990). This finding has been reproduced with the latest generation of global coupled climate models (Haywood et al. 1997; Wetherald and Manabe 1999, Meehl et al. 2000). The increased risk of drought during summer results from a combination of increased temperature and evaporation along with decreased precipitation. Analysis of one GCM showed this effect to be the result of large increases in the frequency of low summer precipitation, a higher probability of dry soil, and the occurrence of long dry spells ascribed to the reduction of rainfall events in the model rather than decreases in mean precipitation (Gregory et al. 1997).

General studies on climate change and storminess note that there are two possible conflicting effects on extratropical storms. Some model projections of CO_2-forced climate change suggest that storms in a climate-changed world should, on average, be fewer in number but stronger in intensity. Enhanced warming at high latitudes near the surface leads to reduced meridional temperature gradients in the lower troposphere and hence fewer storms. In contrast, more warming at the surface than aloft and a wetter atmosphere arising from increased latent heating should result in reduced atmospheric stability, increased convection, and a more vigorous hydrologic cycle, which might support more storms and perhaps more intense storms as well (Carnell and Senior 1998, Hayden 1999). Combining these processes, Lambert (1995) found that earlier scenarios from the Canadian model produced fewer, but more intense storms, on a global basis. Other model studies have also suggested that higher CO_2 levels might produce more intense storm events (Frei et al. 1998).

Limitations in earlier global climate models meant there have been few studies of future changes in the frequency, location, and strength of extratropical storms. Recent improvements in models make such studies more credible, but results are still mixed and highly uncertain. For example, a storm track analysis of a GCM with doubled CO_2 indicates a northeastward shift of storm frequency in the North Atlantic, with little change in storm intensities (Schubert et al. 1998), though another study found a reduction of intensity (Beersma et al. 1997), and still another found an increase (Lunkeit et al. 1996). An analysis of an ensemble of four future climate-change experiments in a global coupled model with increased CO_2 and sulfate aerosols showed a decrease in the total number of Northern Hemisphere storms, but an increase in the number of the most intense storms (Carnell and Senior 1998). Knutson and Tuleya (2000) note increased hurricane intensities with CO_2-induced warming from one GCM.

Both the Canadian and Hadley models show decreases in the number of Atlantic storms, but the Canadian model is able to simulate the storm track along the eastern seaboard, whereas the Hadley model only simulates the storm track in the North Atlantic (Felzer and Heard 1999). Both models show increased storm counts in the Gulf of Alaska where Pacific storms terminate; the Canadian model shows decreased storm counts off the southeastern U.S. where Atlantic storms originate. Because the Atlantic storm track in the Canadian model appears further south and west than that of the Hadley model, the decrease in storms in the Canadian model contributes to the decrease in precipitation seen in the model results for the southeastern U.S. The two models disagree about changes in storm counts in the eastern and western U.S. Both models generally show more intense storms, so regions of decreased storm frequency may actually see increased precipitation (Lambert 1995, Carnell and Senior 1998, Felzer and Heard 1999).

Hayden (1999) also evaluated the Hadley climate models runs for 2030 and 2095 (the Canadian model results were not available at the time). Storm occurrences are calculated from the low-pressure systems or other model outputs (such as variances in geopotential heights). Extratropical storms are an important cause of beach erosion and flooding of wetlands with saline water and they provide essential precipitation that drives much of the hydrological cycle in middle and high latitudes. Using these model output data, Hayden found no sensitivity of North American storm tracks to increasing CO_2. The author notes the need for better regional resolution of storm tracks, particularly in the western U.S. (Hayden 1999). He concludes, however, that GCMs remain the best tool for ultimately accounting for the effect of greenhouse-gas accumulations on storms and recommends that this capacity in model development should be further refined.

A model-based study released in 1999 suggests that the frequency of El Niño events may increase due to greenhouse warming. Timmermann et al. (1999) used a high-resolution global climate model to simulate the El Niño/Southern Oscillation phenomenon (ENSO) under conditions of warming. Their model indicated that the tropical Pacific climate system would undergo systematic changes if greenhouse gas concentrations doubled. In particular, their results suggest a world where the average condition is like the present-day El Niño condition and events typical of El Niño will become more frequent. Their results also found more intense La Niña events and a stronger interannual variability, meaning that year-to-year variations may become more extreme under enhanced greenhouse conditions. More frequent or intense El Niños would alter precipitation and flooding patterns in the United States in a significant way. Conflicting conclusions about storms support the need for higher-spatial-resolution models with better cloud and precipitation processes. Progress in such efforts should be regularly revisited in later assessments.

Snowpack, Glaciers, and Permafrost

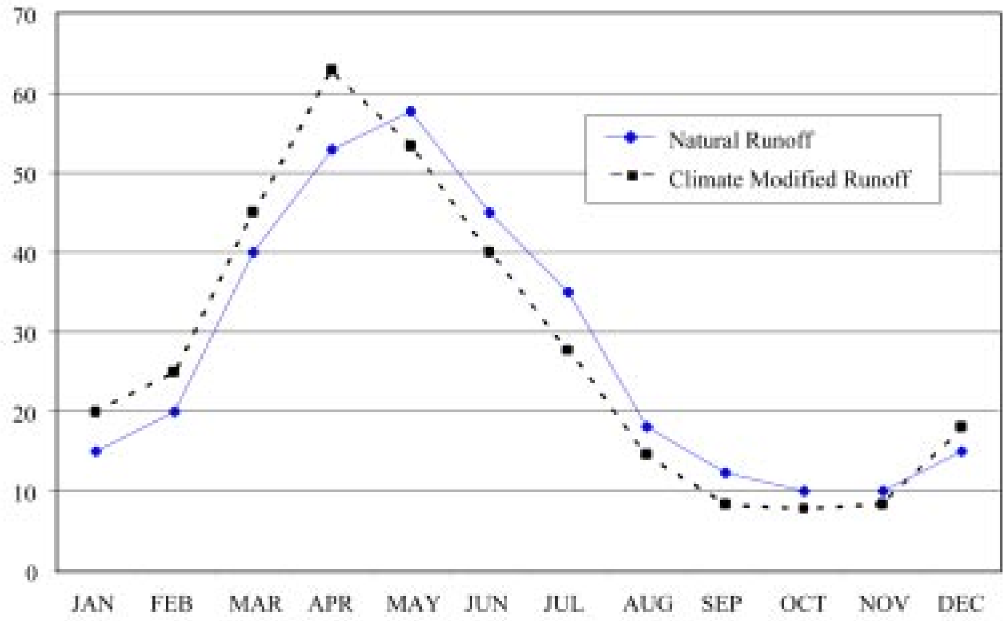
Seasonal snow accumulation is an important source of water storage and runoff in many parts of the world, including the western United States. Despite all of the uncertainties about how increased greenhouse gas concentrations will affect precipitation, there is very high confidence that higher temperatures will result and, as discussed in the following section, are likely already occurring. The greatest increases in temperature are expected to be in higher latitude regions because of the dynamics of the atmosphere and feedbacks among ice, albedo, and radiation. A growing amount of research has established that higher temperatures will lead to dramatic changes in snowfall and snowmelt dynamics in watersheds with substantial snow. Higher temperatures will have several major effects: they will increase the ratio of rain to snow, delay the onset of the snow season, accelerate the rate of spring snowmelt, and shorten the overall snowfall season, leading to more rapid and earlier seasonal runoff. They can also lead to significant changes in the distribution of permafrost and the mass balances of glaciers.

As early as the mid-1980s, regional hydrologic studies of global warming impacts suggested with increasing confidence that higher temperatures will affect the timing and magnitude of runoff in these regions and studies have now shown that all watersheds with substantial snow dynamics are likely to be affected (see, for example, Gleick 1986, Gleick 1987a,b, Lettenmaier and Gan 1990, Lettenmaier and Sheer 1991, Nash and Gleick 1991, Miller et al. 1992, Cooley et al. 1992, Martinec et al. 1992, Rango and Martinec 1994, Rango 1997, Leung and Wigmosta 1999, Hamlet and Lettenmaier 1999). Indeed, over the past two decades, this has been one of the most persistent and well-established findings on the impacts of climate change for water resources in the United States and elsewhere. Figure 10 shows how a snow basin hydrograph may shift with warming. Figure 11 shows how snow levels in higher elevation regions may be affected.

A few broad assessments have simulated the effects of climate change on snowpack in the United States (McCabe and Legates 1995, Cayan 1996, McCabe and Wolock 1999). McCabe and Wolock (1999) evaluated the links between climate conditions and snowpack for over 300 different snow sites in the western U.S., organized into major clusters around the Pacific Northwest, the Sierra Nevada, and the Colorado basin. They used long-term historical records to develop a snow model that used altered climate information from GCMs. For most of the sites, strong positive correlations were found between precipitation and snowpack; strong negative correlations were found between temperature and snowpack. These correlations indicate that the supply of winter moisture is the best predictor of snowpack volume, while temperature is the best predictor of the timing of snowmelt and the overall nature of the snow season. This correlation breaks down only for those high-altitude sites where mean winter temperatures are so cold that the ratio of rain to snow is not affected.

Both the Canadian and the Hadley models project large increases in winter temperature over the next century and increases in winter precipitation for the Sierra Nevada sites

Figure 10:
Hypothetical Natural and Modifed Average Hydrograph For Basins with Snowfall and Snowmelt



Source: Gleick and Chalecki (1999).

Figure 11:
Possible Effects of Warming on Snowline in Higher Elevation Regions

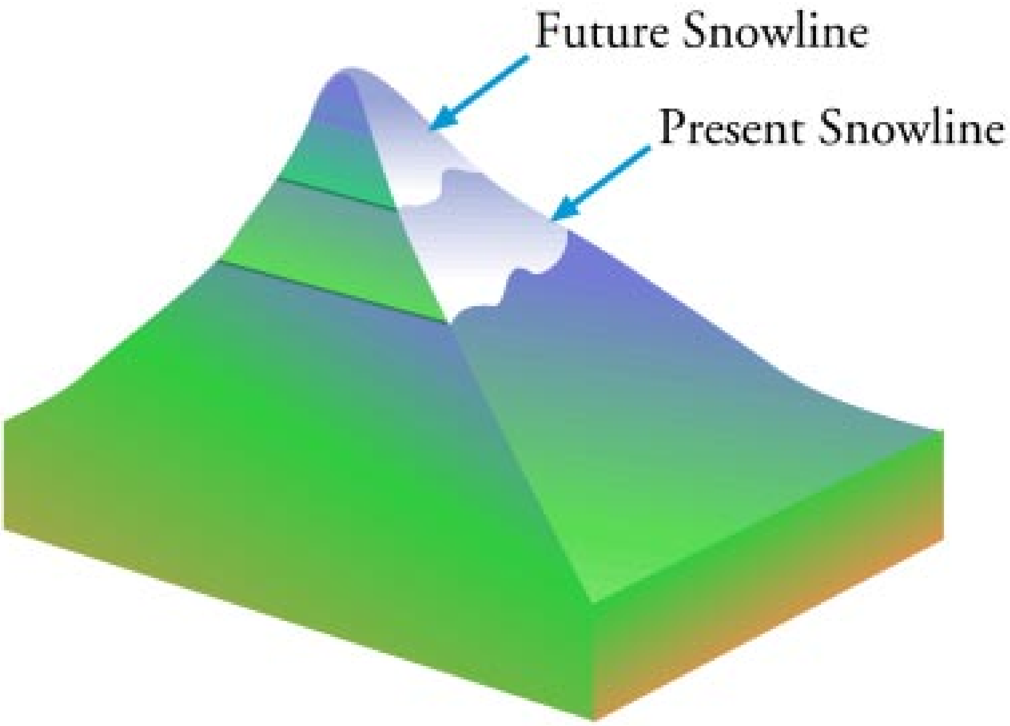
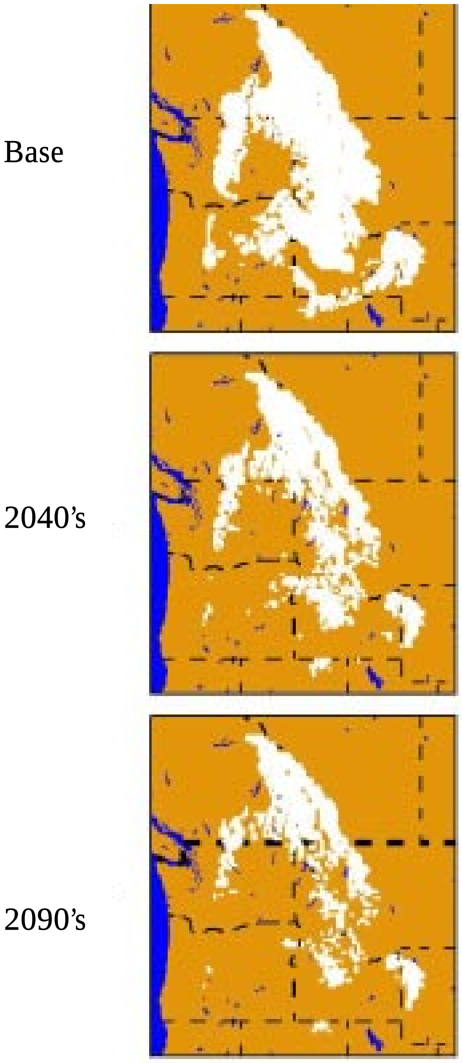


Figure 12:
Average April 1 Snow Cover



Source: Hamlet and Lettenmaier (1999).

(McCabe and Wolock 1999). The Canadian model simulates slight initial decreases in winter precipitation for the other clusters by mid-century and increases for all clusters by the end of the 21st century. The Hadley model simulates increased temperature and precipitation during the coming century for all clusters. As a result of the higher temperatures, both models show large decreases in April 1 snowpack for all of the snow sites in the western U.S., with the exception of the Central Rocky Mountain region in the Hadley model where increases in temperature still did not force winter temperatures above freezing. In some of the more extreme cases, model snowpack is completely eliminated by the end of the next century, although some snowfall and snowmelt would certainly continue in high-altitude sites.

The results from McCabe and Wolock (1999) for the Pacific Northwest are similar to those obtained by Hamlet and Lettenmaier (1999) for the Columbia River basin. Hamlet and Lettenmaier used a regional hydrologic model driven by GCM climate scenarios and found that by 2045, winter precipitation in the Columbia basin would increase significantly but that spring snowpack will be substantially reduced because of higher temperatures. Overall, the timing of runoff peaks shifts dramatically from the spring to the winter, with increases of as much as 50%, followed by decreases in spring and summer runoff. By 2095, the Hadley climate models suggest that the Columbia River basin will no longer be dominated by snowmelt dynamics. Figure 12 shows how long-term average snow conditions on April 1 in the Pacific Northwest will change using changes in climate from the Hadley center projections, for the 2040s and the 2090s (from Hamlet and Lettenmaier 1999).

Other regional snow and ice effects are important to note, particularly in the higher latitudes of the United States. Alaska has extensive glaciers and permanently frozen soil (permafrost). Global warming will have direct and indirect impacts on these resources. Davidovich and Ananicheva (1996) simulated the behavior of Alaskan glaciers under temperature increases and concluded that they will experience significant retreat but also an increase in mass due to increased winter snow accumulation. This result is similar to that of Oerlemanns et al. (1998) who showed in a mass balance of 12 valley glaciers and ice sheets that most climate-change scenarios lead to glacial retreat. In the absence of any change in precipitation, a temperature rise of 0.4° C per decade would virtually eliminate all 12 glaciers by 2100. Even a 0.1° C increase per decade leads to reductions in glacier volume of 10 to 25%.

Thawing of permafrost in interior and northern Alaska will increase rates of soil-moisture infiltration and the amount of water stored in aquifers and the active layer of the soil. This will generally result in decreased flood peaks and increased base runoff. The reduction of peak flow caused by increased infiltration of rain into the aquifer is likely to be offset, however, by increased frequency and quantity of precipitation. Similarly, the increase in baseflow may be offset by increased rates of evapotranspiration and by decreasing volumes of melt water from glaciers over time. Baseflow reductions associated with recession of glaciers will be most severe in basins with small glaciers that disappear during a warmer climate.

A range of other impacts in the high latitudes is also possible. Many of Alaska's hydropower sites obtain runoff from melting glaciers. As glaciers become smaller, flow variability may increase, with reductions in the reliability of hydroelectricity generation. While glacier melt increases, total hydroelectricity production may increase. Baseflows in summer are also critical to transportation – higher base flows mean longer shipping seasons. Increased winter baseflow under warmer climate may increase icing along roads, streams, and culverts, increasing maintenance costs. As permafrost thaws, water tables under hills retreat and wells may have to be drilled deeper or in new locations. Loss of permafrost has already led to subsidence and damage to roads requiring extensive and expensive road repairs (Weller and Anderson 1998). Less extensive permafrost, increased depth to the water table, and increased groundwater fluxes will enhance the performance of sewage disposal systems that discharge to the subsurface. Increased streamflow and decreased ice cover will enhance aeration and dilution of surface-discharged effluent. More water will be available for construction of ice roads, but a shorter freezing season would mean the roads can be used for shorter periods (Weller and Anderson 1998).

Large-Area Runoff

Changes in runoff in the future depend on changes in a wide range of factors, most notably precipitation and temperature. These climate variables have a direct effect on runoff from surface systems, but runoff in actual watersheds or rivers is rarely explicitly evaluated in GCMs because they lack the detailed resolution necessary to include other critical watershed characteristics. Results from two approaches to projecting the impacts of climate change on runoff are presented in this section. The first approach uses general water-balance models to evaluate large regional impacts of GCM-generated climate conditions. The second couples a detailed soil-water assessment tool with a GIS-based watershed-modeling tool. Each approach has advantages and limitations. The following section reports on the use of more detailed regional hydrologic models to evaluate the sensitivities of specific watersheds to anticipated climate changes.

Runoff changes at the largest scales broadly follow changes in precipitation patterns. The Canadian and Hadley models were used in a separate analysis of runoff in the water resource regions of the United States (Wolock and McCabe 1999). (Figure 13 shows a map of U.S. hydrologic regions.) Wolock and McCabe converted GCM-generated estimates of precipitation and temperature into runoff using a modified water-

Figure 13:
U.S. Hydrologic Regions

Source: Wolock and McCabe (1999).

balance model and geographical downscaling of climate parameters. Mean annual runoff was generated for two future decades (2025 to 2034 and 2090 to 2099) for the water resource basins and subbasins in the conterminous United States. Table 7 indicates the percentage changes in mean annual runoff for these regions for the two future periods using the outputs of the two GCMs.

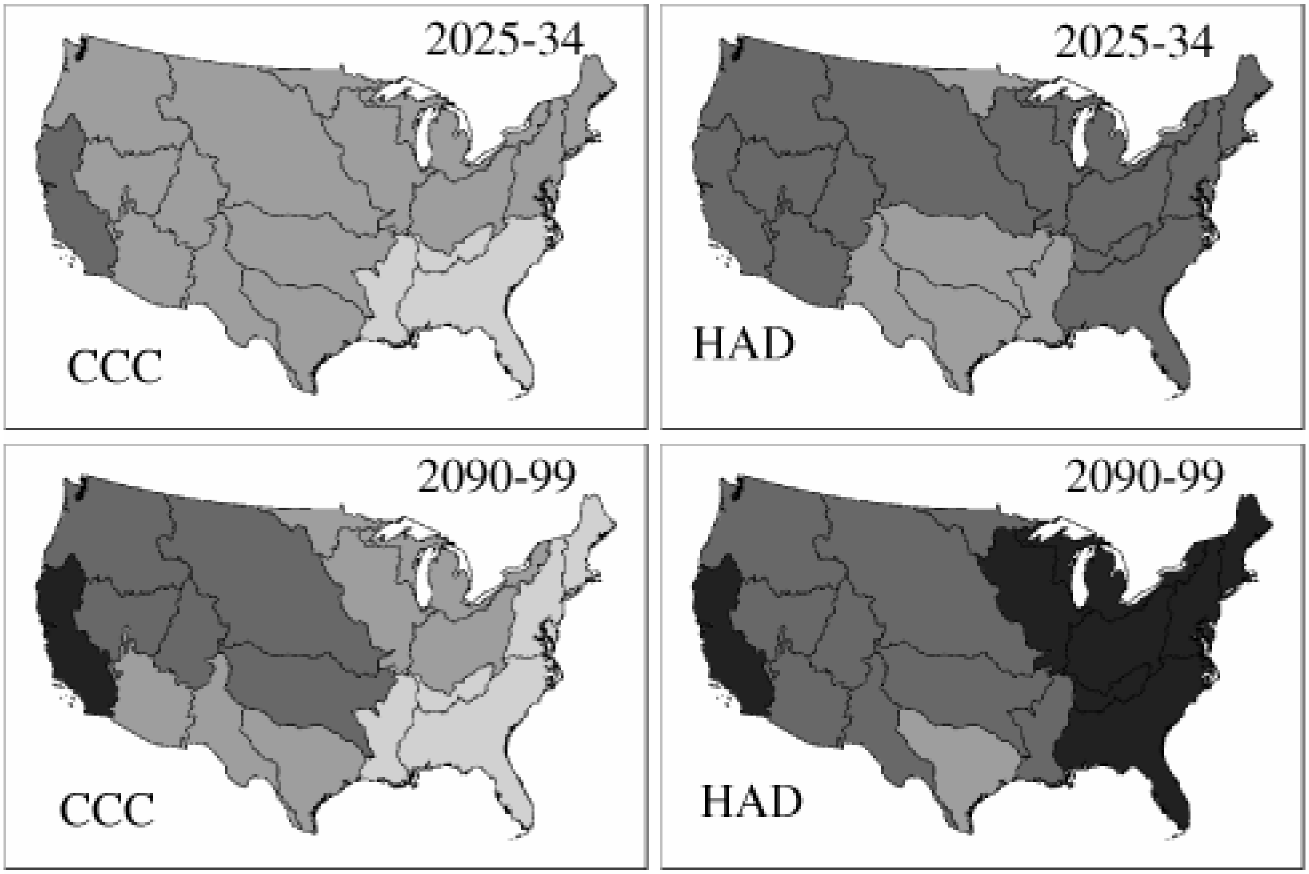
The changes in runoff resembled the overall nature of the changes in precipitation, in large part because precipitation is the primary factor in determining runoff, with increased flows in higher latitude regions and decreases in sub-tropical areas. In most water-resource regions of the United States, the Canadian model produced decreases in runoff and the Hadley model produced increases in runoff (see Figure 14). With the exception of California (which is projected to receive about 30% more runoff in 2030) and the Souris-Red-Rainy region (which is projected to receive 18 to 24% less runoff), the runoff

Table 7:
Percent Changes in Runoff from Two GCM Scenarios

River Basin/ Hydrologic Region	Region No.	Hadley change in runoff 1990-2030 (%)	Hadley change in runoff 1990-2090 (%)	Canadian change in runoff 1990-2030 (%)	Canadian change in runoff 1990-2090 (%)
New England	1	9	28	-8	-19
Mid-Atlantic	2	10	33	-13	-25
South Atlantic-Gulf	3	0	31	-61	-73
Great Lakes	4	20	55	-12	-10
Ohio	5	7	43	-16	-18
Tennessee	6	4	40	-33	-37
Upper Mississippi	7	21	68	-22	0
Lower Mississippi	8	-10	16	-65	-59
Souris-Red-Rainy	9	-18	79	-24	-80
Missouri	10	18	45	-25	48
Arkansas-White-Red	11	-1	43	-39	6
Texas-Gulf	12	-10	-8	-87	-34
Rio Grande	13	-3	60	-63	-56
Upper Colorado	14	7	66	-36	5
Lower Colorado	15	245	1,361	-67	-29
Great Basin	16	21	138	-7	75
Pacific Northwest	17	15	12	-2	18
California	18	30	134	29	161

Note: Region 19 (Alaska), Region 20 (Hawaii), and Region 21 (Puerto Rico/Caribbean) were not included in this analysis.
Source: Wolock and McCabe (1999).

Figure 14:
Changes in Runoff by Hydrologic Region, Using Two GCM Model Results



Change in mean annual runoff (mm)

░ -101 and lower
▒ -100 to 0
▓ 1 to 100
█ 101 and higher

Source: Wolock and McCabe (1999).

projections for the year 2030 derived from the two climate models suggest very different scenarios. The Canadian model results indicate that runoff would decline by 2030 in all regions except California. In 12 of the 18 regions, runoff declines by more than 20%, outcomes that could have serious adverse impacts if not addressed by water managers. In contrast, the Hadley model projects increases in average runoff in most regions: most of the nation's arid and semiarid regions would have substantially more water, reducing problems of water scarcity but perhaps increasing the threat of floods. By the year 2090, most of the U.S. is projected to be even wetter under the Hadley model; the Canadian model suggests some further drying in the East but an increase in supplies in much of the West (Wolock and McCabe 1999). The changes in runoff for the period 2025-2034 were, for the most part, smaller in magnitude than natural variability and the expected error in the simulations. For the period 2090-2099, runoff changes in several regions were more significant, though the overall results are still highly uncertain.

Several different conclusions can be drawn from these results. First, the great differences in results show the difficulty of making accurate "predictions" of future runoff – these results should be viewed as sensitivity studies and used with considerable caution. Second, runoff is extremely sensitive to climate conditions. Large increases in precipitation will probably lead to increases in runoff: such increases can either worsen or lessen water management problems, depending on the region and the nature of the problem. Third, far more work is needed, on a regional scale, to understand how climate will affect national water resources. Until GCMs get better at evaluating regional temperature and precipitation, their regional estimates of future runoff must be considered speculative and uncertain. While it is well established that changes in runoff are likely to occur, we have little confidence that we understand how specific regions will be affected. The above discussion and model results highlight many of the uncertainties surrounding the implications of climate change for overall water availability.

Another large-scale runoff modeling study for the National Assessment was conducted under the auspices of the Pacific Northwest National Laboratory (PNNL) climate group. This project used a GIS-based modeling system (HUMUS) that provides input for a soil water "assessment tool" (SWAT) (Arnold et al. 1998, Arnold et al. 1999, Srinivasan et al. 1993). HUMUS was used to simulate the workings of the hydrologic cycle at the scale of the 8-digit United States Geographic Survey Hydrologic Unit Areas (HUA) (USGS 1987) using inputs assembled for the conterminous United States at the scale of 1:250,000. For the National Assessment project, analysis was confined to the Hadley 2025-2034 and 2090-2099 climate scenarios. The much drier Canadian climate scenarios would have led to quite different conclusions.

The soil-water model represents the basin water balance through four storage volumes: snow, 0-2 meters of soil, the shallow aquifer (2 – 20 m), and the deep aquifer (> 20 m). Hydrologic processes simulated in the model include infiltration, evapotranspiration (ET), net primary productivity, lateral flow, percolation, and total water yields (including surface runoff and changes in groundwater storage). The model also includes algorithms to simulate the effect of higher CO_2 concentrations on photosynthesis and on water-use efficiency (WUE) through increased stomatal resistance for C3 and C4 vegetation (Stockle et al. 1992a, 1992b). The HUMUS simulations of climate change effects in 2030 and 2095 were made under two CO_2 concentrations: recent ambient (365 ppm) levels and levels elevated to represent a doubling of the pre-industrial concentration (560 ppm).

In the model, higher temperatures in the 2030 time period increase evapotranspiration (ET) over most of the United States, most notably in the northern part of the country. These increases result from the combination of higher temperatures and increased precipitation. The extended growing season and increased net primary productivity – two other effects of climate change – also impact ET since both increase plant water use. Annual ET rates in the Lower Colorado and Rio Grande Basins are decreased by 29 and 3 mm, respectively. This, at first glance, appears inconsistent with the higher temperatures and increased annual precipitation projected in these regions. The explanation is found, however, in the seasonality of the precipitation change. The Lower Colorado experiences a 67% increase in precipitation during winter. Most of the added water is lost as runoff during spring snowmelt and is not be available for transpiration by vegetation during the growing season. Offsetting the increased winter precipitation is a 39% decrease in summer precipitation that reduces water available for vegetation during the growing season.

With no CO_2-fertilization, simulated water yields increase from baseline in most of the 2-digit hydrologic regions under the Hadley scenario for 2030 (see Figure 13 for the regions). Greater precipitation in the Pacific Northwest raises water yield; the Lower Mississippi, Souris-Red-Rainy and Texas Gulf regions experience decreases in water yield. While these reductions are primarily driven by reduced precipitation, higher temperatures also contribute to reduced water yield in these regions by increasing ET, which, in turn, reduces lateral flow and groundwater recharge. Water yield in southern U.S. basins (Lower Mississippi, Texas Gulf) may be more sensitive to increased temperature since these regions are already quite warm.

The HUMUS simulations show that ET is increased with further warming and the generally wetter climate projected by Hadley for 2095. Evapotranspiration is most sensitive in the northern United States In the Pacific Northwest, ET increases 37% from baseline; in the Souris-Red-Rainy basin ET increases 34%. Despite these large increases in ET, water yields still increase over almost all of the conterminous United States because of the greater precipitation produced by the Hadley model. One would expect water yields to decline significantly with the scenario of reduced precipitation produced by the Canadian model. Figure 15a and 15b show model changes in water yields throughout the U.S. for the two periods (Brown et al. 1999).

In the western/mountain regions, water yields increase in late winter/early spring because of increased runoff. This is due to the seasonality of the precipitation changes and to an earlier spring snowmelt caused by the projected warming under climate change (see also the discussion of this effect above). Rising temperatures also impact annual water yields by increasing ET, thereby reducing the contribution of lateral flow to streamflow and groundwater recharge. This combination results in a marked increase in water yield during late winter and early spring and in some cases a reduction in water yield during the summer. If there is no general increase in precipitation in these regions the early snowmelt will lead to shortages of water in summer. The hydrology of these systems is controlled by the timing and intensity of the spring snowmelt, impacted principally by the degree of warming during this time period.

Brown et al. (1999) concluded that the potential impact of increased precipitation and the subsequent increases in water yields are of large enough dimensions to require

Figure 15a:
Climate-Induced Changes in Actual Evapotranspiration: Hadley Projections

These maps show annual baseline actual evapotranspiration (AET) by watershed in the United States (top map) and deviations from that baseline for the Hadley climate model (HadCM2) in 2030 (middle map) and 2095 (bottom map). All values are in mm. Source: Brown et al. (1999).

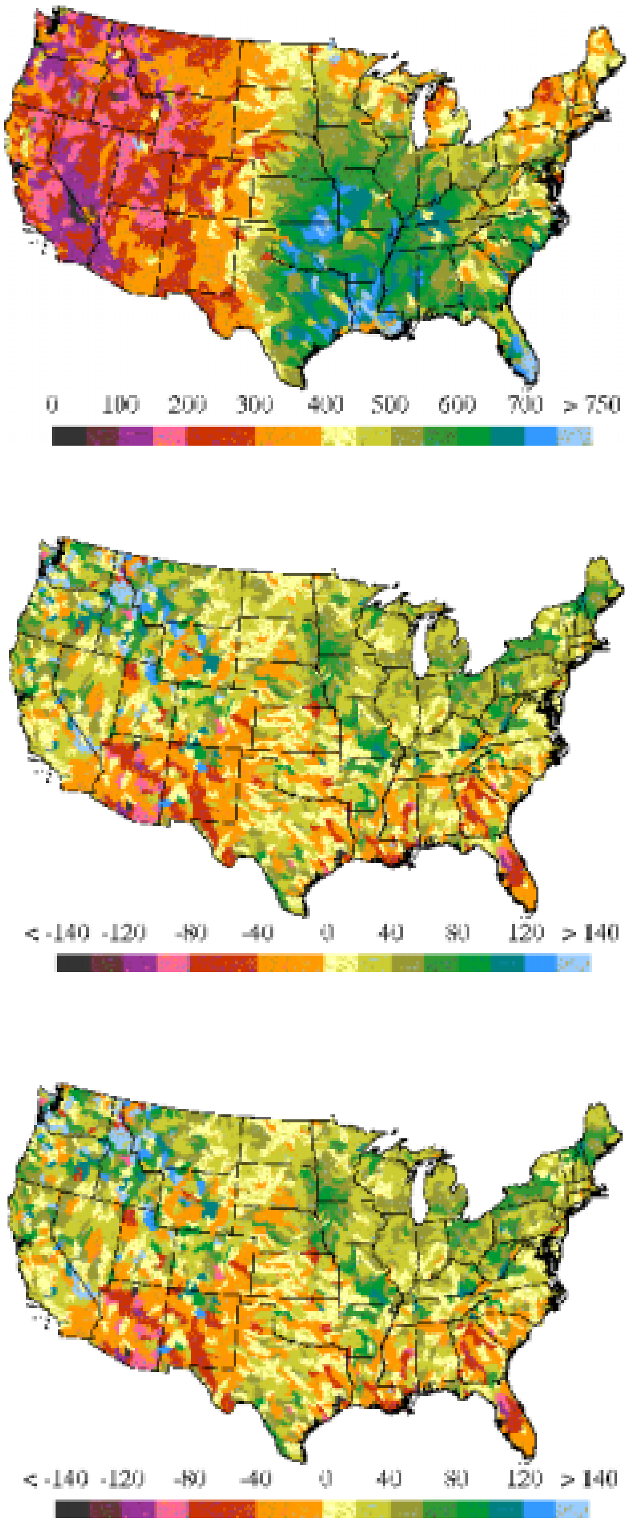
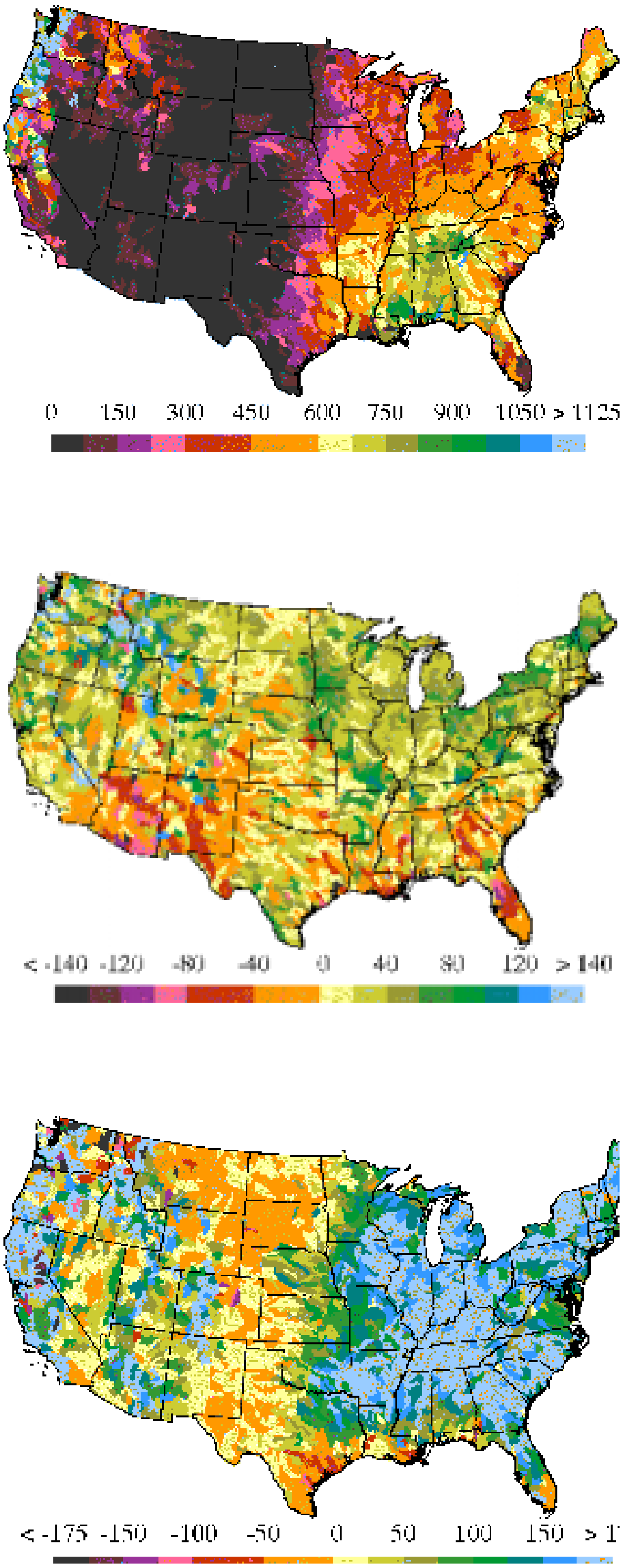


Figure 15b:
Climate-Induced Changes in Water Yields: Hadley Projections

These maps show annual baseline water yields by watershed in the United States (top map) and deviations from that baseline for the Hadley climate model (HadCM2) in 2030 (middle map) and 2095 (bottom map). All values are in mm. Source: Brown et al. (1999).



consideration in any analysis of future regional or national water supply and demand. Table 8 compares the changes in runoff from the Brown et al. results and the results described above from Wolock and McCabe (1999). Although a much wetter climate is projected for most of the country by the Hadley climate model, some regions (such as the western Great Plains of Kansas, Colorado, and Nebraska) will experience decreased streamflow. The Great Plains are already heavily dependent on constrained water supplies for sustaining agriculture and they could be severely affected if the Hadley projections are realized. Another important consideration is the projected change in seasonality of the hydrologic cycle that would affect the heavily managed water systems of the western United States Because this study used climate change scenarios that maintained present-day climate variability, the results provide no insight as to how climate change would affect interannual variability of the spring snowmelt/runoff events.

Table 8:
Comparison of Wolock and McCabe (1999) and Brown et al. (2000) Simulated Changes in Runoff/Water Yield Driven by the Hadley 2035 and 2090 Climate Change Scenarios

Hydro Region	Region No.	Wolock and McCabe 1990-2030 change in runoff (%)	Brown et al. 1990-2035 change in runoff (%)	Wolock and McCabe 1990-2090 change in runoff (%)	Brown et al. 1990-2090 change in runnoff (%)
New England	1	9	12	28	32
Mid-Atlantic	2	10	18	33	43
South Atlantic-Gulf	3	0	13	31	42
Great Lakes	4	20	13	55	41
Ohio	5	7	18	43	50
Tennessee	6	4	22	40	63
Upper Mississippi	7	21	17	68	53
Lower Mississippi	8	-10	-2	16	35
Souris-Red-Rainy	9	-18	-29	79	14
Missouri	10	18	7	45	35
Arkansas-White-Red	11	-1	7	43	51
Texas-Gulf	12	-10	-5	-8	22
Rio Grande	13	-3	40	60	120
Upper Colorado	14	7	50	66	128
Lower Colorado	15	245	91	1,361	280
Great Basin	16	21	25	138	100
Pacific Northwest	17	15	45	12	44
California	18	30	24	34	82

Source: Brown et al. (1999).

Regional Runoff

Runoff integrates changes in hydrologic characteristics over a large area and is a particularly valuable indicator of climate change. As noted in the section above, however, large-area estimates of runoff are both uncertain and less valuable for regional water managers. Many detailed estimates of changes in runoff due to climate change have been produced for the United States using regional hydrologic models of specific river basins. In spite of their inevitable uncertainties, it is instructive to review the results of these past studies. By using anticipated, hypothetical, or historical changes in temperature and precipitation and models that include realistic small-scale hydrology, modelers have consistently seen significant changes in the timing and magnitude of runoff resulting from quite plausible changes in climate variables. With some exceptions, however, there is low confidence in specific regional projections because estimates of precipitation changes at regional and finer scales vary substantial from climate model to model. Society and natural ecosystems are highly dependent upon river flows and any changes caused by the greenhouse effect would be cause for concern. Specific regional impacts will depend on both future climate changes as well as the economic, institutional, and structural conditions in any region.

In the arid and semi-arid western United States, it is well established that relatively modest changes in precipitation can have proportionally large impacts on runoff. Even in the absence of changes in precipitation patterns, higher temperatures resulting from increased greenhouse gas concentrations lead to higher evaporation rates, reductions in streamflow, and increased frequency of droughts (Schaake 1990, Rind et al. 1990, Nash and Gleick 1991, 1993). In such cases, increases in precipitation would be required to maintain runoff at historical levels.

In cold and cool-temperate zones of the United States, which includes most mid- to high-latitude areas and large areas of mountains, a large proportion of annual runoff comes from spring snowmelt. The major effect of warming in these regions is a change in the timing of streamflow, including both the intensity and timing of peak flows. A declining proportion of total precipitation falls as snow as temperatures rise, more winter runoff occurs, and remaining snow melts sooner and faster in spring (Gleick 1986, 1987a,b, Lettenmaier and Gan 1990, Nash and Gleick 1991, Miller et al. 1992, Cooley et al. 1992, Martinec et al. 1992, Burn 1994, IPCC 1996c, Leung and Wigmosta 1999, Hamlet and Lettenmaier 1999). In some basins, spring peak runoff may increase; in others, runoff volumes may significantly shift to winter months.

In southern portions of the United States, runoff is affected much more significantly by total precipitation. In these regions, the hydrologic regime is not dominated by snowfall and snowmelt but by seasonal cycles of rainfall and evaporation. In the arid and semi-arid regions of the United States, runoff is extremely sensitive to rainfall: a small percentage change in rainfall can produce a much larger percentage change in runoff (i.e., rainfall/runoff ratios are large).

Considerable effort has been made to evaluate climate impacts in particular river basins, including the Sacramento, the San Joaquin, the Delaware, the Mississippi, the Colorado, the Columbia, the Carson/Truckee, the Apalachicola-Chattahoochee-Flint, and others. Many of them show large possible changes in future hydrologic conditions relative to historical conditions. Table 9 and Figure 16 provide estimates of the impacts of a range of temperature and precipitation changes on annual runoff for several mountainous river basins in the western United States. These model studies used a variety of climate scenarios ranging from GCM-derived temperature and precipitation estimates to paleoclimatic and hypothetical temperature and precipitation data used as sensitivity studies.

The results of the simulation studies summarized in Figure 16 and Table 9 support the conclusion that relatively small changes in temperature and precipitation can have large effects on runoff. In every one of these studies, an increase in temperature and no change in precipitation resulted in decreases in runoff. With no change in precipitation, estimated runoff declines by 3 to 12% with a 2° C increase in temperature and by 7 to 21% with a 4° C increase in temperature. A 10% reduction in precipitation and a 2°C increase in temperature reduce estimated runoff by between 13 to 40% in most studies. Increasing precipitation by 10% approximately balances evaporative losses resulting from an increase in temperature of 4°C. These results are not comprehensive, but are suggestive as to the possible magnitude and uncertainty surrounding the hydrologic implications of a greenhouse warming. In contrast to these variable results, shifts in runoff timing in basins with snowfall and snowmelt are consistent in all studies that looked at daily or monthly runoff. These studies show with very high confidence that increases in winter runoff, decreases in spring and summer runoff, and higher peak flows will occur in such basins if temperatures rise.

Georgakakos and Yao (2000a) investigated the response of eight basins in Georgia and Alabama using hydrologic watershed models forced by historic (1939 to 1993) and future (1994 to 2093) climate scenarios. The latter were generated using the Canadian and Hadley model projections. Compared to the historical (baseline) response, under the Canadian model results all basins exhibit less precipitation (ranging from 15 to 22% of the historical values), increased evapotranspiration (16 to 22% below historical values), less runoff (28 to 48% below historical values), and smaller runoff coefficients (13 to 35% below historical values). By contrast, under the Hadley model, the non-snowmelt driven basins experience higher precipitation (7 to 14 % above historical values), higher evapotranspiration (8 to 11% above historical values), higher runoff (7 to 21% above historical values), and higher runoff coefficients (1 to 10% above historical values). No appreciable seasonal shift was noted for any of these variables since these basins have limited snow, while runoff exhibited higher variability (Georgakakos and Yao 2000a).

Soil Moisture

Soil moisture is a crucial hydrologic variable of particular interest to many, including ecologists and farmers. Precipitation that does not evaporate back into the atmosphere, transpire immediately from vegetation, becomes incorporated into plant material, gets captured by humans for direct use, or runs off into rivers, lakes, or the ocean, infiltrates into the soil, where part of it may filter down to groundwater. The amount of water stored in the soils is influenced by vegetation type, soil type, evaporation rates, and precipitation intensity. Soil moisture is critically important in both supporting agricultural production and defining natural vegetative type and extent. Any changes in climate that alter precipitation patterns and the evapotranspiration regime will directly

Table 9:
Percent Changes in Runoff for Hypothetical Precipitation and Temperature Changes in Semiarid U.S. River Basins

Precipitation Changes	T + 2 C	T + 4 C	Watershed [Source]
-25%	-25%	-25%	Carson [7]
-25%	-51%	-54%	American [7]
-20%	—-	-41%	Upper Colorado [3]
-20%	-26%	-32%	Animas [3]
-20%	-31%	-34%	Sacramento [2]
-20%	-19%	-25%	East River
-20%	—-	-30%	East River [8]
-20%	-23%	-26%	White River
-12.50%	-24%	-28%	Carson [7]
-12.50%	-34%	-38%	American [7]
-10%	-28%	—-	Great Basin Rivers [1]
-10%	-18%	-21%	Sacramento River [2]
-10%	-23%	-31%	Colorado River (inflow to Lake Powell) [3]
-10%	-14%	-18%	White River [3]
-10%	-19%	-25%	East River [3]
-10%	-35%	—-	Upper Colorado [4]
-10%	-56%	—-	Lower Colorado [4]
-10%	-40%	—-	Colorado River [5]
-10%	-17%	-23%	Animas River [3]
0	-3%	-7%	Sacramento River [2]
0	-12%	-21%	Colorado River (inflow to Lake Powell) [3]
0	-4%	-8%	White River [3]
0	-9%	-16%	East River [3]
0	—-	-4%	East River 8]
0	-7%	-14%	Animas River [3]
0	-2%	—-	Animas River [6]
10%	27%	—-	Great Basin Rivers [1]
10%	12%	7%	Sacramento River [2]
10%	1%	-10%	Inflow to Lake Powell [3]
10%	7%	1%	White River [3]
10%	1%	-3%	East River [3]
10%	-18%	—-	Colorado River [5]
10%	3%	-5%	Animas River [3]
12.50%	13%	7%	Carson [7]
12.50%	20%	19%	American [7]
20%	—-	2%	Upper Colorado [3]
20%	14%	5%	Animas [3]
20%	12%	7%	East River [3]
20%	—-	23%	East River [8]
20%	19%	12%	White River [3]
20%	27%	23%	Sacramento [2]
25%	39%	32%	Carson [7]
25%	67%	67%	American [7]

[1] All Great Basin Rivers results from Flaschka, et al. (1987).

[2] All Sacramento River results from Gleick (1986, 1987a,b).

[3] All Lake Powell, White, East, and Animas River results from Nash and Gleick (1993).

[4] Stockton and Boggess (1979).

[5] Revelle and Waggoner (1983).

[6] Schaake (1990).

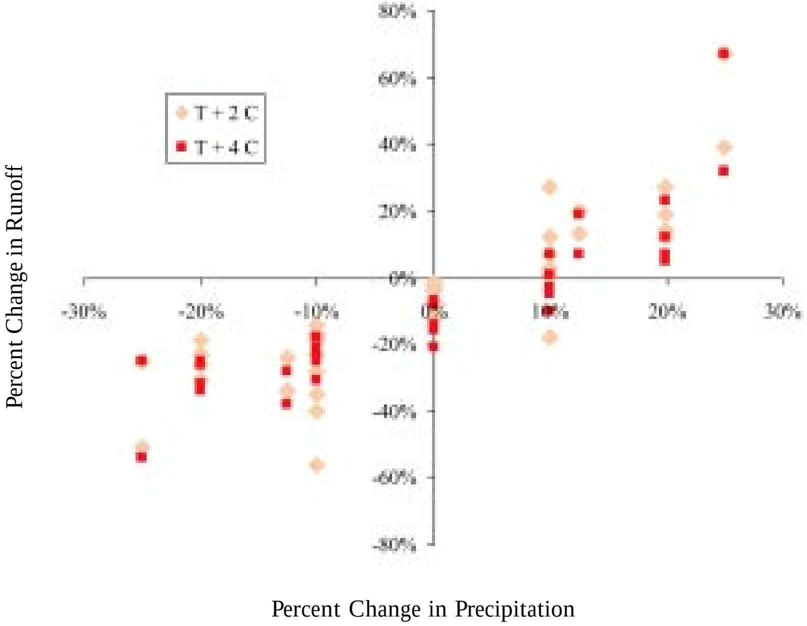
[7] Carson and American Rivers (North Fork) are from Duell (1992).

[8] McCabe and Hay (1995).

affect soil-moisture storage, runoff processes, and groundwater recharge dynamics. In regions where precipitation decreases, soil moisture may be significantly reduced. Even in regions with precipitation increases, soil moisture on average or over certain periods may still drop if increases in evaporation owing to higher temperatures are even greater, or if the timing of precipitation or runoff changes. Where precipitation increases significantly, soil moisture is likely to increase, perhaps by large amounts.

Most GCMs model soil moisture directly, but their scale tends to be very coarse and their characterizations of soils tend to be simplified. Many climate models show increased soil moisture in the high northern latitudes, typically above 50°N, where increases in precipitation greatly outpace increases in evapotranspiration, but even in Alaska increases in summer evapotranspiration often outpace increased precipitation in the Hadley and Canadian results. At the same time, most models in response to higher greenhouse gas concentrations also suggest large-scale drying of the Earth's surface over mid-latitude continents in northern summer owing to higher temperatures and either small precipitation increases or actual reductions in rainfall. Drying in these regions would have significant impacts, particularly on agricultural production and both the supply of and demand for water. One consequence of this is an expected increased incidence of droughts in some regions, measured by soil-moisture conditions, even where precipitation increases, because of the increased evaporation (Rind et al. 1990, Vinnikov et al. 1996).

Figure 16:
Effects of Hypothetical Climate Changes on Runoff in Western Mountainous River Basins of the United States



This figure plots the sensitivity of average annual runoff to changes in temperature (increases of 2 and 4° Celsius) and precipitation (increases and decreases of 10, 12.5, 15, 20, and 25%) for a large variety of watersheds in the western United States (the watersheds are listed in Table 9). Source: Gleick and Chalecki (1999).

Research from individual basins indicates similar results. In the Sacramento Basin in northern California, a study identified reductions in summer soil moisture of 30% or more resulting from a shift in the timing of runoff from spring to winter, a decrease in snow, and higher summer temperatures and evaporative losses (Gleick 1986, 1987a,b). This finding has also been seen in some of the detailed hydrologic modeling of the Colorado River basin, where large increases in precipitation were found to be necessary in order to simply maintain soil moisture at present historical levels as temperatures and evaporative losses rise (Nash and Gleick 1991, 1993).

More recently, Gregory et al. (1997) noted that sensitivity studies using the Hadley model led to reduced soil-moisture conditions in mid-latitude summers in the northern hemisphere as temperature and evaporation rise and winter snow cover and spring runoff decline. In another sensitivity analysis of GCM results, Wetherald and Manabe (1999) investigated the temporal and spatial variation of soil moisture associated with global warming in a coupled ocean-atmosphere model. Their results show both summer soil moisture dryness and winter wetness in middle and high latitudes of North America and southern Europe. In the Wetherald and Manabe study, the percentage reduction of soil moisture in summer is large, and soil moisture is decreased for nearly the entire year in response to greenhouse warming.

In order to explore the question of the expected tendencies and sensitivities of soil moisture over the conterminous United States given different climate projections, a macroscale hydrologic model was developed. This model includes soil moisture, runoff, and snow accumulation and ablation, and is forced by precipitation, temperature, and potential evapotranspiration using spatial digital data of soil texture and plant cover. The model determines soil-moisture field capacity, hydraulic conductivity, and plant phenology seasonal coefficients, and yields good reproduction of observed conditions over the historical record (Brumbelow and Georgakakos 2000, Georgakakos and Smith 2000).

Assuming a one-percent greenhouse-gas increase scenario through the period 1999 to 2050 results in a reduction of the average soil-moisture content of the conterminous United States in the model (Figure 17). Significant changes were projected for the eastern United States (both southeast and northeast) where an increasing trend of soil-moisture dryness was seen during the period 2025-2060. It was also found that with the increase of greenhouse gases there would be an increase in soil-moisture variability, with regional enhancement of the range of extreme soil-moisture values. If these model results are accurate, the severity of future droughts and floods would increase in these regions.

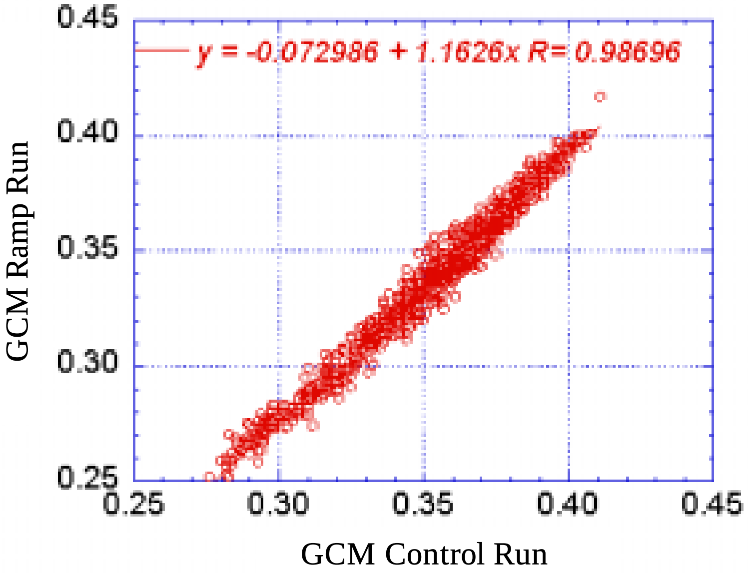
In the southeastern United States, Georgakakos and Yao (2000a) found that soil moisture in the model declines sharply (by as much as 30 to 40%) under the Canadian scenario, and increases somewhat (by 10 to 20%) under the Hadley scenario. The authors note the poor ability of the Canadian model to reproduce current climate in this region. Figure 18 portrays the expected sequences of a soil-moisture index (normalized by its average historical value) for four ACF sub-basins, depicting these trends but also indicating the tendency of the soil moisture to become more and more variable under both scenarios (Georgakakos and Yao 2000a). As noted in the section on agriculture, soil-moisture response has important implications for crop yield and irrigation demand (Brumbelow and Georgakakos 2000).

Water Quality

The quality of water resources can be as important or even more important than water quantity. Water quality affects natural ecosystems, human health, and economic activities. At the same time, human activities directly affect water quality. Concentrated pollutants entering surface waters from specific locations (point-source discharges) and dispersed pollutants generated from local or small-scale activities (non-point source discharges) add large quantities of nutrients, pathogens, and toxins to the nation's water resources. These problems are often exacerbated by human withdrawals of water for myriad uses, which can lead to concentrations of contaminants.

Global climate changes have the potential to significantly alter water quality by changing temperatures, flows, runoff rates and timing, and the ability of watersheds to assimilate wastes and pollutants. Higher flows of water could reduce pollutant concentrations or increase erosion of land surfaces and stream channels, leading to higher sediment, chemical, and nutrient loads in rivers. Changes in storm flows will affect urban runoff, which already has adverse water-quality impacts on discharges to the oceans. Lower flows could reduce dissolved oxygen concentrations, reduce the dilution of pollutants, and increase zones with high temperatures. For almost every body or source of water, land use and agricultural practices have a significant impact on water quality. Changes in these practices, together with technical and regulatory actions to protect water quality, can be critical to future water conditions. The net effect on water quality for rivers, lakes, and groundwater in the future therefore depends not just on how climate conditions might change but also on a wide range of other human actions.

Figure 17:
Conterminous U.S. Average Soil Moisture, Years 1999-2050



Association of soil moisture resulting from the CGCM control scenario with that resulting from the Canadian (one percent annual greenhouse gas increase – "Ramp Run") scenario. Soil moisture is averaged over the conterminous United States. Drier conditions are simulated for the greenhouse increase scenario, especially for lower soil moisture averages. K. Georgakakos and D. Smith (2000).

In a review of potential impacts of climate change on water quality, Murdoch et al. (2000) conclude that significant changes in water quality are known to occur as a direct result of short-term changes in climate. They note that water quality in ecological transition zones and areas of natural climate extremes is vulnerable to climate changes that increase temperatures or change the variability of precipitation and argue that changes in land and resource use will have comparable or even greater impacts on water quality than changes in temperature and precipitation. They contend that long-term monitoring of water quality is critical for identifying severe impacts, as is developing appropriate management strategies for protecting water quality.

Water quality is a direct result of the chemical inputs received from air and the surrounding land and the biogeochemical processes that transform those inputs (Murdoch et al. 2000). Direct chemical contributions come from atmospheric deposition or point source discharges. Indirect contributions come from water that flows off watersheds through vegetation, soils, and aquifers, each of which contributes to water chemistry. Climate changes will influence water quality by altering these contributions, particularly through changes in temperature and moisture. A comprehensive summary of many of these changes can be found in Murdoch et al. (2000).

Global and regional increases in air temperature, and the associated increases in water temperature, are likely to lead to adverse changes in water quality, even in the absence of changes in precipitation. The southeastern U.S., for example, has significant variability in streamflow due to seasonal changes in evapotranspiration rates. Mulholland et al. (1997) projected increased rates of oxygen depletion in already eutrophied waters of this region if global warming occurs. Warming has been shown to increase the rate of biological production and decomposition by increasing rates of metabolism, the duration of the growing season, and the volume of lakes that are biologically active (Covich et al. 1997, Hauer et al. 1997). Increases in productivity increase nutrient cycling and accelerate eutrophication in lakes with sufficient nutrients and oxygen (Mulholland et al. 1997). In oxygen-poor waters, increased productivity could lead to oxygen depletion, which would subsequently limit overall productivity. Fang and Stefan (1997) evaluated changes in lake stratification in cold regions of the north-central United States under conditions of climate changes. They showed that winter stratification would be weakened as average temperatures increased and that the anoxic zone could disappear.

Moore et al. (1997) note that increased water temperatures enhance the toxicity of metals in aquatic ecosystems and that increased lengths of biological activity could lead to increased accumulation of toxics in organisms. Ironically, increased bioaccumulation could decrease the concentration of toxics in the water column, improving local water quality. Similarly, higher temperatures may lead to increased transfer of chemicals from the water column to sediments.

Changes in terrestrial ecosystems will also lead to changes in water quality by altering nutrient cycling rates and the delivery of nutrients to surface waters. Nitrification rates in soils are temperature dependent and in some regions, mean annual nitrate concentrations in streams are highly correlated with average annual air temperature (Murdoch et al. 1998). Similarly, a significant correlation has been observed between soil respiration rates and temperature. Alexander et al. (1996) looked at nutrient loadings to coastal zones as a function of streamflow volume. Because streamflows along Atlantic coast states increased under many climate scenarios, nutrient loads also increased. Extended droughts in boreal regions have been shown to increase the risk of acidification of streams due to the oxidation of pools of organic sulfur in soils (Schindler 1997). Ultimately, the water-quality response to climate change will depend on specific temperature changes, biogeochemical processes, existing thresholds for plant and animal species, and other factors.

Changes in precipitation will also play a crucial role by affecting water quantity, flow rates, and flow timing. Decreased flows can exacerbate temperature increases, increase the concentration of pollutants, increase flushing times, and increase salinity in arid regions (Schindler 1997, Mulholland et al. 1997). Decreased surface-water volumes can increase sedimentation, concentrate pollutants, and reduce non-point source runoff (Moore et al. 1997, Rouse et al. 1997, Mulholland et al. 1997). Where surface runoff decreases, erosion rates and sediment transport may drop and lake clarity may increase with increased penetration of ultraviolet-B (UV-B) radiation (Murdoch et al. 2000). Increases in water flows can dilute point-source pollutants, increase loadings from non-point source pollutants, decrease chemical reactions in streams and lakes, reduce the flushing time for contaminants, and increase export of pollutants to coastal wetlands and deltas (Jacoby 1990, Mulholland et al. 1997, Schindler 1997). Higher flows can increase turbidity in lakes, reducing UV-B penetration.

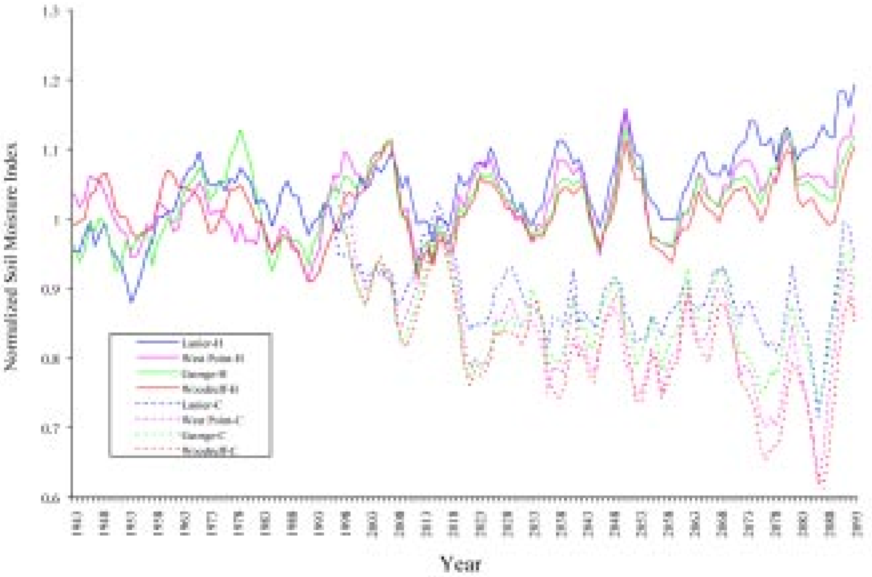
In a study of climate change and the Colorado River basin, estimates were made how changes in flow would affect the salinity of water measured in the lower portion of the river. Salinity is already a major concern of agricultural and urban water users in the basin as well as a source of tension between the United States and Mexico. In the early 1970s, the two countries negotiated a formal agreement on the quality of water to be delivered to

Table 10:
Sensitivity of Water-Supply Variables to Climate Change in the Colorado River Basin

Change in Natural Flow (percent)	Changes in Actual Flow (a) (percent)	Change in Storage (b) (percent)	Change in Power Generation (b) (percent)	Change in Salinity (c) (percent)
-20	- 10 to - 30	-61	-57	15 to 20
-10	-7 to -15	-30	-31	6 to 7
-5	-4 to -7	-14	-15	3
5	5 to 7	14	11	-3
10	11 to 16	28	21	-7 to -7
20	30	38	39	-13 to -15

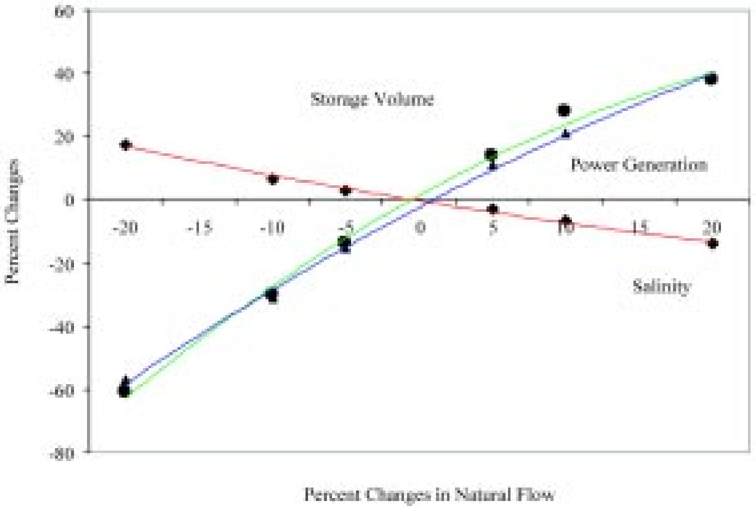
Notes
(a) Changes in flow represent the range of changes at five points: Green River, Cisco, Bluff, Lee Ferry, and Imperial Dam.
(b) Mean storage or power generation throughout the basin.
(c) The range of changes in salinity at three points: Davis, Parker, and Imperial dams.
Source: Nash and Gleick (1993).

Figure 18:
Historical and Future Soil-Moisture Trends for Four ACF River Basins in the Southeastern U.S.



Sequences of a soil-moisture index are shown for the Canadian (C) and Hadley (H) climate scenarios, normalized by their average historical value (1943-1993). Source: Georgakakos and Yao (2000a).

Figure 19:
Sensitivity of Water Management Variables to Changes in Colorado River Flows



Changes in natural flow, indicated along the x-axis, lead to changes in storage volumes in Colorado River reservoirs (green), hydroelectric power generation (blue), and salinity (red). For example, as natural flows increase, salinity decreases. As natural flows decrease, both power generation and reservoir storage volumes decrease substantially. These model runs assumed that current operating rules on the Colorado River would not change. More work is needed to evaluate how changes in operating rules could mitigate these climate-related impacts. Source: Nash and Gleick (1993).

Mexico under the 1944 Colorado River treaty, constraining salinity and requiring the U.S. to undertake a series of land-use and water-management changes in order to keep salts out of the river. Nash and Gleick (1991, 1993) evaluated how climate-induced changes in long-term average runoff would affect salinity (defined as total dissolved solids) in the river, assuming current salinity control projects are in place and operating. Figure 19 and Table 10 show that even modest decreases in average runoff would lead to significant increases in salinity and violations of salinity standards, in part because of the existing difficulty of meeting those standards. A decrease in runoff of only five percent would cause the salinity criteria to be exceeded essentially all the time. While increases in average flows would be helpful, salinity criteria in the model were still violated for long periods, even with 20% increases in average runoff. If such salinity problems were to materialize, federal and state agencies would be forced to implement additional projects, even beyond those already planned, to control salinity levels in order to meet water-quality standards and treaty obligations with Mexico.

Eheart et al. (1999) recently completed a sensitivity analysis of the possible impacts of a set of climate change scenarios on low streamflows in the Sangamon River watershed in the midwestern U.S. Synthetic weather data were generated assuming no change in precipitation, decreases in mean precipitation by 25%, a doubling of the standard deviation of precipitation, and both decreasing precipitation and doubling the standard deviation. Three sets of streamflow data were generated assuming no basin irrigation or irrigation strategies designed to maximize agricultural profits or yields. The paper evaluated the 7-day, 10-year low flow ($_7Q_{10}$) as critical dilution flow to determine impacts on water quality. The authors note that the ultimate effects will, of course, depend on the actual nature of future precipitation patterns, which remain uncertain.

For most pollutants, the likelihood of water-quality standards being violated under the model scenarios was very closely approximated by the probability of streamflow level falling under a design minimum. For the scenarios with climate changes and without basin irrigation, streamflows experienced significant decreases, ranging from –57% to –84%. With irrigation and no climate changes, streamflow changes ranged from a modest increase (+2%) to a dramatic drop (-30%). Including both climate changes and in-basin irrigation would reduce the assimilative capacity of the river to as low as 16% of the pollution waste load. Eheart et al. (1999) concluded that the potential impact of climate changes on low-flow standards, critical water quality, and the frequency and duration of water-quality violations could be substantial and damaging to ecosystems and human users. Low-flow events on which discharge permits are based were quite sensitive to climate changes: for example, a 25% decrease in mean precipitation results in a 63% reduction in design flow. If climate changes cause design flows to be less than half their current level, then allowable discharge levels must also be reduced to less than half the current level; if design flows fall 80%, as in a few scenarios, then pollutant levels must decrease a comparable amount to meet current standards.

The authors also noted the importance of management decisions in determining the final impacts. Under the current regulations, riparian owners are allowed to withdraw water without permits, and negative consequences are assessed only after the withdrawal has taken place. If low-flow events worsen under climate change, the authors suggested that the permit system for waste discharge might need to be reviewed and overhauled, with improvements in oversight of interstate rivers (Eheart et al. 1999).

A broad assessment of the impacts of climate changes on water quality in the southeastern United States used climate scenarios developed from the Hadley and Canadian models to simulate climate from now to 2100 (Cruise et al. 1999). This study looked at water quality on a broad scale, with a focus on levels of pH, nitrates, and dissolved oxygen in USGS hydrological regions or "hydrological units" (HUs). Most HUs in the southeast do not currently experience quality problems under normal conditions, but many water-quality indices are approaching recommended levels. Existing stresses appear to be related to intense agricultural practices, coastal processes, and mining activities. Without climate changes, preliminary findings showed that there are low dissolved oxygen (DO) levels near the coast and in agricultural regions. There are also higher nitrate levels in agricultural areas and in proximity to Gulf coast, but the low-DO areas do not necessarily correlate to the areas with high nitrates. Since only larger basins are evaluated, local-scale problems may still occur but be missed by this approach. Finally, high pH levels occurred much more often than low pH levels.

The two climate models used for the National Assessment were evaluated and the results for the periods 2020-2039 and 2080-2099 compared with observed water-quality data from 1974-1993. The authors concluded that both models led to worsening water-quality conditions in the southeastern U.S. during 2020-2039 due to drier late spring/summers and falls, corresponding to periods of intensive agriculture. Water quality then begins to improve as regional precipitation increases toward the end of the century. The authors also note that regions affected by climate-induced stresses could also be affected by sea-level rise, leading to increased salinity (an indicator not measured in this study) and high nitrate levels (Cruise et al. 1999). This work should be considered preliminary and it highlights areas and issues for which more research is necessary.

Lake Levels and Conditions

While most research has focused on rivers and runoff, some studies have looked at the impacts of climate change on lakes. Lakes are known to be sensitive to a wide array of changes in climate conditions: variations in temperature, precipitation, humidity, and wind conditions can alter evaporation rates, the water balance of a basin, ice formation and melting, and chemical and biological regimes (McCormick 1990, Croley 1990, Bates et al. 1993, Hauer et al. 1997, Covich et al. 1997, Grimm et al. 1997, Melak et al. 1997). Closed (endorheic) lakes are extremely sensitive to the balance of inflows and evaporative losses. Even small changes in climate can produce large changes in lake levels and salinity (Laird et al. 1996).

Several studies have also shown that large open (exorheic) lakes are sensitive to changes in inflows and outflows. The levels of the Great Lakes, shared by the United States and Canada, change as temperatures increase and precipitation patterns change. In work done on the impacts of climate changes on the Great Lakes, including Lake Erie, lake levels were projected to drop under most GCM-generated scenarios, decreasing hydropower revenues, increasing navigation costs, reducing cold-water fish habitat, and reducing the costs of flooding and shoreline erosion (Chao et al. 1999). This study also noted that the actual impacts depended on assumptions about how the connected lakes were operated.

Hostetler and Small (1999) modeled the response of hypothetical lakes throughout the

United States to climate changes using an energy-balance model that simulates the vertical structure of temperature, stratification, lake ice formation, and evaporation. The results for the climate-change scenarios differ from the results for the control lakes in a number of ways. Lake ice cover decreases or even disappears entirely. Ice-free boundaries shift northward. Summer lake temperatures increase, leading to inhibited mixing of thermal layers. Higher evaporation and changes in precipitation lead to changes in net moisture depending on the model used. Despite the large differences among the models, there are some areas of agreement: for example, ice-free lakes warmed by approximately 3° C and nearly 5° C over higher latitude lakes due to feedbacks with winter ice cover and albedo.

As air temperatures increase, fewer lakes and streams in high-latitude areas will freeze to the bottom and the number of ice-free days will increase, leading to increases in nutrient cycling and productivity (Anderson et al. 1996, Rouse et al. 1997, Magnuson et al. 1997). Other effects of increased temperature on lakes could include higher thermal stress for cold-water fish, higher trophic states leading to increased productivity and lower dissolved oxygen, degraded water quality, increased summer anoxia, and a loss of productivity in boreal lakes. Among the effects of loss of ice cover are increased growth of warm-water fish (though productivity may be curtailed by lack of food supply) and decreased winter anoxia. Decreases in lake levels coupled with decreased flows from runoff and groundwater may exacerbate temperature increases and loss of thermal refugia and dissolved oxygen. Increased net evaporation may increase salinity of lakes. Hostetler and Small (1999) also note that climate variability may amplify or offset changes in the mean state under climate changes and may ultimately be more important than changes in average conditions. Some non-linear or threshold events may also occur, such as a fall in lake level that cuts off outflows or separates a lake into two isolated parts.

Groundwater

Groundwater accounted for 22% of total U.S. freshwater withdrawals in 1995 (Solley et al. 1998). In some areas, current levels of groundwater use are already unsustainable. For example, declining aquifer levels and higher pumping lifts have increased water costs in the southern High Plains, leading farmers to take millions of acres out of production in recent decades. Groundwater overdrafts in California in the drier years of the 1990s averaged nearly 1.5 million acre-feet per year (California Department of Water Resources 1998). Pumping from some coastal aquifers in California, Cape Cod, Long Island, New Jersey, and Florida has exceeded the rates of natural recharge, resulting in saltwater intrusion into the aquifers.

Little work has been done on the impacts of climate changes for specific groundwater basins, or for general groundwater recharge characteristics or water quality. Recharge and withdrawal rates are relatively balanced in some watersheds and any change in recharge rates could have a major effect on the long-term sustainability of a basin. Aquifers are replenished by rainfall above the rate of evaporation and where soils are sufficiently saturated to permit additional storage to flow into subsurface basins. Changes in recharge will result from changes in effective rainfall as well as a change in the timing of the recharge season. Increased winter rainfall, expected for some mid-continental, mid-latitude regions could lead to increased groundwater recharge. Actual recharge will also depend on the period over which soils are frozen. Higher temperatures could increase the period of infiltration. Higher evaporation or shorter rainfall seasons, on the other hand, could mean that soil deficits persist for longer periods of time, shortening recharge seasons (Leonard et al. 1999).

Vaccaro (1992) studied the climate sensitivity of groundwater recharge for the Ellensburg basin of the Columbia Plateau in Washington and concluded that median recharge rates could decrease by as much as 25% under the climate scenarios studied. A study of a semi-arid basin in the United States, the Edwards aquifer under Texas, showed that six of seven GCM-based scenarios led to reductions in groundwater levels and spring flows (Loaiciga et al. 1998). In another study, Rosenberg et al. (1999) noted that climate changes can affect aquifers indirectly. Estimated irrigation demands in Kansas and Nebraska under current climate conditions and conditions similar to a drier, warmer period were compared. This analogue study showed dramatic increases in irrigation water needs – as much as 39% higher in Nebraska and 14% higher in Kansas, assuming no change in irrigated area. Such needs would have to be met with increased groundwater pumping.

Several international groundwater and climate studies have relevance for similar kinds of United States regions and climate zones. A study of a semi-arid basin in Africa concluded that a 15% reduction in rainfall could lead to a 45% reduction in groundwater recharge (Sandstrom 1995). Similar sensitivities were seen in two studies of the effects of climate changes on groundwater in Australia, where proportionally larger decreases in groundwater levels were seen for a given reduction in precipitation (Sharma 1989, Green et al. 1997). Groundwater-streamflow interactions under conditions of climate change were studied in a mountainous basin in central Greece and large impacts were seen in spring and summer months because of temperature-induced changes in snowfall and snowmelt patterns (Panagoulia and Dimou 1996).

Groundwater and sea level (discussed in the next section) interact in coastal areas. As sea level rises, saltwater intrusion into coastal aquifers increases. Many regions of the United States are vulnerable to such impacts but relatively few detailed regional studies have been conducted. In a study of the impacts of climate change on groundwater discharge to the ocean, Oberdorfer (1996) used a simple water-balance model to test how changes in recharge rates and sea-level would affect groundwater stocks and flows in a California coastal watershed. While some sensitivities were identified, the author notes that the complexity of the interactions among the variables required more sophisticated analysis.

Sea Level

Relative sea-level rise will affect groundwater aquifers and coastal ecosystems. Rising sea level will cause an increase in the intrusion of salt water into coastal aquifers, depending on the groundwater gradients and pumping rates. Shallow island aquifers (such as those found in Hawaii, Nantucket, Martha's Vineyard, and along the southeastern seaboard) together with coastal aquifers supporting large amounts of human activity (such as those in Long Island, New York, and central coastal California) are at greatest risk. Other impacts could include changes in salinity distribution in estuaries, increased risk of salt-water contamination at water-supply intakes, altered circulation patterns, increased pressure on coastal levee systems, and effects on biodiversity (Ray et al. 1992). An early summary of the kinds of impacts possible for the United States from climate-change induced sea-level rise can be found in Titus (1986). While researchers have high confidence that sea-level rises will adversely affect coastal ecosystems and some groundwater aquifers, they have only medium confidence in the expected range of sea-level rise.

One of the first efforts to evaluate regional sea-level rise impacts on water-resource systems was done for the San Francisco Bay and the Sacramento-San Joaquin River delta in northern California (Williams 1985, 1987, SFBCDC 1988). This delta region is of critical importance for water supply for much of the state's population and is one of the few coastal estuaries in the western United States with significant remaining biological resources. Williams evaluated how sea-level rise would affect the location of the salt front and the stability of delta levees. These levees are vital for protecting transportation systems, agriculture, and homes in the region. Among the conclusions was that the fragile levees of the delta would fail at a higher rate, sediment movements would be changed, mudflats and salt marshes would experience more erosion, and ecosystem impacts could be substantial. For a one-meter sea level rise, the area and volume of this large west coast estuary could triple from 1,100 square kilometers to over 3,500 square kilometers if substandard levees were allowed to fail. Williams also concluded that the average salinity level could migrate roughly 15 kilometers upstream, leading to massive impacts on the state's water supply infrastructure. Other conclusions were that tidal marshes in parts of the San Francisco Bay where salt and freshwater ecosystems interact would be submerged by a one-meter sea-level rise (SFBCDC 1988).

Changes in climate were evaluated in the Delaware River basin in an effort to understand how changes in runoff and sea level might affect the position of the salt front in the Delaware River estuary relative to intakes of fresh water for major metropolitan areas (Wolock et al. 1993). The authors concluded that changes in management of the reservoirs would be necessary to prevent saltwater intrusion to freshwater supplies. Simulations also suggested that reservoir depletion was more likely to occur than changes in the movement of the salt front because managers were assumed to increase freshwater releases to keep the salt front below water-supply intakes. The authors noted that reservoir releases would be limited by overall water available in storage.

Direct Effects on Ecosystems

The health and dynamics of ecosystems are fundamentally dependent on a wide range of climate-sensitive factors, including the timing of water availability, overall water quantity, quality, and temperature. All of these factors may be altered in a changed climate. Humans, in turn, are dependent upon ecosystem processes to supply essential goods and services: for example, primary productivity and inputs from watersheds support food webs yielding fish for commercial and recreational purposes; decomposition and biological uptake purify water by removing organic materials and nutrients. Freshwater systems are rich in biological diversity, and a large part of the fauna is under threat of extinction (Naiman et al. 1995). A changing climate may intensify these threats in many ways, such as by accelerating the spread of exotic species and further fragmenting populations (Firth and Fisher 1991, Naiman 1992). While we note that some climate scenarios can produce conditions that might reduce stresses on certain ecosystems, experience with ecosystem dynamics strongly suggests that perturbing ecosystems in any direction away from the conditions under which they developed and thrive will have adverse impacts on the health of that system (Peters and Lovejoy 1992, IPCC 1996c).

The direct effects of climate change on ecosystems will be complex, depending on the nature of the change, the systems affected, and the nature and scope of intentional interventions by humans. Previous assessments have established a wide range of possible direct effects, including changes in lake and stream temperatures, lake levels, mixing regimes, water residence times, water clarity, thermocline depth and productivity, invasions of exotic species, fire frequency, permafrost melting, altered nutrient exchanges, food web structure, and more (see, for example, Peters and Lovejoy 1992 and the 1997 special issue of Hydrological Processes (Volume 11, Number 8, including Covich et al. 1997, Grimm et al. 1997, Hauer et al. 1997, Melak et al. 1997, and Schindler 1997). These impacts could lead to a wide range of serious adverse impacts on ecosystems, with changes in vegetation patterns, possible extinction of endemic fish species already close to their thermal limits, declining area of wetlands, precipitating reductions in waterfowl populations, concerns about stream health, and major habitat loss (Westman and Malanson 1992, Billings and Peterson 1992, Eaton and Scheller 1996, Covich et al. 1997; Hauer et al. 1997; Meyer 1997; Schindler 1997; Meyer et al. 1999). This section focuses on the direct effects of climate changes on aquatic ecosystems, though reference is also made to work done on terrestrial ecosystems. For more detail on the effects of climate changes on coastal ecosystems, please see the separate sectoral report on this issue prepared for the National Assessment.

The effects of climate change on aquatic ecosystems will depend on the magnitude and rate of changes in climate as well as the current state of the ecosystem. Patterns of temporal variation in streamflow differ among watersheds because of regional variations in climate, geology, soil conditions, and vegetative cover. The ecological response to a modification in natural flow regime resulting from climate change depends on how the regime is altered relative to the historical conditions (Meyer et al. 1999). For example, a system that has historically experienced predictable, seasonal flooding, such as snowmelt-dominated streams and rivers, may show dramatic changes in community composition and ecosystem function if the seasonal cycles are eliminated or substantially altered, as has been documented for the loss of riparian trees along western watercourses (Auble et al. 1994). A river characterized by highly variable flows would not likely show much response to a climate change that exacerbated this already harsh regime; however, a climate change shift to more perennial and stable flows would be expected to elicit great response (Poff 1992). These observations also apply to lakes: paleoecological studies have demonstrated that the hydrologic setting of a lake determines how it responded to past climate change (Fritz 1996). Thus understanding local factors that control water volume and quality is necessary to predict climate impacts (Murdoch et al. 2000). The biological and chemical processes that control aquatic ecosystem health are a function of the evolutionary history of a region as well as its geologic and climatic setting; how these local processes respond to climate shifts determines the impact of that shift on ecosystem health. Continuing land-use changes that have profound impacts on aquatic ecosystems will also complicate predicting and interpreting the consequences of climate change (Dale 1997). Projected climate change can be viewed as another form of anthropogenic environmental alteration that will modify the ecological organization of aquatic ecosystems (Grimm 1993, Poff et al. 2000). We can only plan for climate change based on local understanding of processes controlling water quantity and quality and ecosystem health (Murdoch et al. 2000).

It is likely that the ecosystems most vulnerable to climate change are those that are already near important thresholds, such as where competition for water is occurring, where summer water temperatures are already near the limit for a species of concern, or where

climate change will act in concert with other anthropogenic stressors such as large water withdrawals or wastewater returns (Meyer et al. 1999, Murdoch et al. 2000).
Slight shifts in climate can also alter the boundaries of terrestrial ecosystems, plant compositions, and the rate of supply of organic matter, with resulting impacts on the health of aquatic ecosystems (Meyer and Pulliam 1992, Hauer et al. 1997). Transition zones, where species compositions alter dramatically, may show the earliest evidence of change, and the changes may not be gradual. Better information is needed on which ecosystems change gradually and which may be subject to dramatic or sudden changes when a threshold is reached (Meyer et al. 1999). Understanding these responses would enhance our ability to detect and predict the impacts of climate change.

Future climate scenarios, such as those evaluated for the National Assessment, suggest a future climate that is warmer with altered patterns and intensity of precipitation. We consider first some of the changes expected to result from warmer temperatures and then look at effects projected with altered hydrology.

There will be both positive and negative direct effects of increasing temperatures on aquatic and terrestrial ecosystems. In general, while many uncertainties remain, ecologists have high confidence that warming will produce a shift in species distributions northward, with extinctions and extirpations of temperate or cold-water species at lower latitudes, and range expansion of warm-water and cool-water species into higher latitudes. Mean summer air temperature increases of 2-6^o C are projected to reduce the suitable habitat for cold- and cool-water fish species in streams of the conterminous United States by over 50% (Eaton and Scheller 1996). A 4^o C increase in mean air temperature is projected to expand the ranges of smallmouth bass and yellow perch northward across Canada by about 500 km (Shuter and Post 1990). Some fish species may be eliminated from drainages, particularly those oriented east-west rather than north-south (Carpenter et al. 1992). Predicted warming of surface waters in the western and northern Great Plains could lead to increasing salinity and to extinction of endemic fish species already close to their lethal thermal limits (Covich et al. 1997). One likely consequence of a warmer climate is increasing fragmentation of cold-water fish habitats in headwaters and potential shifts in the competitive dominance of salmonid species (Mulholland et al. 1997, Hauer et al. 1997, Melack et al. 1997). Shifts are also likely in distributions of insects, whose development and generation times are highly sensitive to temperature (see, for example, Sweeney et al. 1992 for work on aquatic insects).

Climate warming could result in substantial changes in the mixing properties of many high and mid-latitude lakes (Hostetler and Small 1999), which would alter deep-water dissolved oxygen concentrations and primary productivity via effects on nutrient supplies and exposure of phytoplankton to light. Ice-free conditions under double CO_2 climate scenarios are projected to shift northward by 10^o (Hostetler and Small 1999), which would change mixing regimes and alter ecological conditions (Porter et al. 1996). In saline lakes, reductions in streamflow are linked to increased incidence of permanent stratification and reduced productivity (Melack et al. 1997), while increases in streamflow could have the opposite effect. In deep, thermally-stratified lakes in the mid- and high latitudes, winter survival, growth rates, and thermal habitat for fish generally increase under doubled CO_2 climate simulations, although the models do not take changes in oxygen into account (Magnuson and DeStasio 1996), and dissolved oxygen below the thermocline is predicted to decrease (Magnuson et al. 1997).

Changes in thermal regime pose threats to a broad range of population and community interactions, ranging from direct mortality from acute temperature stress, chronic bioenergetic stresses, and shifts in the balance of interspecies competition as habitat space for some species is reduced (Meyer et al. 1999). Chao (1999) notes that for ten steady-state and transient climate scenarios, the area of cold-water habitat in the Great Lakes decreases by 40 - 85%. The effects of higher water temperatures are sufficient, even in the most modest impacts, to lead to a higher proportion of areas suffering from oxygen depletion. In smaller mid-latitude lakes and reservoirs, warming may also reduce habitat for many of the cool- and cold-water species because deep-water thermal refuges with adequate oxygen are not present in summer (Stefan et al. 1996). Thermal refugia are a critical component of aquatic ecosystems that are difficult to capture using current climate models.

A recent assessment of the impacts of changing water temperatures on the economic yield from recreational fisheries concluded that changes in cool- and cold-water fisheries could lead to net economic losses ranging from $85 - $320 million/yr (Abt Associates 1995), although these estimates are speculative because the extent of any tradeoff from cold- to warm-water fisheries is unknown and hard to monetize. Flow alterations were not formally considered in the analysis, but the authors concluded that they would likely increase calculated losses. Qualitative benefits expected in a warmer climate include increased productivity of warm-water fisheries and aquaculture as well as reduced winter fish kill.

Warmer temperatures in the Arctic are predicted to increase aquatic primary and secondary productivity because of increased decomposition rate and water residence time; yet these increases in production may not be adequate to make up for the increased metabolic demand of higher temperatures for fishes (Rouse et al. 1997). Top predators (grayling and lake trout) appear particularly vulnerable to climate change, and reductions in their abundance would likely have effects throughout Arctic food webs. Abundant boreal and Arctic peatlands are vulnerable to changes in water table depth influenced by permafrost melting and altered water balances. The southern boundary of continuous permafrost is projected to shift north by 500 km over the next 50 years due to warming projected by general circulation models (Anisimov and Nelson 1996, Burkett and Kusler 2000). Gorham (1995) projected that a 5° C warming in Alaska would eventually melt virtually all of the subarctic permafrost in Alaska, which would affect more wetland area than currently found in the rest of the United States. Changes in hydrology resulting from this permafrost melting have not been adequately assessed (Gorham 1995), although soil movement, terrain slumping or subsidence, increased sediment loads, and changes in flow regimes are likely (IPCC 1998, Burkett and Kusler 2000). Peatlands are vulnerable to drying and fire, and a warmer climate would shift them from a net sink to a net source for CO_2 (Burkett and Kusler 2000). This is of considerable significance in the global carbon budget because estimates of carbon stored in boreal peatlands range from 20% to 35% of global terrestrial carbon (Patterson 1999).

Mulholland et al. (1997) evaluated the implications of a range of future climate scenarios for the freshwater ecosystems in the southeastern U.S. Among the projected impacts of higher temperature are: reduction in habitat for cool-water species, such as brook trout and many aquatic insects, which are near the southern extent of their ranges; greater summer drying of wetland soils resulting in greater fire threat; northward expansion of subtropical species, some of which are nuisance exotics (e.g. *Melaleuca*); more extensive summer deoxygenation in reservoirs (also seen in Chang et al. 1992); and increased rates of production and nutrient cycling with both higher temperature and longer growing season.

In addition to warmer temperatures, aquatic ecosystems are sensitive to changes in hydrologic regime. Murdoch et al. (2000) recently reviewed likely impacts of possible future “warmer and wetter” vs. “warmer and drier” climates on water quality. These impacts are a function of direct effects on processes regulating water quality in aquatic ecosystems as well as indirect effects via climate impacts on terrestrial ecosystems. For example, changes in water quality result from differences in depth of snowpack, likelihood of soil freezing, and extent of microbial processing occurring in the soil (Murdoch et al. 2000). Nitrification rates in the soil and nitrate concentrations in streams are correlated with air temperature in the Catskills (Murdoch et al. 1998). Warmer and drier conditions could increase residence times in lakes and reservoirs with increased ability of biological processes to reduce pollutant concentrations (Schindler 1997). Enhanced metal toxicity and increased bioaccumulation are possible with warmer temperatures (Moore et al. 1997). Under warmer, drier conditions, concentrations of constituents derived from surface and shallow soil runoff during high flows (such as nitrogen and acidity) and through erosion (including organic material) will decrease; and the proportion of concentrations of constituents derived from deeper flow paths (base cations, silica) and from point sources (sewage and industrial waste water) will increase (Murdoch et al. 2000). Under warmer, wetter conditions, Murdoch et al. (2000) predict greater dilution of point source inputs, but less instream biological uptake and transformation because of shorter residence time. Hydrologic changes that increase stream discharge or water velocity without commensurate increases in biological uptake reduce nutrient retention efficiency (Meyer et al. 1999). In addition, increased erosion could wash additional contaminants into streams from source areas.

Nutrient loading generally increases with runoff, particularly in human-dominated landscapes (Alexander et al. 1996). Thus, increases in runoff due to increased precipitation are likely to increase the flows of nutrients into rivers and lakes. Of particular concern in a wetter climate are episodic water-quality excursions beyond particular thresholds (Murdoch et al. 2000). Delivery of constituents like phosphorus, pesticides, or acids in pulses are known to have adverse consequences for fishes, depending on their frequency, duration, and intensity. For example, annual export of hydrogen ions in the Catskills depends more on the magnitude and duration of episodic events than on ion concentrations in baseflow (Murdoch 1991, Baldigo and Murdoch 1997). Increased numbers of water-quality excursions that exceed ecological thresholds will limit the effectiveness of policies designed for mean conditions (Murdoch et al. 2000).

In north-temperate regions, dissolved organic carbon (DOC) concentrations are projected to decrease because of reduced runoff from drier catchments, resulting in increases in water clarity, thermocline depth, productivity, and UV-B penetration. Schindler (1997) estimates that this latter effect could lead to a greater exposure of aquatic animals to ultraviolet radiation than would result from reductions in the ozone hole (Schindler 1997). Extended droughts in boreal regions have been shown to result in acidification of streams due to oxidation of organic sulfur pools in soils (Schindler 1997). Lake levels are highly sensitive to changes in precipitation and evaporation. Lakes in dry evaporative drainage basins in the north-central U.S. (fed primarily by ground water, precipitation, and spring snowmelt) are among the most sensitive to changes in climate that produce drier conditions (Covich et al. 1997).

In snowmelt rivers of the Pacific Northwest, likely shifts in the hydrologic regime toward earlier and higher winter and spring flows and lower summer flows could exacerbate the stresses resulting from changes in population and land use and lead to water quality and quantity problems (Miles et al. 2000). Peak flows occurring much earlier in the season (Leung and Wigmosta 1999, Hay et al. 2000) could result in washout of early life-history stages of autumn-spawning salmonids. Altered runoff regimes, increased sediment loads, and decreased channel stability would reduce benthic diversity in glacial-fed rivers and reduce growth rates of economically important species such as salmon (Melack et al. 1997). Changes in sediment loading and channel morphology in an altered climate can impact processes regulating nutrient cycling and community composition (Ward et al. 1992).

Burkett and Kusler (2000) recently reviewed likely climate change impacts on wetlands. They concluded that expected changes in temperature and precipitation would alter wetland hydrology, biogeochemistry, plant species composition, and biomass accumulation. Because of fragmentation resulting from past human activities, wetland plants often cannot migrate in response to temperature and water-level changes and hence are vulnerable to complete elimination. Wetland plant response to increased CO_2 could also lead to shifts in community structure with impacts at higher trophic levels. Small changes in the balance between precipitation and evapotranspiration can alter groundwater level by a few centimeters, which can significantly reduce the size of wetlands and shift wetland types. Loss of remnant plant and animal species from alpine wetlands seems likely since there is little opportunity to migrate. Mid-continental wetlands that depend on precipitation as a primary water source are especially vulnerable to climate variation and change (Winter 2000). Climate scenarios for the Northern Great Plains region suggest that increased temperatures over the next 50 years would result in a 40% or more decline in the number of prairie potholes and the population of ducks (Sorenson et al 1998, Poiani et al. 1995). Wetland species are also sensitive to changes in seasonality of precipitation. For example, reduced winter precipitation can affect bird migration or reduce nesting success even if mean annual precipitation remains constant (Burkett and Kusler 2000). Increased periods of inundation for wetlands would result in increased rates of methane production (Meyer and Pulliam 1992) and other anaerobic processes such as mercury methylation (Rudd 1995).

In addition to the direct effects of temperature and flow on organisms and ecological processes, indirect effects mediated through food web interactions are also likely in an altered climate. Occasional extreme temperatures that lead to fish kills can have long-lasting impacts because they result in cascading effects throughout the food web (Carpenter et al. 1992). Relative strengths of year classes are altered by conditions during spawning and early life, and variations in year classes of top predators can alter food web structure at lower trophic levels (Carpenter et al. 1992). In rivers with reduced winter floods, insect grazer populations are maintained, and their grazing pressure reduces the likelihood of spring *Cladophora* blooms (Power 1992). Modeling the complexity of the interaction between food webs and hydrologic regime is in its infancy (Power et al. 1995) and more research is needed here. More complex dynamic models based on an understanding of mechanisms linking environmental variables and species performance in the context of complex food webs would help to develop useful projections of the impacts of climate-induced changes in hydrologic regime on endangered species, nuisance species, fisheries yields, and overall health of aquatic ecosystems.

Several researchers have reviewed likely impacts of climate change on aquatic ecosystem health, water quality, and wetlands (Firth and Fisher 1992, McKnight and Covich 1997, Meyer et al. 1999, Murdoch et al. 2000, Burkett and Kusler 2000, respectively). Meyer et al. (1999) identified the most vulnerable regions in the U.S. to include the Arctic, Great Lakes, and the Great Basin. Table 11 summarizes some important findings with respect to vulnerabilities of different ecosystem types. Wetlands are particularly sensitive to changes in water balances that lead to reduced areal extent, altered species composition, increased vulnerability to fire, and altered rates of exchange of greenhouse gases. The changes identified in lakes are associated with altered mixing regimes, delivery of nutrients and organic carbon from the watershed, availability of thermal refuges, and alteration of population sizes of the top predators with cascading effects on lower trophic levels. In streams, the changes are closely linked with climate impacts on riparian zone, species-specific thermal tolerances, and alterations in flow regime.

Researchers express concern for the limited ability of natural ecosystems to adapt or cope with climate changes that occur over a short time frame, especially in the context of the anthropogenic alterations to aquatic ecosystems that have already occurred (Naiman et al. 1995). This limited ability to adapt to rapid changes may lead to irreversible impacts, such as extinctions. While some research has been done on these issues, far more is needed.

Burkett and Kusler (2000) note that there are no practical options for protecting wetlands as a whole from rising temperature and sea level and changes in precipitation. Some management measures could be applied to specific places to increase ecosystem resilience or to partially compensate for negative impacts, but there is often no explicit economic or institutional support for doing so. Among the options for mitigation are development setbacks for coastal and estuarine wetlands, linking fragmented ecosystems to provide plant and animal migration routes, using water-control structures to enhance ecosystem function, and explicit protection and allocation of water needed for ecosystem health. Some research has been done on these issues, but far more is needed.

River Channel and Geomorphology

River channel erosion and sedimentation are a function of many variables, including the characteristics of soils, precipitation, and streamflow. Very little research has been done on the implications of climate changes for river channels and erosion, in part because of uncertainties about how precipitation – and especially extreme precipitation events – will change. Hanratty and Stefan (1998) simulated streamflow and sediment yield in a small river basin in Minnesota and concluded that the lack of physically-based models of channel dynamics hindered their ability to evaluate impacts. In the scenario they used, sediment yields decreased because of reduced soil-erosion rates, but the authors state that their confidence in the model results was low. Erosion and sedimentation rates will have effects on reservoir yields, water quality, ecosystem structure, and much more, and we urge more research on this issue.

Table 11:
Impacts of Climate Change on Aquatic Ecosystem Functioning and Health

Region	Potential Climate Effect	Ecosystem Considerations
Great Lakes/ Precambrian Shield	Warmer, more precipitation, but drier soils possible, depending on the magnitude of precipitation increase.	Altered mixing regimes in lakes (e.g. longer summer stratification; Changes in DOC concentration, changes in thermocline depth and productivity; Decreased habitat for cold and cool water fishes, increased habitat for warm water species.
Arctic and Sub-Arctic North America	Much warmer, increases in precipitation	Loss or reduction of deltaic lakes; Reduction in area covered by permafrost, leading to drainage of lakes and wetlands, land slumping, sedimentation of rivers; Increased primary productivity, but perhaps not enough to compensate for increased metabolic demands in predatory fish.
Rocky Mountains	Warmer	Changes in timberline would affect stream food webs; Increased fragmentation of cold-water fish habitat; Fishless alpine lakes sensitive to changes in nutrient loading and sedimentation; Current anthropogenic changes are threatening aquatic ecosystems.
Pacific Coast Mountains and Western Great Basin	Warmer, less snow but more winter rain, less summer soil moisture	Increases in productivity in alpine lakes; Increased meromixis and decreased productivity in saline lakes; Altered runoff regimes and increased sediment loads leading to decreases in channel stability and negative impact on economically important fish species.
Basin and Range, Arid Southwest	More precipitation, warmer, overall wetter conditions	Aquatic ecosystems highly sensitive to changes in quantity and timing of stream flow; Intense competition for water with rapidly expanding human populations.
Great Plains	Warmer with less soil moisture	Historical pattern of extensive droughts; Reduced water level and extent of open water in prairie pothole lakes with negative effects on waterfowl; Increasing warming and salinity in northern and western surface waters threatening endemic species; Reduction in channel area in ephemeral streams.
Mid-Atlantic and New England	Warmer and somewhat drier	Potentially less episodic acidification during snowmelt; Possible increase in bioaccumulation of contaminants; Bog ecosystems appear particularly vulnerable.
Southeastern U.S.	Warmer with possible precipitation increases and greater clustering of storms	Increases in rates of primary productivity and nutrient cycling in lakes and streams; More extensive summer deoxygenation in rivers and reservoirs; Loss of habitat for cold water species like brook trout, which are already at their southern limit; Drying of wetland soils; Northward expansion of nuisance tropical exotic species; Increased construction of costly water supply reservoirs.

Adapted from Meyer et al. (1999).

Is Climate Change Already Affecting the Nation's Water? Evidence of Hydrologic Trends

Introduction

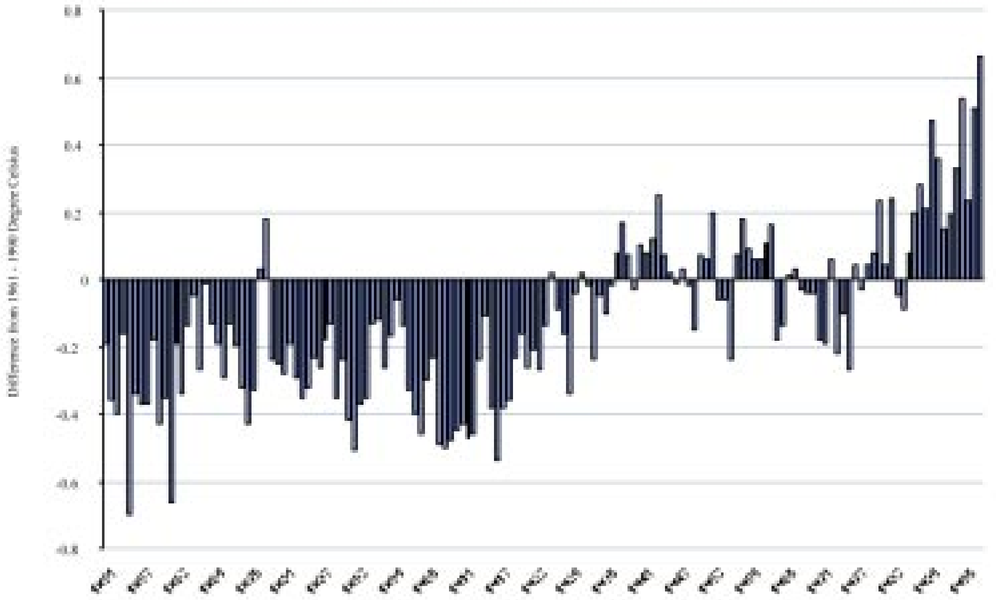
There is a very high degree of confidence in the scientific community that unchecked increases in atmospheric greenhouse-gas concentrations will eventually lead to changes in the Earth's climate, including the variability of that climate. There is also an increasing amount of evidence accumulating that some changes are already occurring. The executive summary of the 1995 IPCC report stated that the weight of evidence suggests a discernible human influence on climate (IPCC 1996a). Nearly five more years of evidence of various kinds have accumulated since that report was completed. Indeed, a primary reason for the rapidly growing concern about global climate change is the observation from more and more data sets of departures from historical averages, combined with a growing understanding of how current climate variability affects humans in their day-to-day lives. Despite gaps in data, inadequate and uneven climate monitoring, short record length, and biases in instrumental data, recent research suggests that changes and variations in the hydrologic cycle of the earth may already be occurring as a result of growing greenhouse gas concentrations. Trends of increasing temperature have been noted and debated for more than twenty years and recently departures from historical averages have been observed for the timing of snowmelt, runoff magnitudes, flowering dates, ice retreats, borehole temperatures, butterfly ranges, onset of egg-laying in birds, and many other things (see, for example, Changnon et al. 1993, Groisman et al. 1994, Beaubien and Johnson 1994, Moore and McKendry 1996, Dettinger and Cayan 1995, Cayan 1996, Ainley and Divoky 1998, Hodge et al. 1998, Crick and Sparks 1999, Parmesan et al. 1999, Schwartz and Reiter 2000, McCabe et al. 2000). Detection of trends in hydrological time series is notoriously difficult because of the normally large variability in natural systems and because of inadequate or incomplete long-term data records. Nevertheless, a number of the observed changes are sufficiently different from the past record to be considered the result of something other than natural variability.

A similar conclusion can be drawn for the United States. In work done by the National Climate Data Center, Karl and associates analyzed national weather-related trends since 1910 and found, within 95% confidence limits, that actual climate trends in the United States are consistent with projected trends due to a human-induced warming effect resulting from increased concentrations of greenhouse gases (http://www.ncdc.noaa.gov/ol/climate/research/gcps/papers/amsbull/amsbull.html). Given all the current research results and observations, we conclude that the evidence that humans are changing the water cycle of the United States is increasingly compelling.

Temperature and Related Trends

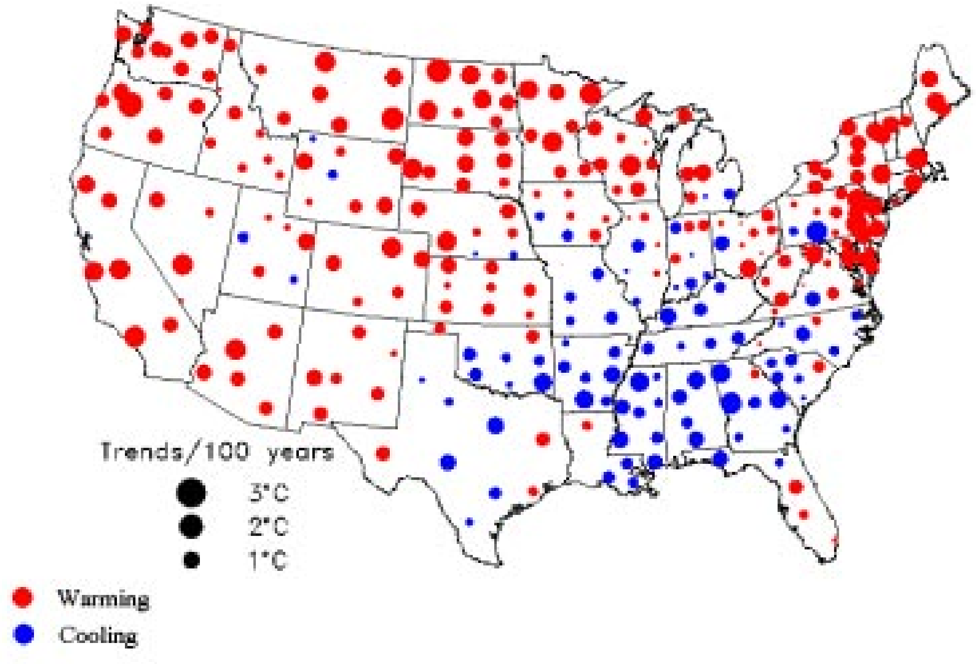
The climate change that has received the most attention is the increase in average temperature. Data from a network of ground- and ocean-based sites suggest that the average surface temperature of the Earth has increased by over a degree Fahrenheit (around 0.6^{o} Celsius) over

Figure 20:
Temperature Anomalies in the Northern Hemisphere: Departures from 1961-1990 Mean



Source: UK Meterological Office (1999). http://www.met-office.gov.uk/sec5/sec5.html

Figure 21:
Temperature Trends in Degrees Celsius in the Continental United States (1900 to 1994)



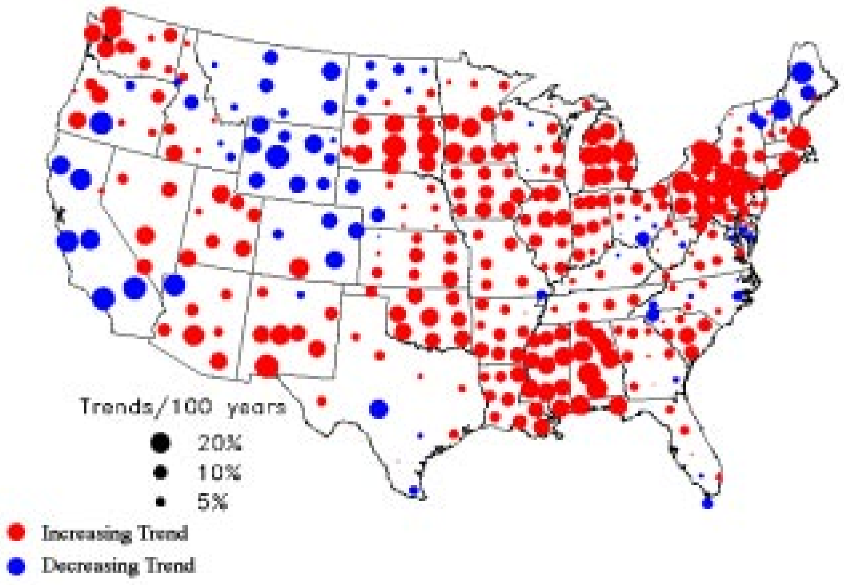
Source: Karl and Knight (1998).

the past century (NRC 2000). The fifteen warmest years this century have all occurred since 1980, the 1990s were the warmest decade of the entire millennium, and 1998 was the warmest year on record (Mann et al. 1999). 1999 was the fifth warmest year since 1860 and seven of the ten warmest years on record occurred in the 1990s (see Figure 20) (UK Met Office 1999). These changes appear to be outside the range of natural variability (IPCC 1996a,b; Mann et al. 1999). The higher latitudes have warmed more than the equatorial regions, in agreement with what the climate models project for greenhouse warming (IPCC 1996a).

Temperatures in the United States have also increased. Figure 21 shows temperature trends for the continental U.S. from 1900 to 1994. Regions of both warming and cooling can be seen, while the overall United States has warmed by about two-thirds of a degree C. Pronounced warming has occurred in winter and spring, with the largest increases in the period March-May over the northwestern United States (Lettenmaier et al. 1994, Dettinger et al. 1995, Vincent et al. 1999).

Additional evidence supports the temperature data. Between 1981 and 1991, satellite imagery documented an increase in the length of the growing season in the northern high latitudes (between 45 and 70° N) by a total of up to 12 days. Vegetation bloomed up to eight days earlier in spring and summer, and continued to photosynthesize an estimated four days longer. Permafrost in the Alaskan and Siberian arctic is beginning to thaw, mountain glaciers are melting at unprecedented rates, and mean sea level has risen between 10 and 20 centimeters since the 1890s (IPCC 1996a). Arctic ice thickness has declined significantly from the 1958-1976 period, according to data from both satellite sensors and direct measurements from U.S. naval submarines. These changes are greater than would be expected from natural variability (Vinnikov et al. 1999, Levi 2000).

Figure 22:
Precipitation Trends (1900 to 1994) in Percent per Century



Source: Karl and Knight (1998).

Precipitation Trends

Considerable uncertainty remains in evaluating trends in precipitation. Records are incomplete, measurements vary in accuracy, and perhaps most importantly, precipitation is naturally highly variable, making trends difficult to detect. Additional analysis will be necessary before researchers have a very high degree of confidence that trends in precipitation have been detected and whether or not such trends are attributable to anthropogenic climate change. Some analyses, however, have begun to report statistically significant trends in both global and North American precipitation patterns. By the late 1980s, observers had noticed a general increase in precipitation outside of the tropics, with a tendency for rainfall declines in the subtropics, particularly in the northern tropics of Africa (IPCC 1990, 1996a). Between 1900 and 1988, precipitation over land increased by 2.4 millimeters (mm) per decade and global mean rainfall rose by more than two percent. These results show that global rainfall now is about 22 mm per year higher than it was at the turn of the century (Dai et al. 1997a,b). Consistent with the upward trend in global precipitation, the average mean interval between two drier-than-average-months increased by approximately 28% from 1900-1944 to 1945-1988.

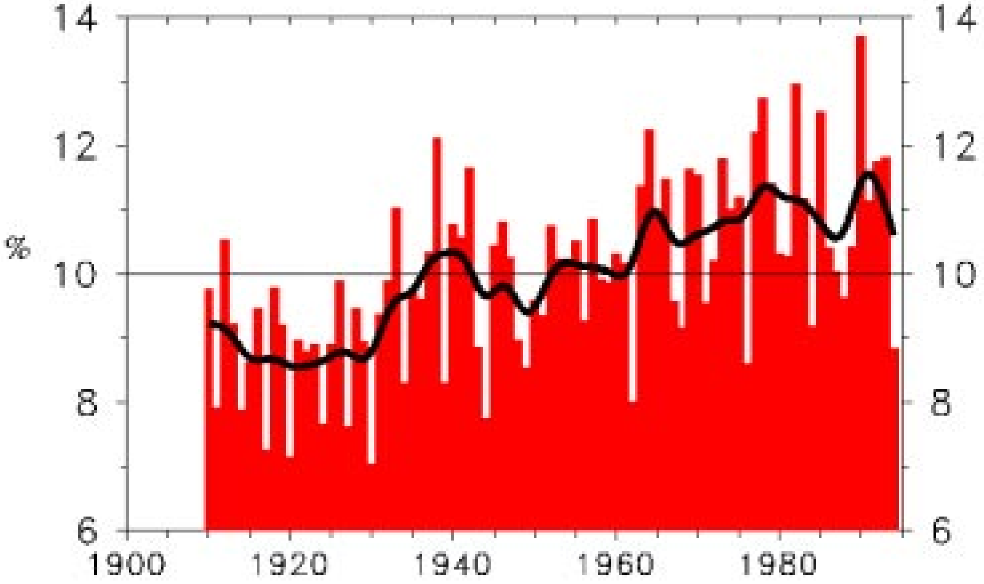
There is also evidence of an historical trend of both increasing and decreasing precipitation in different regions of North America since 1900 (Lettenmaier et al. 1994, Karl et al. 1995). The percentage of wet areas over the United States has more than doubled (from ~12% to >24%) since the 1970s while the percentage of dry areas has decreased by a similar amount since the 1940s. Figure 22 shows precipitation trends in the continental United States from 1900 to 1994. Precipitation has increased over land in the high latitudes of the Northern Hemisphere, particularly during winter. These trends have been supported by regional, national, and global studies, even correcting for known biases of precipitation measurements (Karl et al. 1995).

In another analysis, Karl and Knight (1998) show an increase in precipitation in the continental United States, with most of the increase in the highest annual one-day precipitation event – a potentially worrisome trend in regions where flooding is a problem (Figures 23 and 24). By analyzing long-term precipitation trends in the United States, they determined that:

- Precipitation over the contiguous United States has increased by about 10% since 1910;
- The intensity of precipitation has only increased for very heavy and extreme precipitation days;
- Increases in total precipitation are strongly affected by increases in both the frequency and the intensity of heavy and extreme events, measured as the highest 1-day annual precipitation event;
- The probability of precipitation on any given day has increased;
- The proportion of total precipitation from heavy events has increased at the expense of moderate precipitation events.

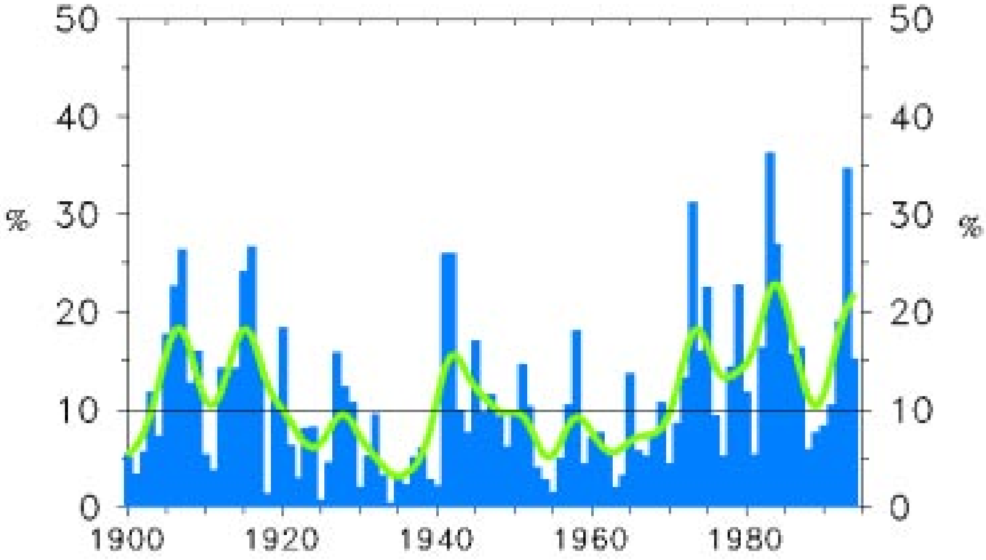
Regional analyses support some of the conclusions of the continental trends. For example, Angel and Huff (1997) found an approximately 20% increase in the number of daily precipitation events of two inches or more in the midwestern U.S. between 1901 and 1994.

Figure 23:
Percent of United States with Extreme Precipitation Events



Source: http://www.ncdc.noaa.gov/ol/climate/research/gcps/papers/amsbull/amsbull.html

Figure 24:
Percent of the United States in Severe Moisture Surplus



Source: http://www.ncdc.noaa.gov/ol/climate/research/gcps/papers/amsbull/amsbull.html

Karl and Knight (1998) also found an increase in the upper 10th percentile of daily precipitation amounts in this region, which feeds the Mississippi River. As discussed later, climate change-induced increases in the frequency and magnitude of extreme precipitation events could have important ramifications for water management, system operation, and the probability or consequences of water-related disasters.

Snowpack and Ice Cover Trends

Climate models and theoretical studies of snow dynamics have long projected that higher temperatures would lead to a decrease in the extent of snow cover in the Northern Hemisphere (see, for example, Rango 1992, Dettinger and Cayan 1995, Cayan 1996, Rango 1997). Recent field surveys corroborate these findings. Snow cover over the Northern Hemisphere land surface has been consistently below the 21-year average (1974 to 1994) since 1988 (Robinson et al. 1993, Groisman et al. 1994), with an annual mean decrease in snow cover of about 10% over North America. These changes have been linked to the observed increases in temperature. Continuous and discontinuous permafrost has warmed considerably in Alaska and is thawing in some locations (Lachenbruch and Marshall 1986, Osterkamp 1994, Osterkamp and Romanovsky 1996). Eight glaciers (seven in Alaska and one in Washington State) showed on average a decrease in thickness of 10 meters between the late 1950s and mid 1990s (Sapiano et al. 1998). Other effects include earlier lake ice melting, earlier snowmelt-related floods in western Canada and the western United States, and earlier warming of Northern Hemisphere land areas in the spring (Nicholls et al. 1996). At the same time that snow and ice cover seem to be decreasing and melting earlier, total annual snowfall in the far northern latitudes seems to be increasing, consistent with the observed increases in northern latitude precipitation where even the higher winter temperatures do not get above freezing.

Surface and satellite observations of the extent of sea ice in the Northern Hemisphere also show extensive decreases over the period 1953 to 1998. A comparison of these trends with model estimates reveals that the observed decreases agree with the climate model simulations and that both trends are much larger than would be expected from natural climate variability (Vinnikov et al. 1999, Levi 2000). Changes in Arctic ice and permafrost, described above in the Temperature section, are additional observational evidence supporting detection of climate change.

Runoff Trends

River runoff or discharge is considered to be an excellent integrator of climate factors, which makes it an important indicator of climate variability and change. Long records of runoff are essential to determining whether runoff is changing over time, but the number of rivers with reliable records longer than several decades is limited and records longer than a century are extremely rare. Similarly, discharge also integrates numerous human influences such as flow diversions for irrigation and municipal use, natural streamflow regulation by dams and reservoirs, and baseflow reduction by groundwater pumping. Detecting a climate signal in the midst of these complicating factors can be difficult (Changnon and Demissie 1996). Importantly, however, not all watercourses are subject to such confounding human activities and discharge data sets specifically designed to be sensitive to the effects of climate have been assembled and published (Wallis et al. 1991, Slack and Landwehr 1992, see also http://wwwrvares.er.usgs.gov/hcdn_report/content.html.)

A small number of analyses of nationwide streamflow trends in the United States have been completed using these data sets; their conclusions should be considered preliminary and incomplete. Although each used a different approach, their results will form the basis for further work in the future. Lins and Michaels (1994) looked at trends in monthly mean flow in 11 broad regions of the United States between 1941 and 1988. They found statistically significant increases in nine of the 11 regions and, in nearly all instances, the trends were observed in autumn and early winter months. The largest increases occurred in the upper Mississippi and Ohio River valleys.

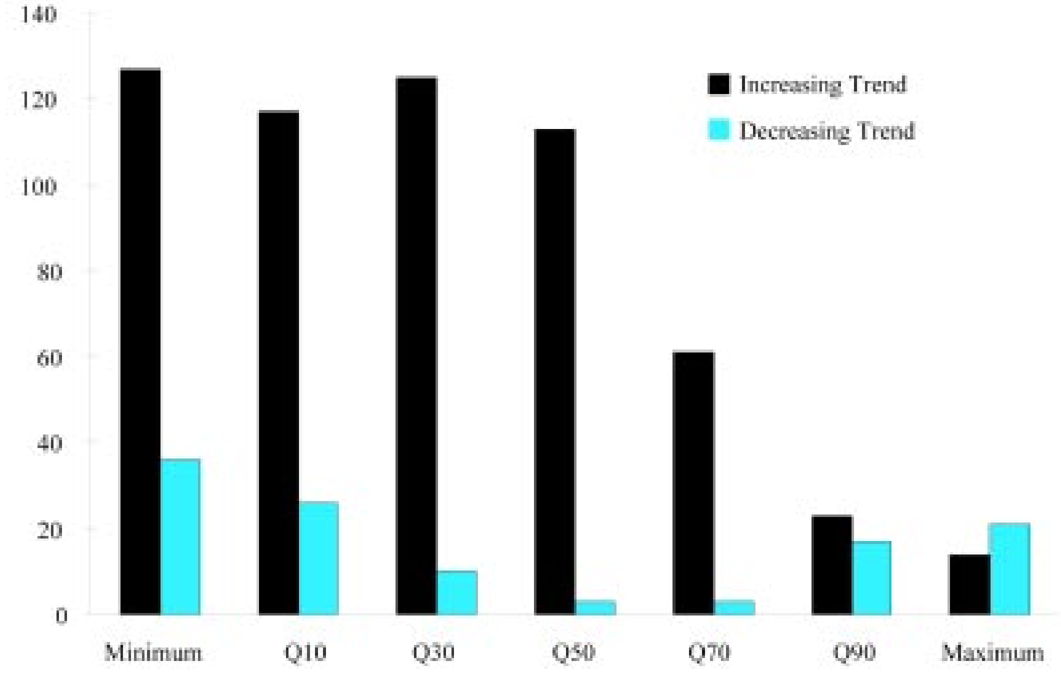
Lettenmaier et al. (1994) also evaluated trends using monthly mean discharge, but did so for 1,009 stations for the period 1948 to 1988. They found significant increases in winter and early spring streamflow across much of the United States. Although the trends were geographically widespread, there was a distinct concentration in the upper Mississippi and Ohio River valleys, consistent with the Lins and Michaels findings. Lins and Slack (1999) analyzed trends in U.S. streamflow using daily discharge records across a range of flow quantiles, from the annual minimum to the annual maximum discharge. These quantiles were not fixed over the analysis period, but varied from year-to-year so for example, the 90th percentile in a low flow year could be less then the long-term mean median flow. The assessment evaluated trends of 30- to 80-year periods, each ending in 1993, providing insights on interdecadal variability in streamflow trends. Their analysis suggests that by the early 1990s discharge had increased across broad sections of the United States, and that the greatest percentage increases occurred primarily in the lowest half of the streamflow distribution from the annual minimum to the annual median discharge (see Figure 25). Their results indicate no systematic trend in the annual maximum streamflow and no continental-scale seasonal shift in peak discharges. These results suggest that average runoff in the United States was increasing but getting less extreme up to the early 1990s, though small percentage increases in the highest percentiles can still be large absolute increases in flow.

To help reconcile apparent discrepancies between observed increases in heavy daily and weekly precipitation during much of the 20th century as reported by several studies (see, for example, Karl et al. 1996, Karl and Knight 1998, Kunkel et al. 1999), Groisman et al. (2000) analyzed the co-variations of daily precipitation and streamflow for events above various precipitation and runoff thresholds. The period studied included much of the 20th century, but focused on the periods of most extensive data, 1939-99 and 1939-93. In the mountainous western part of the country their analysis found little relation between increases in heavy precipitation and changes in high streamflow, similar to Lins and Slack (1999). In this area snow cover has significantly retreated during the latter half of the 20th century. Streamflow decreases were observed in the months of maximum streamflow and were found to be related to decreases in snow cover extent causing a shift in the seasonal peak discharges. For much of the eastern half of the United States, Groisman et al. (2000) found a significant and coherent signal of increasing heavy precipitation contributing to increasing high streamflows (those in the upper five and one percent of the observations). They found statistically significant increases when averaged across the nation for both streamflow and precipitation during the period 1939-99 for heavy precipitation events and high streamflow (upper 5%), but much of this increase was due to changes in the eastern United States.

Yoshino (1999) examined trends in 161 gauging stations on 108 major world basins using data to 1990. He found some trends in some parts of the world, including a decline in runoff in the Sahel and weak increasing trends in western Europe and eastern North America, and also showed that many rivers in arid and semi-arid regions were beginning to exhibit increased relative variability. The differences between the results of Lins and Slack (1999) and those of Karl and Knight (1998) reported above suggest that the observed changes in precipitation events may not be the kinds that lead to flooding, but much more work is needed in this area. The past decade has been warmer, and new analyses using updated runoff data and different kinds of analysis could be available soon.

Another aspect of runoff trends relates to seasonal rather than annual changes. In some watersheds in western North America, the timing of runoff appears to be shifting from early spring to late winter (medium confidence). Such a pattern is consistent with a variety of climate model simulations and regional studies that indicate a shortening of the winter snow accumulation season and an earlier melting of the snowpack will occur as temperature increases (Gleick 1986, 1987b). Burn (1994) found a statistically significant trend toward earlier spring runoff in west-central Canada on more than 70% of

Figure 25:
Number of Streamgages, Out of a Total of 395, With Statistically Significant ($p \leq 0.05$) Trends for the 50-Year Period 1944-1993.



Source: Lins and Slack (1999).

80 natural rivers, primarily since 1950. Dettinger and Cayan (1995) reported that between 1948 and 1991, snowmelt-generated runoff came increasingly early in the water year in many basins in northern and central California. They noted that a declining fraction of the annual runoff was occurring during the months of April to June in middle-elevation basins, and that an increasing fraction was occurring earlier in the water year, particularly in March. Gleick and Chalecki (1999) observed this same basic pattern in an analysis of the Sacramento and San Joaquin Rivers over the entire 20th century (Figures 26 and 27). In these important watersheds, the fraction of total annual runoff that occurs during April through July (the spring snowmelt season) has been steadily decreasing, even correcting for human water withdrawals and the operation of reservoirs (Gleick and Chalecki 1999). This was also confirmed by the analysis of Groisman et al. (2000) showing the relationship between decreased spring snow cover extent and streamflow in the northwestern U.S. and Missouri River Basin.

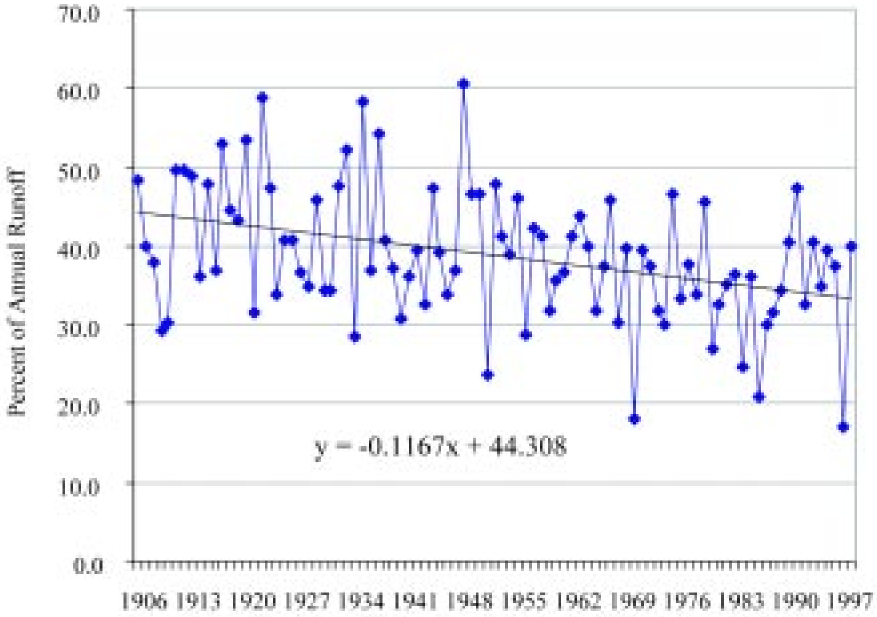
Snowmelt-runoff timing shifts, especially in middle-elevation mountainous river basins are of interest because, as Dettinger and Cayan (1995) point out, such basins are quite sensitive to changes in mean winter temperatures. Thus, these areas are likely candidates for early detection of a greenhouse-induced hydrologic change signal. However, as Dettinger and Cayan further note, the observed hydrologic shifts in these areas can involve more than simple relationships with air temperature alone. In the coastal regions of the western U.S., for example, they can be associated with complicated atmospheric patterns that arise from a progressively northward-displaced jet stream during winter that is linked to warm North Pacific sea-surface temperatures since about 1976. Changes in the pattern of North Pacific sea-surface temperatures since about 1995, possibly toward a cool phase, may augur a change in the character of atmospheric circulation and air temperatures over the eastern North Pacific and western North America (Mantua et al. 1997, Minobe 1997). The implications of such changes on the timing of snowmelt-generated runoff in the western United States are still unknown.

A more detailed assessment of trends in river flows and floods, using data reaching to the present, is needed to determine if changes in climate are yet producing changes in runoff, as is a better understanding of the implications of changes in larger atmospheric conditions for runoff. As Arnell (1996) states: “The evidence for global warming having a noticeable effect on hydrological behaviour is not yet convincing, but it does seem to be accumulating.”

Variability and Extreme Events

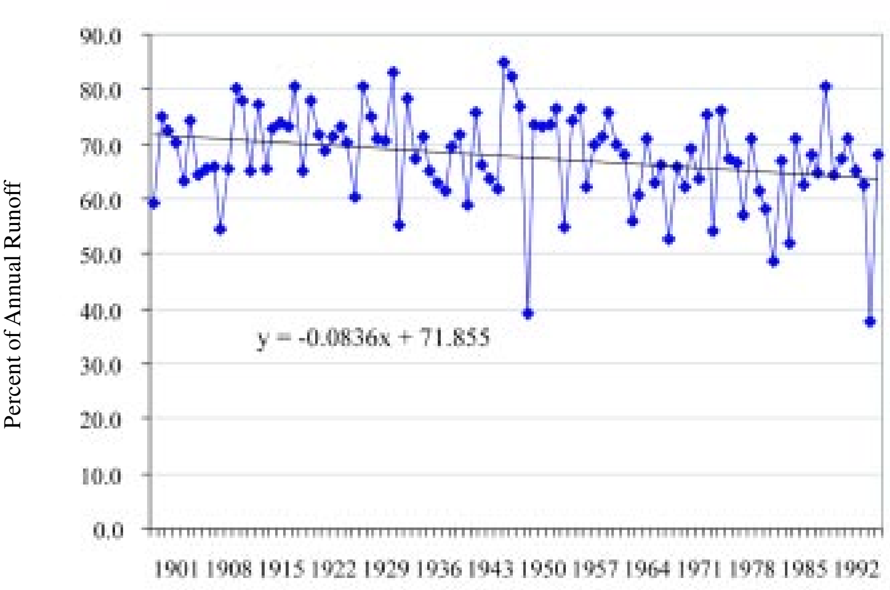
Most climate impacts result from extreme weather events and we expect the same will hold for the impacts of climate change. The El Niño/Southern Oscillation, which is the strongest natural interannual climatic fluctuation, has effects on the entire global climate system and the economies and societies of many regions and nations, including the United States. The strong El Niños of 1982/83 and 1997/98, along with the more frequent occurrences of El Niños in the past few decades, have forced researchers to try to better understand how human-induced climate change may affect interannual climate variability (Trenberth and Hoar 1996, Timmermann et al. 1999).

Figure 26:
Sacramento Index: April to July Runoff (as Percent of Annual Runoff)



Source: Gleick and Chalecki (1999).

Figure 27:
San Joaquin Index: April to July Runoff (as Percent of Annual Runoff)



Source: Gleick and Chalecki (1999).

Limited research has been conducted on trends in the frequency and intensity of extreme hydrologic events, though in the past few years more efforts have been made in this area. Clear evidence of very few trends has yet appeared, and much more effort is needed, even to identify appropriate indicators of such changes and to compile the data needed to do a comprehensive assessment (Meehl et al. 2000, Easterling et al. 2000). As noted above, Karl and Knight (1998) reported an increase in the highest 1-day annual precipitation records, but efforts to assess changes in actual storm frequencies or intensities, or extreme runoff, are just beginning.

Hayden (1999) reviewed storm tracks and strengths from 1885 to 1997. Breaking North America into 180 grid cells and tracking storm during this period revealed no indication of any overall trends. He also concluded that there has been neither a systematic increase or decrease in the number of storms since 1885. Landsea et al. (1999) found a statistically significant decrease in intense hurricanes that cause the most damage. An analysis of precipitation, runoff, and flood data for the Upper Mississippi and lower Missouri rivers concluded that flood risk has increased in recent decades. Analysis of flows on tributaries of the Missouri and Meremac rivers shows “a significant increase in flood risk over time in the last century” (Olsen et al. 1999). There are several possible competing explanations for these apparent changes, including human-induced climate ange, natural variability in precipitation in the region, measurement errors, or anthropogenic change such as levee construction and alteration of local geomorphology. Some of the changes in risk are also certainly due non-climatic factors, including land-use changes, population increases in vulnerable areas, and changes in structural protection. Rossel and Garbrecht (1999) examined systematic spatial and random spatial variability of precipitation in central Oklahoma and related it to temporal variability for the years 1919-1996. Both natural temporal and spatial variability of precipitation are large and the authors note that using regional precipitation data from large-scale model outputs to draw conclusions about how local conditions might change in the future is risky, since accurate regional and local precipitation patterns are not reproducible yet.

Winstanley and Changnon (1999) reviewed how existing variability in weather and climate affected water conditions for the state of Illinois, from 1901 to 1997. The results for Illinois were considered representative of impacts over other midwestern states. They also evaluated how regional hydrologists perceive the relative importance of various weather factors in altering water availability and quality. The water factors studied included streamflow, reservoir supplies, groundwater supplies, and the quality of both surface and ground water. These water factors were most sensitive to weather conditions in spring and summer, and less sensitive to conditions in the fall and winter. The major seasonal impacts identified were:

- Wet/Warm springs led to mixed effects on surface water quantity and water quality, and positive effects on groundwater quantity;

- Dry/Warm springs led to negative effects on surface water quantity and mixed effects on water quality;

- Wet/Warm summers led to mixed effects on surface water quantity and negative effect on water quality; and

- Dry/Warm summer led to negative effects on all water factors.
- Cool conditions, whether wet or dry, had little effect.

Analyses of flood risks are traditionally based on past data and on a fundamental assumption that peak floods are “random, independent, and identically distributed events.” This assumes that climate trends or cycles are not affecting the distribution of flood flows and that the future climate will be similar to past climate. Current concern over natural variability, anthropogenic climate change, and possible impacts on hydrology, however, calls this assumption into question (NRC 1998).

Climate Change and Impacts on Managed Water-Resource Systems

Introduction

Climate change will affect the availability of water in the United States, as well as its quality, distribution, and form. Climate change will also affect the complex infrastructure and systems in place to manage the nation's water and existing climate variability. There is a growing literature about how different climate changes may affect the infrastructure and complex systems built to manage United States water resources (Chalecki and Gleick 1999: see http://www.pacinst.org/CCBib.html for a searchable bibliography). Research has been conducted on potential impacts over a wide range of water-system characteristics, including reservoir operations, hydroelectric generation, navigation, and other concerns. At the same time, significant knowledge gaps remain and far more research is needed. Priorities and directions for future work should come from water managers and planners as well as from the more traditional academic and scientific research community.

Precipitation, temperature, and carbon dioxide levels affect both the supply of, and demand for, renewable water resources. Irrigation, which accounts for 39% of all U.S. water withdrawals and 81% of consumptive use (Solley et al. 1998), is particularly sensitive to climate conditions (see Figure 2). Water for household purposes — drinking, preparing food, bathing, washing clothes and dishes, flushing toilets, and watering lawns and gardens — accounts for eight percent of withdrawals and seven percent of consumptive use in the United States (Solley et al. 1998). While indoor domestic water use is not very sensitive to temperature and precipitation, outdoor uses for gardens and parks are very climate dependent. In some regions of the U.S., particularly the arid and semi-arid west, climate-induced changes in domestic demand can aggravate the problems of balancing supplies with demands.

Industrial use, which includes water for processing materials, washing, and cooling, accounts for seven percent of withdrawals and three percent of consumptive use in the United States. Thermoelectric power use in the U.S., which includes water for cooling to condense the steam that drives the turbines in the generation of electric power with fossil fuel, nuclear, or geothermal energy, accounts for 39% of all withdrawals but only three percent of consumptive use (Solley et al. 1998). A rise in air and water temperatures might have several effects on these water uses. For instance, higher water temperatures would reduce the efficiency of cooling systems and increase the demand for cooling water. Increased air and water temperatures can also cause plant deratings, forced shutdowns due to environmental constraints, or violation of safety water intake limits.

Changing air temperatures would alter energy use for summer air conditioning and winter space heating. These changes in the temporal and spatial demand for energy could also alter the demand for cooling water. The effect on consumptive water use, however, would be small because more than 95% of the freshwater withdrawn for industrial and thermoelectric power use is now returned to ground and surface water sources where it can be reused.

Water Supply Infrastructure

A major challenge facing hydrologists and water managers is to evaluate how changes in system reliability resulting from climate change may differ from those anticipated from natural variability and, in theory, already anticipated in original project designs. Both surface and groundwater supply systems are known to be sensitive to the kinds of changes in inflows and demands described earlier. In one of the earliest studies on these issues, Nemec and Schaake (1982) showed that large changes in the reliability of water yields from reservoirs could result from small changes in inflows. This finding has now been seen in many other studies from many regions (USEPA 1989, Lettenmaier and Sheer 1991, McMahon et al. 1989; Cole et al. 1991; Mimikou et al. 1991; Nash and Gleick 1991, 1993). Lettenmaier and Sheer (1991), for example, noted the sensitivity of the California State Water Project to GCM-derived scenarios of climate change under current operating rules. They concluded that changes in operating rules might improve the ability of the system to meet delivery requirements, but only at the expense of an increased risk of flooding. This kind of trade off is now being seen in a broader set of analyses.

Nash and Gleick (1991, 1993) evaluated the implications of climate change for deliveries of water to several of the major users on the Colorado River, taking into account the legal and institutional regulations and water-rights agreements already in place as well as existing operating rules for the reservoirs. Both hypothetical and GCM-based scenarios were evaluated. This complex basin already experiences stresses imposed by large conflicting demands for a limited resource. The study concluded that climate change might have dramatic impacts on the reliability of water deliveries, but that the overall impacts were highly dependent on the legal and institutional conditions in place.

Table 12:
Percent Frequency with which CRSS Scheduled Annual Deliveries are Met or Exceeded

Runoff Scenario	Metropolitan Water District of Southern California (500,000 acre-feet Scheduled Delivery)	Central Arizona Project (1,467,000 acre-feet Scheduled Delivery)	Mexico (1,515,000 acre feet Scheduled Delivery)
- 20 percent	100	0	64
- 10 percent	100	28	94
-5 percent	100	35	100
Base Case	100	59	100
+5 percent	100	77	100
+10 percent	100	95	100
+20 percent	100	97	100

Source: Nash & Gleick (1999).

Estimates of consumptive use of water in the basin were reported in terms of depletions and deliveries. Some users are guaranteed, by law, minimum deliveries. Deliveries of water from the upper to the lower basin fall below legal requirements 23% of the time in the base case. If average flows drop only five percent, this frequency rises to 41%. Under the Colorado River Simulation System operating assumptions, the scheduled deliveries of water to the Metropolitan Water District of Southern California are met in all years under all scenarios because of their higher water right. Annual deliveries to the Central Arizona Project, which has a more junior right, meet or exceed scheduled deliveries only 40% of the time in the base case and fall to their minimum level in 50% of the years when long-term runoff drops only five percent. Table 12 summarizes the percent frequency with which scheduled deliveries to MWD, CAP, and Mexico are met or exceeded. Deliveries to Mexico fall under the level specified by international treaty when long-term average runoff decreases by 10% or more. Potential changes in water demand due to climate change were not addressed by the study, but would further complicate basin management.

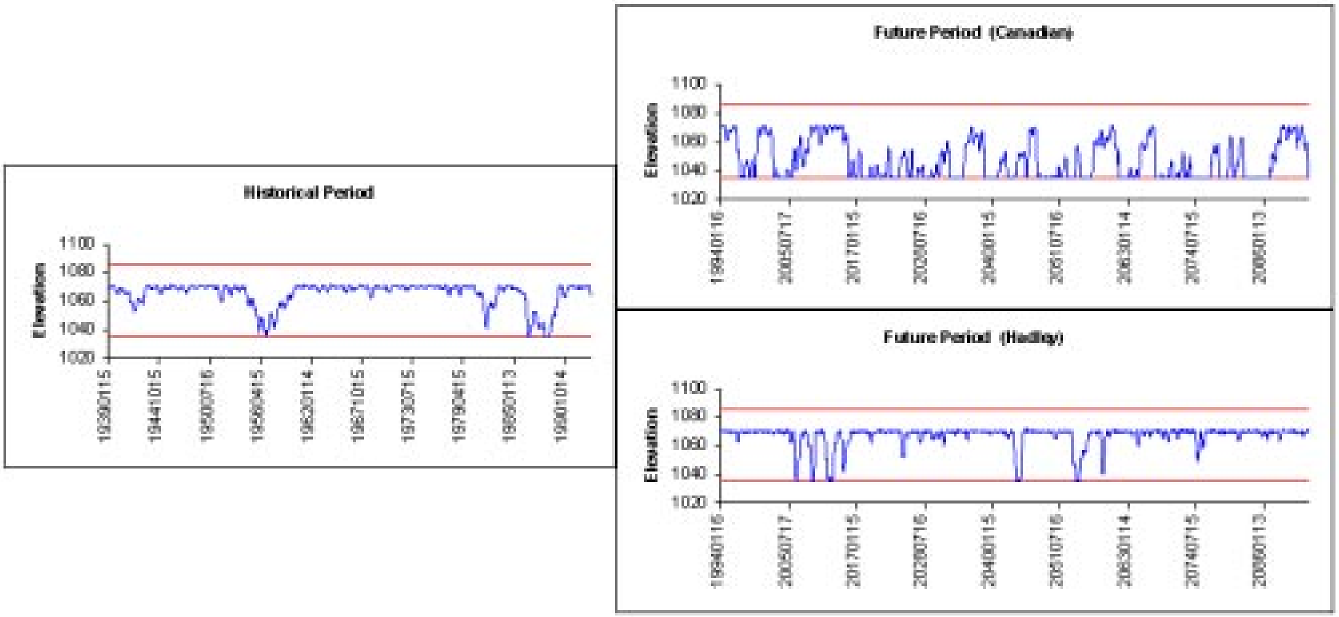
Lettenmaier et al. (1999) conducted a broad assessment of the sensitivity of six major U.S. water resource systems to climate change and evaluated the performance of multiple-use systems. These studies applied a range of transient GCM scenarios and evaluated the effects on end users of water. Six systems were studied in all: two very large river basins (the Columbia and Missouri), two moderate size basins (the Savannah and Apalachicola-Chattahoochee-Flint (ACF)); and two urban water-supply systems (Boston and Tacoma). For each system, several indicators were evaluated, including system reliability (defined as the percentage of time the system operates without failure), the system resiliency (defined as the ability of the system to recover from a failure), and the system vulnerability (defined as the average severity of failure).

Changes in runoff were the most important factors determining the climate sensitivity of system performance (Lettenmaier et al. 1999), even when they evaluated the direct effects of climate change on water demands. These sensitivities depended on the purposes for which water was needed and the priority given to those uses. Higher temperatures increased system use in many basins, but these increases tended to be modest, as were the effects of higher temperatures on system reliability.

One complication of this analysis is the difficulty of projecting future water demands in the absence of climate change. Wood et al. (1997) and Lettenmaier et al. (1999) noted that the influence of long-term demand growth on system performance had a greater impact than climate change when long-term withdrawals are projected to grow substantially. In the Boston and Tacoma areas, traditional projections of large growth in municipal and industrial water use led to a greater mismatch between supply and demand than did most of the climate scenarios. Kirshen and Fennessey (1995) also evaluated the potential impacts of both changes in demand and climate change on the Boston water-supply system and noted that supply deficits caused by these factors could cost as much as $700 million to make up, while implementing demand-management options, such as installing water-conserving fixtures and appliances, fixing leaks, and modifying industrial processes, could reduce this amount to under $150 million. As was shown earlier in Figure 5, general projections for the United States have regularly and significantly overestimated future withdrawals, often by a factor of two or more. The same is true for local and regional estimates. Actions to reduce demands or to moderate the rate of increase in demand growth can therefore play a direct role in moderating the impacts of climate change as well, with concomitant effects on system reliability.

Georgakakos and Yao (2000b) investigated the impacts of climate change on the Apalachicola-Chattahoochee-Flint (ACF) river basin in the southeastern United States. Their assessment is based on a decision-support system developed for the ongoing water-allocation negotiations among the states of Georgia, Alabama, and Florida. This assessment system is a detailed river-basin management model that represents all storage reservoirs, hydropower facilities, water-supply withdrawals (agricultural, municipal, and industrial), environmental flow requirements, lake recreational constraints, and navigational needs. Reservoir operation policies are generated dynamically using updated information on streamflow forecasts and system conditions. In this respect, their analysis permits an evaluation of the ability of a real system to mitigate the adverse effects of climate variability and change through changes in operating rules and policies. The model was run under historical conditions as well as for the Canadian and Hadley climate scenarios, and for water demands projected for the year 2050. The results indicate that under the Canadian scenario, the ACF river basin would experience severe water shortages and stresses. Under the Hadley scenario, which is considerably wetter, shortages are not experienced and the system can prevent flooding if operating behavior and rules are changed.

Figure 28:
Historical and Future Water Level Sequences for Lake Lanier



Historical and future water level sequences for Lake Lanier. These sequences were generated by the Apalachicola-Chattahoochee-Flint Decision Support System using the Canadian and Hadley climate scenarios. During the historical record, minimum reservoir levels are rarely reached; for the dry Canadian scenario, minimum levels are a persistent problem. Source: A. Georgakakos and Yao (2000b).

For the Canadian scenario, water-supply deficits would increase more than 50-fold in the upper part of the basin while reservoir levels would experience frequent and very severe drawdowns. Unmistakable evidence of this is shown in Figure 28, which depicts the historical and future water-level fluctuations for Lake Lanier, the largest of the ACF reservoirs. Among other detrimental consequences, water-level fluctuations of such magnitude would sharply diminish the ability of the lake to provide relief during droughts, generate dependable energy, and maintain its high recreational value. Under the Canadian climate scenario, the ACF system would also frequently fail to meet the low-flow targets throughout the basin, degrading environmental quality and compromising ecosystem health. These adverse effects are exacerbated if the reservoirs are operated according to the historical operational practices. Figure 28 also portrays the Lake Lanier fluctuations for the Hadley scenario. In this scenario, all ACF reservoirs exhibit a markedly different response: water-supply shortages and flow target violations are not recorded in this case, while the risk of flooding is fully controlled. These results underscore the uncertainty associated with climate scenarios and emphasize the need for flexible water-allocation agreements and adaptive management strategies that explicitly account for uncertainty.

Hydropower and Thermal Power Generation

In parts of the United States, substantial amounts of electricity are produced by hydroelectric facilities. Table 13 shows the production of hydroelectricity in 1995 by water-resource region. The amount and value of hydropower production from a given hydroelectric power plant is a function of the amount of water available, the height that water falls before going through a turbine, and operational decisions about scheduling releases.

Variability in climate already causes variations in hydroelectric generation. During a recent multi-year drought in California, decreased hydropower generation led to increases in fossil-fuel combustion and higher costs to consumers. Between 1987 and 1991, these changes cost ratepayers more than $3 billion and increased greenhouse gas emissions (Gleick and Nash 1991). Because of conflicts between flood-control functions and hydropower objectives, human-induced climate change in California may require more water to be released from California reservoirs in spring to avoid flooding. This would result in a reduction in hydropower generation and the economic value of that generation. At the same time, production of power by fossil fuels would have to increase to meet the same energy demands in California at a cost of hundreds of millions of dollars and an increase in emissions of greenhouse gases (Hanemann and McCann 1993).

Climate changes that reduce overall water availability or change the timing of that availability have the potential to adversely affect the productivity of U.S. hydroelectric facilities. In contrast, reliable increases in average flows would increase hydropower production. A growing number of regional assessments have begun to look at these issues. Nash and Gleick (1993) evaluated how equilibrium and transient climate scenarios would affect hydroelectricity production in the Colorado River system. Hydroelectricity production in the lower Colorado Basin was determined to be more sensitive to changes in runoff in the basin than any of the other variables studied, including salinity, reservoir levels, and deliveries of water to users. Under current operation laws and rules, Lake Mead has a relatively high minimum power pool and water deliveries are constrained to maintain some power-generating capacity. As a result, power is generated at a relatively constant level until critical (*i.e.*, minimum power pool) reservoir levels are reached. At this point power generation ceases. A 10% increase in average runoff was estimated to increase basin hydroelectricity production by 11%. Decreases in runoff of only 10% were projected to decrease hydroelectricity production from the whole Colorado basin by 15% and from the lower basin by 36% because minimum power-pool levels are more frequently reached. An average drop in runoff of 20% resulted in a 57% decrease in hydroelectricity production in the whole basin and a 65% decline in hydroelectricity

Table 13:
Hydroelectric Power Water Use by Water-Resources Region, 1995

Region	Water Use (Mgal/d)	Water Use (Thousand acre-feet/year)	Power Generated (million kWh)
New England	156,000	175,000	6,720
Mid-Atlantic	144,000	162,000	5,260
South Atlantic-Gulf	229,000	256,000	17,100
Great Lakes	340,000	382,000	24,200
Ohio	172,000	192,000	5,250
Tennessee	209,000	235,000	16,000
Upper Mississippi	119,000	133,000	2,990
Lower Mississippi	78,200	87,700	1,320
Souris-Red-Rainy	3,970	4,450	100
Missouri Basin	141,000	159,000	16,000
Arkansas-White-Red	95,400	107,000	6,740
Texas-Gulf	14,500	16,300	1,050
Rio Grande	3,860	4,320	464
Upper Colorado	17,900	20,000	7,220
Lower Colorado	23,400	26,300	9,740
Great Basin	5,060	5,670	633
Pacific Northwest	1,260,000	1,410,000	140,000
California	140,000	157,000	47,000
Alaska	2,090	2,340	1,440
Hawaii	229	256	148
Caribbean	349	391	101
Total	3,160,000	3,540,000	310,000

[Figures may not add to totals because of independent rounding. Mgal/d = million gallons per day; kWh = kilowatthour] Source: Solley et al. (1998).

production in the lower basin. Table 10 and Figure 19 show the sensitivity of water-supply variables including hydroelectricity production to changes in the natural flows of the Colorado under the current law of the river. No runs were made to explore the impacts on water deliveries or reservoir levels if operators try to maximize power production, but presumably hydropower production could be increased at the cost of a reduction in the reliability of water deliveries.

A more sophisticated study by Lettenmaier et al. (1999) looked at how climate change would affect a wide range of system characteristics for major watersheds, complex reservoir systems, and urban areas in several parts of the United States. They evaluated the impacts of a range of climate change scenarios, including three transient scenarios and an equilibrium doubled-CO_2 scenario. Among the effects studied were hydroelectric power operations. Their analysis concluded that power operations would be most sensitive to climate change in the Missouri River, where the climate scenarios would result in declines in the reliability of meeting monthly energy targets of as much as 15 to 35%. For the Columbia River basin, shifts in the seasonal hydrograph are critical, as are operating policies. In this region reliability of firm energy production showed progressive declines of as much as 5 to 15 % over time as climate changes; more modest decreases were seen in the equilibrium doubled-CO_2 scenario. For the Savannah River, two out of the three transient scenarios led to increases in hydroelectricity production; the third had slight declines. Results for the ACF basin were similar in direction to the Savannah basin, but smaller.

While most of the scenarios were evaluated assuming current operating conditions, some alternative operational scenarios were evaluated. For example, the current conflicts in the Columbia basin over fisheries protection versus hydropower generation could lead to a reprioritization of operational rules. Another possibility is that hydropower generation might be constrained by recreational needs to maintain reservoir levels in summer. Both of these alternatives were evaluated under conditions of climate change, and the overall effects on hydropower were on the order of those effects for the most severe climate scenarios using current operating rules (Lettenmaier et al. 1999).

Georgakakos and Yao (2000b) conducted a detailed hydropower assessment for the ACF river basin under historical and future (Canadian and Hadley) climate scenarios. Their model includes details of the basin's hydropower facilities and optimizes peak and off-peak energy generation subject to all other water-use commitments and constraints. Relative to the historical response, the dry Canadian climate scenario resulted in a 33% reduction in total energy generation, a 14% reduction in peak energy generation, and a 35% reduction in off-peak energy generation. By contrast, the wetter Hadley Climate Scenario increased total energy generation by 21%. In this assessment, all hydropower facilities were scheduled to generate at peak power for only one hour per day. Raising the peak power requirement from one to four hours per day leads to water shortages and stresses for all scenarios comparable to those of the Canadian scenario. Thus, water-use changes may be as consequential as climate change. Furthermore, Georgakakos and Yao (2000b) estimated that if reservoir operators use adaptable policies rather than traditional operating rules, energy generation gains as high as 20% could be achieved without any adverse impact to other water uses. The implication of this finding is that dynamic management strategies could be effective in mitigating the adverse impacts of climate change.

Chao (1999) evaluated ten different steady-state and transient climate scenarios and modeled changes in the value of hydropower generation in the Great Lakes compared with a base climate. Hydropower plants and their diversion works along the St. Mary's and St. Lawrence rivers serve as water-level control structures for Lake Superior and Lake Ontario. The model also includes hydropower generated at Niagara. Treaties between the United States and Canada determine flow releases, but there are exceptions in the treaties when levels and flows fall outside treaty conditions. In all ten scenarios, hydropower generation decreased because of projected decreases in lake levels. On average, hydropower dropped 7 to 10%, though it decreased in some scenarios by as much as 20% (Chao 1999).

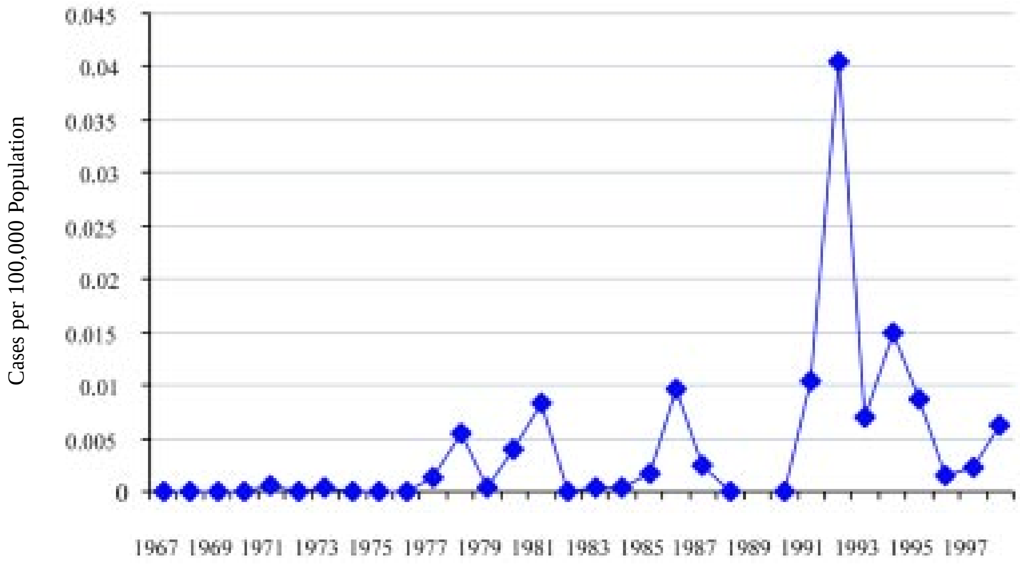
Climate also plays a role in power production from conventional fossil fuel and nuclear power plants by affecting cooling water temperatures and plant efficiencies. In an unusual study of the impacts of climate change on river temperatures, Miller (1993) concluded that the Tennessee Valley Authority would be forced to reduce power generation and shut down fossil and nuclear plants more frequently to avoid violating temperature standards set for regional rivers. Plant efficiencies, which depend in part on the temperature of cooling water, would be reduced (medium confidence) and cooling towers required more often.

Human Health

There are direct and indirect links between water availability and quality and human health. Efforts are just beginning to explore the complex connections among climate, water, and human health (Bernard et al. 1999). A separate effort of the National Assessment has been devoted to this problem, and interested readers are urged to read the analyses prepared for that sector. Many urban areas already have a problem with urban storm runoff that, when untreated, leads to problems with both inland and coastal water quality, which in turn has well documented direct effects on human health. Changes in climate conditions can affect the intensity of urban storm runoff, particularly in regions where precipitation increases. Climate change will also affect the viability of disease vectors like mosquitoes. The viability and transport of water-borne pathogens such as *Cryptosporidium* is known to be affected by changes in precipitation and runoff intensities and by land-use practices. *Cryptosporidium* has been responsible for an increasing number of drinking water advisories in recent years and a major outbreak in Milwaukee in 1993 led to more than 100 deaths and 400,000 illnesses. Hantavirus, a disease spread by deer mice, has been linked to ENSO-related climate variability. Higher rainfall has led to increased rodent populations and increased contact between humans and rodents. The distribution of *Vibrio cholerae*, the bacteria responsible for cholera, is affected by climate conditions, including El Niño, temperature, and ocean salinity (Colwell 1996, Motes et al. 1998, Harvell et al. 1999). Figures 29 and 30 (from MMWR 1999) show the incidences of cholera and malaria in the United States, two diseases related to the quality of water or vectors that breed in water.

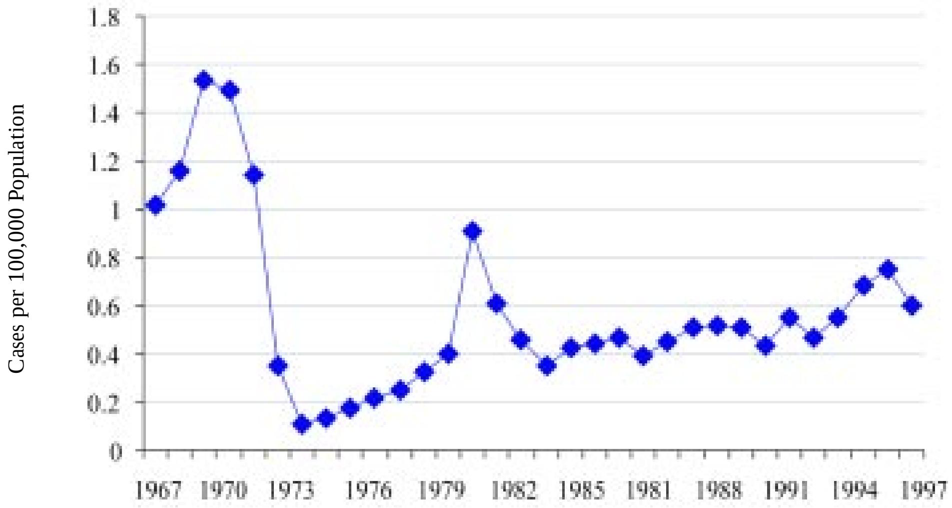
Many of the cases of cholera, malaria, dengue fever, and other diseases reported in the United States are actually imported by travelers from other parts of the world. Increases in water-related diseases elsewhere, therefore, can have an indirect effect on United States cases. Over 740,000 cases of dengue fever were reported for 1998 by Pan American Health Organizations countries, more than twice the total for 1997. Continued expansion of dengue in Latin America will ultimately have an effect on the United States either through direct or imported incidences. In 1998, 90 probable or confirmed cases of dengue fever were

Figure 29:
Cholera Incidence in the United States



Source: MMWR (1999).

Figure 30:
Malaria Incidence in the United States



Source: MMWR (1999).

reported in the United States, up from 56 cases in 1997 (MMWR 1999). No clear evidence is available yet to conclude how climate change will ultimately affect these factors or to suggest any climate-related change in the incidences of these kinds of diseases in the United States, but we urge more research and careful monitoring of water-related disease vectors and data.

Navigation and Shipping

Water-borne shipping is an important means of transportation for certain regions and industries. River and lake navigation and shipping are sensitive to flows, water depth, ice formation, and other climate factors. A warming would increase the potential length of the shipping season on some northern lakes and rivers that typically freeze in winter. Decreases in river flows would reduce the periods when navigation was possible, increase transportation costs, or increase the conflicts over water allocated for other purposes. An increase or reduction in storm frequency or intensity would affect Great Lakes navigation.

An assessment of the impacts of ten different climate scenarios on navigation in the Great Lakes evaluated the monthly cost of shipping per ton as a function of Great Lakes levels (Chao 1999, Chao et al. 1999). The analysis takes into account water depth, ship classes, ship draft, loading capacities, routes, commodity demands, and various costs. As expected, differences in the GCM estimates of impacts on lake levels led to differences in consequences for shipping. Decreases in inflows under all ten GCM scenarios result in higher costs by as much as 35%. Average increases in costs among the scenarios were around 15% (Chao 1999).

In Lettenmaier et al. (1999), navigation in each of six basins studied was affected in various ways, depending on the characteristics of the region and the modeled climate conditions. Reliability of lock operations on the Snake River decreased significantly for some scenarios and the reliability of water-depths sufficient for navigation in the Missouri also decreased.

Agriculture

Assessing the impacts of climate change on agriculture requires integrating a wide range of factors, including soil conditions, insect, weed, and disease prevalence, the effects of carbon dioxide on plant physiology, local and international market forces, farmer behavior, economic conditions, and the availability and quality of water. A completely separate assessment of the impacts of climate change and variability for the U.S. agricultural sector has been prepared and interested readers should seek out that research. Nevertheless, the strong links between water-resources availability and use and agricultural productivity deserve some comment here. In particular, relatively small changes in water availability could lead to relatively large impacts in the agricultural sector.

In the mid-1990s, approximately 80% of all water consumption occurred in the agricultural sector (Solley et al. 1998). In the western portion of the United States, the vast majority of agricultural production requires irrigation water from both surface and groundwater sources to supplement water received from precipitation. Increases in water availability due to climate change could help reduce the pressures faced by growers;

conversely, decreases in water availability are likely to affect growers more than other users for two reasons: urban and industrial users can pay more for water; and proportional reductions in water availability would lead to larger overall reductions to farmers. If irrigators holding senior water rights in the western United States are allowed to sell or transfer those rights, some could actually benefit from decreases in water availability.

Recent studies of U.S. agriculture suggest that overall production of food may not be seriously threatened by climate changes as currently projected by GCMs. Indeed, in the climate scenarios evaluated for the National Assessment the net economic effects of changes in agriculture were generally positive, although there were substantial regional differences and some regions suffered production declines (Reilly 1999). The overall results showed a decline in water demand for irrigation of between 5 and 35%, largely because of the differential effects of climate change on productivity of irrigated versus non-irrigated crops, and the assumed positive effects of higher levels of CO_2. The agricultural assessment also studied interactions of agriculture, groundwater, ecosystems, and urban demand in the Edwards aquifer and found significant threats to springflows that feed the aquifer. Pumping limits exist to protect the springflows and these limits would have to be decreased to maintain the endangered species habitat the limits are intended to protect. The agricultural assessment also found that runoff from nitrogen agriculture in the Chesapeake Bay could increase by 25 to 50% under these scenarios.

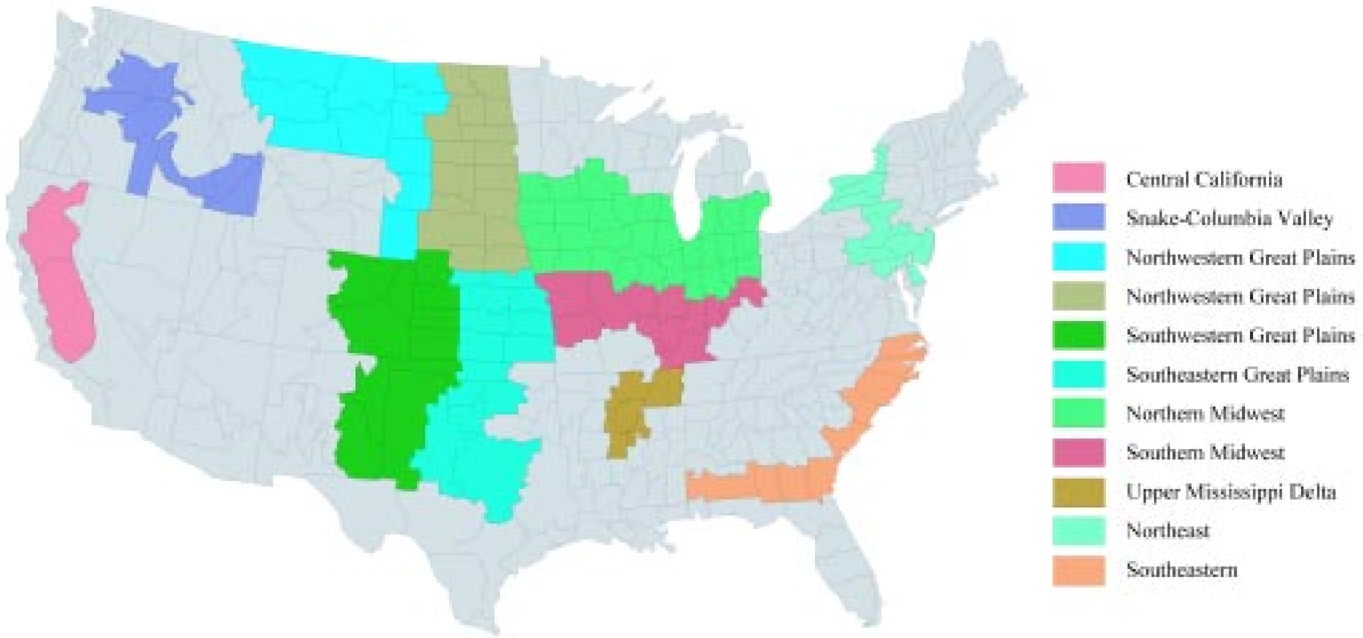
At the same time, there are serious caveats that accompany the research done to date, including some related to water availability and quality. Reliable information on changes in storm frequency and intensity is not yet available. Integration of indirect effects of climate change on hydrology and water into agroclimatic models has not yet been widely done, particularly effects of pests, soil conditions, disease vectors, and socioeconomic factors. Integrating these and other links between water and food should remain a high priority for researchers (see, for example, the discussions in Rosenzweig and Parry (1994) and Reilly and Schimmelpfennig (1999)).

Even less work has evaluated the impacts of changes in climate variability for agriculture. A paper by Chen et al. (1999) for the agricultural sector assessment evaluated the possible impacts on U.S. agriculture of the increases in El Niño projected by Timmermann et al. (1999). This analysis concluded such a change in variability would cost between $300 and $400 million per year, though no other changes in water availability were included.

Rounsevell et al. (1999) note that water available in soils has an important influence on agricultural productivity, and the work of Brumbelow and Georgakakos (2000) described below, highlights the importance of including this factor. Soil moisture responds to changes in temperature, precipitation amounts and frequency, CO_2 concentrations, and more. In regions where soil moisture decreases, artificial irrigation is the typical response, but such irrigation may ultimately be limited by other social and environmental factors. Patterson et al. (1999) summarize the effects of changes in precipitation patterns and soil-moisture availability for weeds and pests, and suggest that the overall challenge to agriculture from pests will probably increase with anticipated climate changes.

As part of the National Assessment water-sector work, Brumbelow and Georgakakos (2000) assessed changes in irrigation demands and crop yields using a suite of physiologically based crop models. The models were calibrated using both historical values of crop yield obtained from the U.S. Department of Agriculture and the moisture stress threshold that matches the simulated and historical crop yields. It was thus assumed that farmers' drought tolerance and irrigation attitude will be the same in the future as they have been in the past. The results were expressed as crop irrigation demands and associated potential crop yields. Soil-moisture content in the root zone was initialized at the beginning of each growing season using the values calculated by the macroscale soil-moisture model of Georgakakos and Smith (2000). This is a distinguishing difference of this study and the studies reported by the agricultural sector of the National Assessment. To match the spatial resolution of the soil-moisture model, the crop assessments were conducted using the NCDC (National Climate Data Center) climate divisions as fundamental units. Because the crop models work on a daily time step, the climate (in this case from the Canadian climate model) were downscaled from monthly to daily values using a stochastic weather generator that preserved the monthly statistics of the climate scenario and the historical interrelationships of the atmospheric variables. All simulations accounted for the effect of atmospheric CO_2 on crop growth. Assessments were conducted for five crops: peanuts, durum wheat, soybeans, winter wheat, and corn. These crops were selected because they have a cumulative cultivation area that includes most of the conterminous United States, their respective growing seasons extend throughout most of the year, and they represent a large share of the national agricultural economy (over $44 billion in 1998 farm-to-market value). Changes in irrigation demand and crop yield were assessed by comparing values from the 1994-2013 period of the Canadian climate scenario with values from the 2041-2060

Figure 31:
Agricultural Production Changes Resulting from Canadian Climate Scenarios



Agricultural production changes resulting from Canadian climate scenarios were evaluated for the regions highlighted in this map.
Source: Brumbelow and Georgakakos (2000).

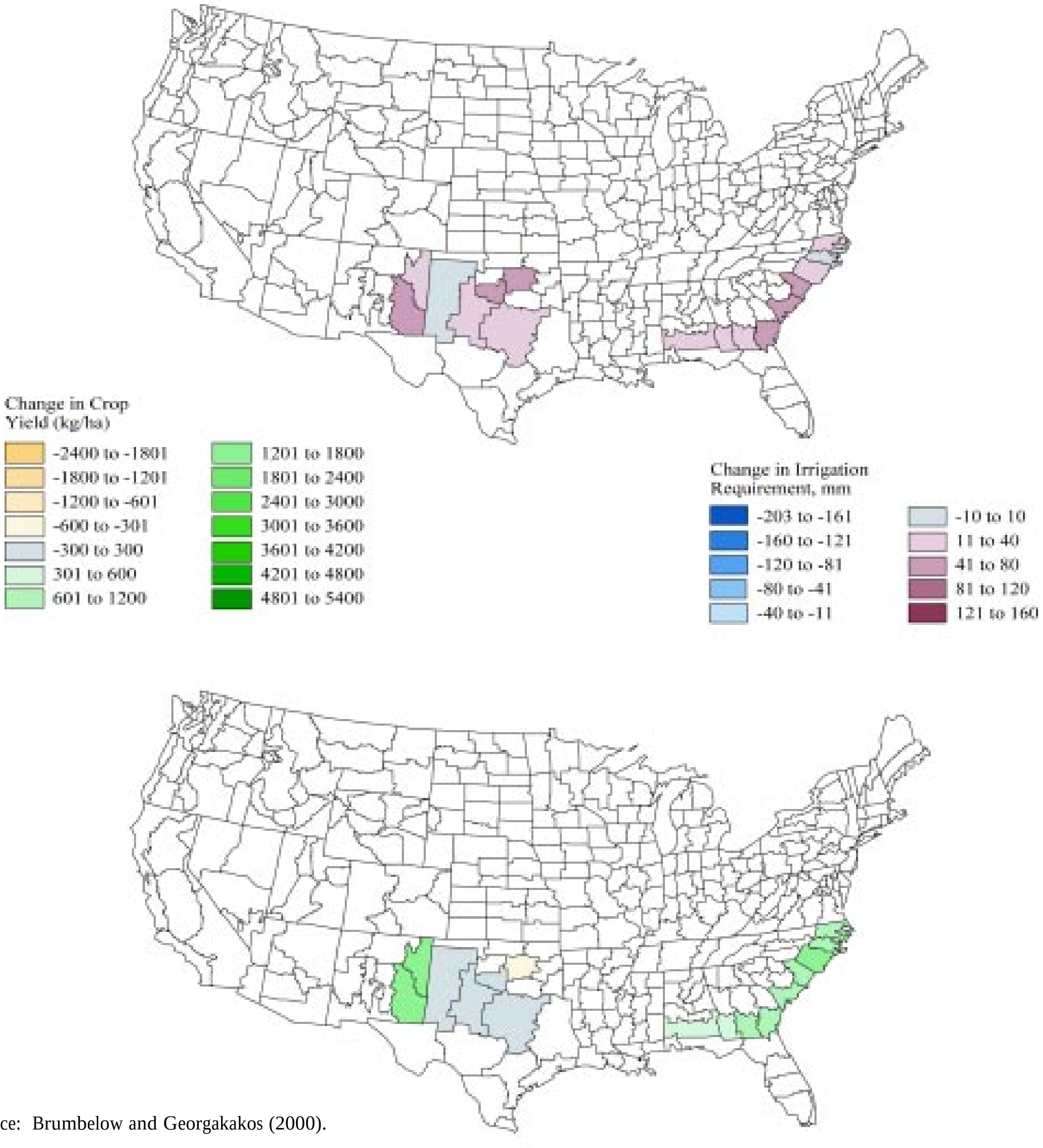
period. These two periods were chosen to represent the current climate conditions and the future conditions after significant warming and CO_2 accumulation takes place. The assessment looked at both mean trends and extreme drought tendencies.

Brumbelow and Georgakakos (2000) reached several important conclusions for regional agricultural changes, though their results are dependent upon a single climate scenario. Irrigation demands for peanuts increased along with the growing season both in the Southeast (96% increase in mean demands) and Southern Great Plains (22% to 51% increase) with a significant increase in variability in the Southeast. Durum wheat irrigation needs decreased significantly in California (82% decrease) and remained at near-zero levels in the Northern Great Plains. Soybean irrigation requirements increased significantly in the southern portion of its cultivation range (86% to 158% increase) with an accompanying increase in variability, but northern areas had only slight changes in irrigation demands (6% to 31% increase). Winter wheat irrigation needs decreased in the northern and western regions (27% to 74% decrease) and increased in the Southern Great Plains and Southeast (22% to 75% increase). Corn irrigation demands strongly decreased west of the 104th meridian (40% to 75% decrease) and were otherwise only slightly changed. In all regions, the length of the overall growing season increased. While these trends are in general agreement with the Agricultural Sector assessments, the variability estimates reported are consistently higher. The authors attribute at least part of this difference to the fact that the Agricultural Sector studies do not fully incorporate the soil-moisture variability implied by the Canadian climate scenario. Soil moisture is both spatially and temporally variable (Georgakakos and Smith 2000, Georgakakos and Yao 2000a) and has a significant influence on irrigation demands and crop yields. In this regard, the need for reliable soil-moisture measurements cannot be overstated.

The same study also estimated that crop yields mostly increased (assuming that the irrigation demands are met), with notable exceptions for winter wheat in the southern regions, and corn in all areas except the extreme northern and northwestern areas. Variability in crop yields increased for almost all areas for peanuts, durum wheat, soybeans, and winter wheat, and it increased for corn in the southern areas.

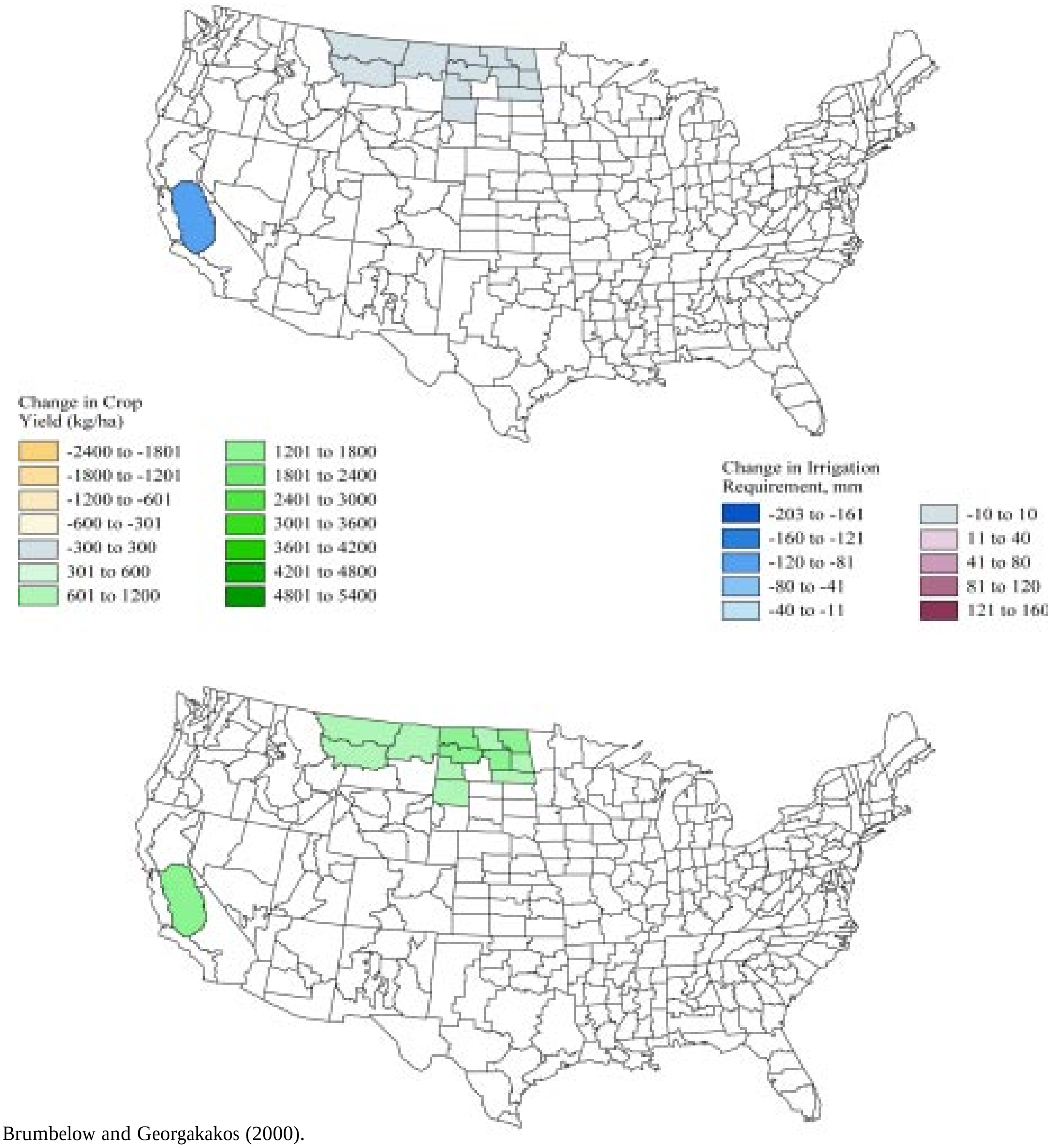
Brumbelow and Georgakakos' assessment of the agricultural impacts in the United States are in agreement with the Canadian climate scenario trends of a wetter climate in the west, a dryer climate in the east, and warmer temperatures throughout the country. Depending on which particular factor is most limiting for crop growth over the growing season (*i.e.*, water availability, temperature, or both) the U.S. agricultural response exhibits marked regional changes in a west-to-east direction around the 104th meridian for corn, a north-to-south direction around the 40th parallel for soybeans and durum wheat, and a northwest-to-southeast direction for winter wheat. Figure 31 shows the climate divisions grouped into the regions under which results are reported. Figures 32a-32e present maps of changes in mean irrigation requirements and changes in mean yields for the five crops studied.

Figure 32a:
Changes in Mean Irrigation Requirements (Top) and Mean Crop Yield (Bottom) for Peanuts for the Mid-21st Century Under the Canadian Climate Projection



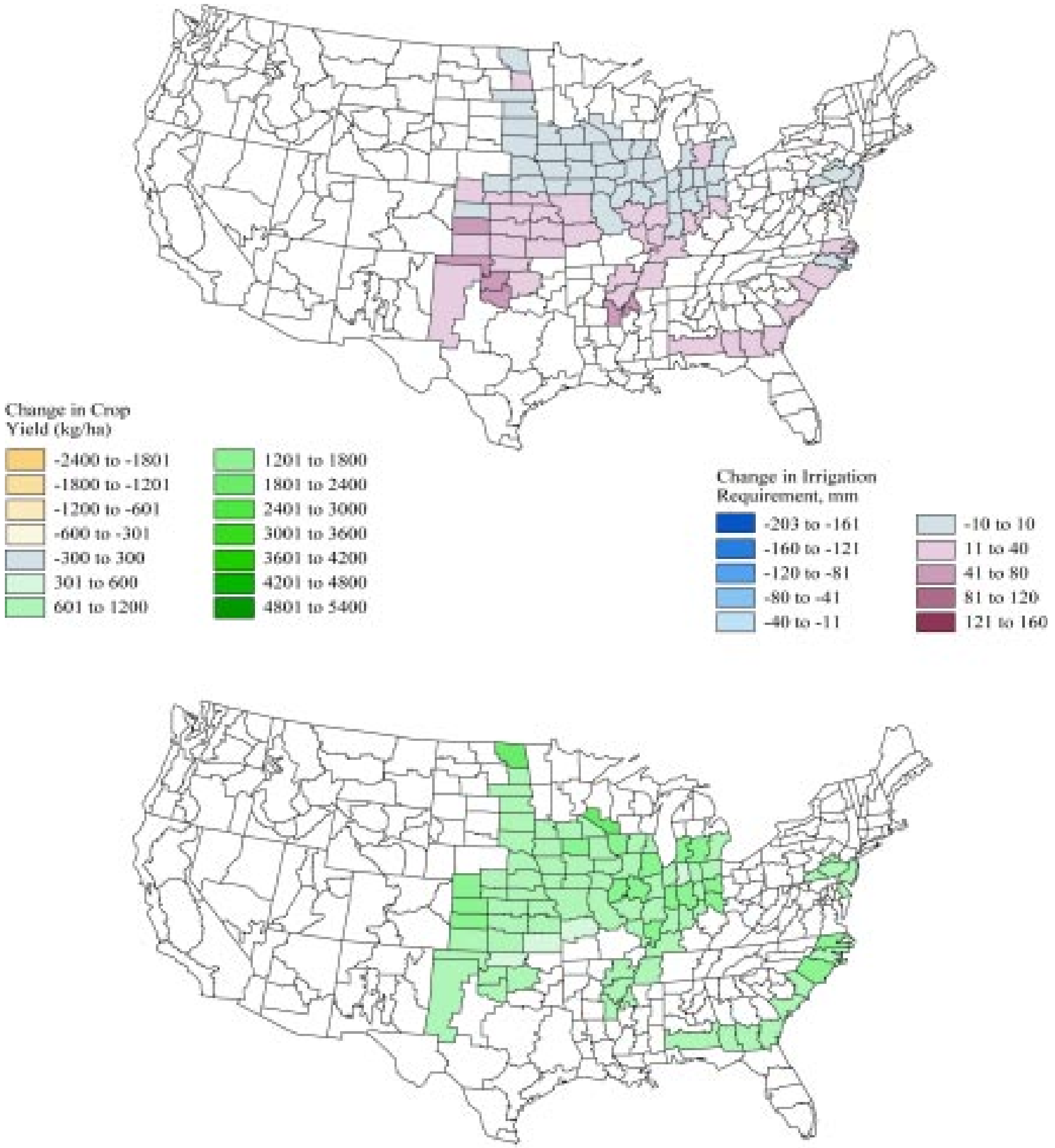
Source: Brumbelow and Georgakakos (2000).

Figure 32b:
Changes in Mean Irrigation Requirements (Top) and Mean Crop Yield (Bottom) for Durum Wheat for the Mid-21st Century Under the Canadian Climate Projection



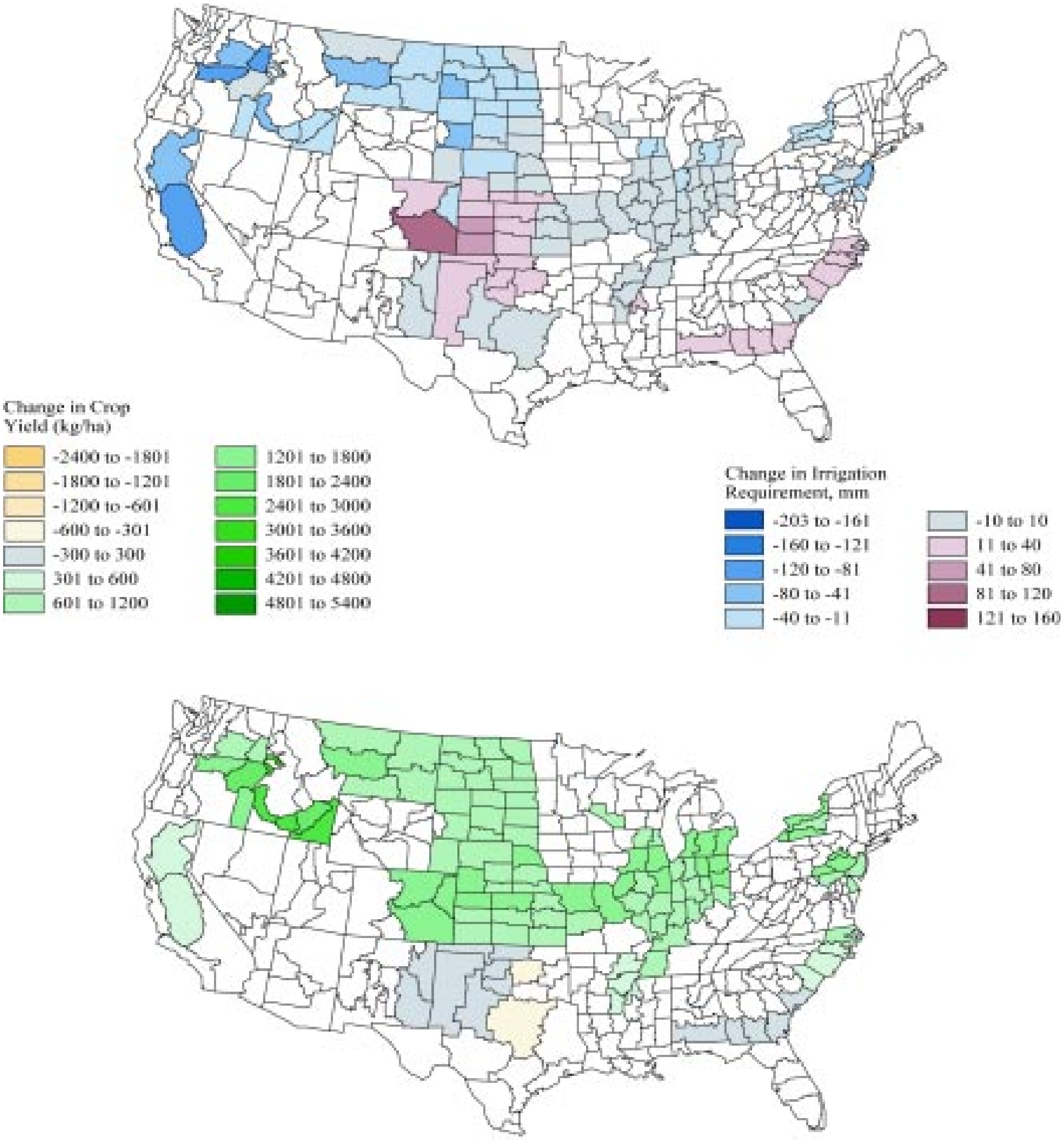
Source: Brumbelow and Georgakakos (2000).

Figure 32c:
Changes in Mean Irrigation Requirements (Top) and Mean Crop Yield (Bottom) for Soybeans for the Mid-21st Century Under the Canadian Climate Projection



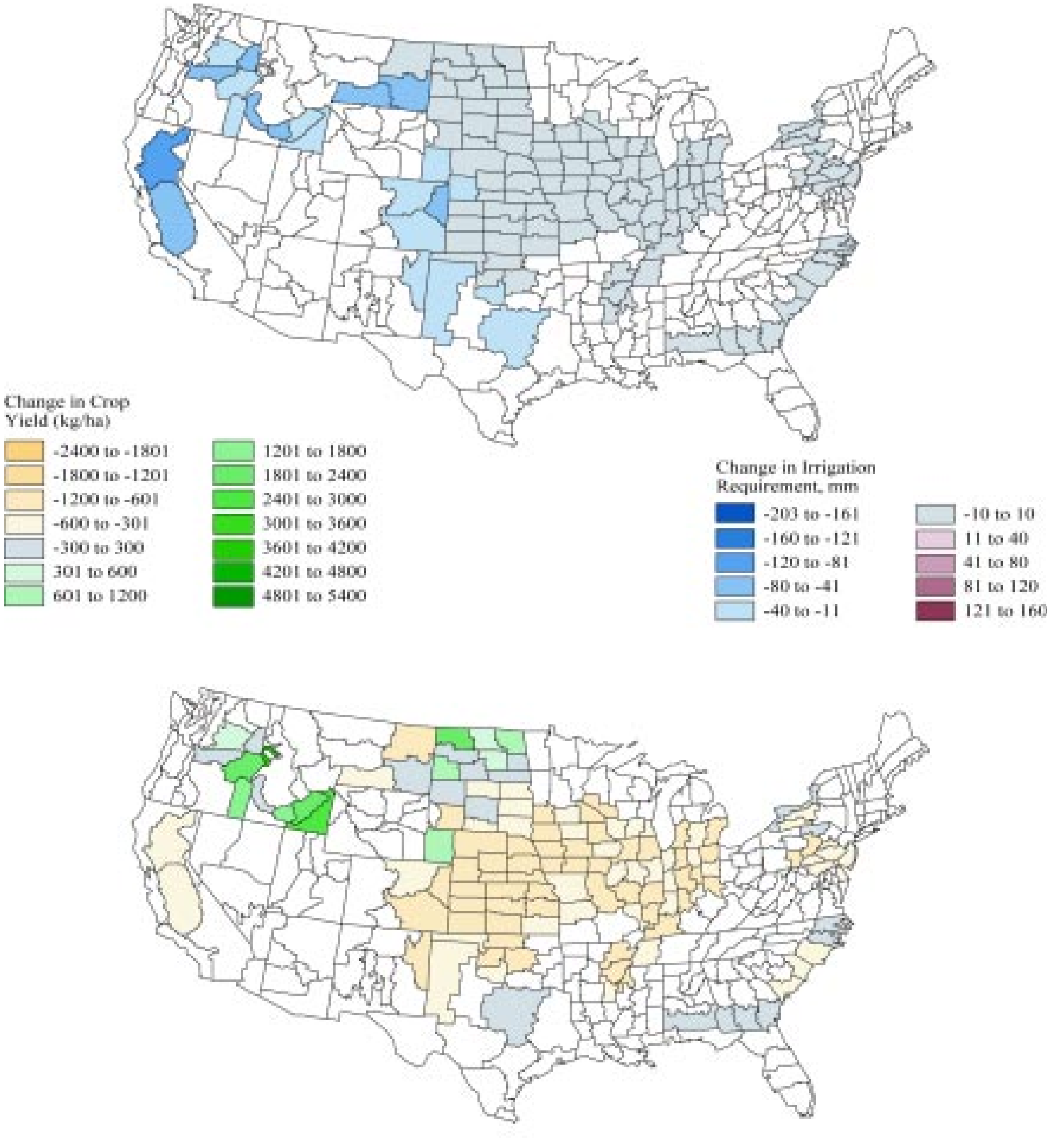
Source: Brumbelow and Georgakakos (2000).

Figure 32d:
Changes in Mean Irrigation Requirements (Top) and Mean Crop Yield (Bottom) for Winter Wheat for the Mid-21st Century Under the Canadian Climate Projection



Source: Brumbelow and Georgakakos (2000).

Figure 32e:
Changes in Mean Irrigation Requirements (Top) and Mean Crop Yield (Bottom) for Corn for the Mid-21st Century Under the Canadian Climate Projection



Source: Brumbelow and Georgakakos (2000).

Extreme Events

Much of the analysis of climate and water impacts looks at how changes in various means will affect water and water systems, such as mean temperatures, average precipitation patterns, mean sea-level, and so on. While many factors of concern are affected by such average conditions, some of the most important impacts will result, not from changes in averages, but from changes in local extremes. Water managers and planners are especially interested in extreme events and how they may change with climate change. Unfortunately, this is one of the least-well understood categories of impacts and we urge more effort be devoted to studying it. Hydrological fluctuations impose various types of costs on society, including the costs of building and managing infrastructure to provide more even and reliable flows, and the economic and social costs of floods and droughts that occur in spite of these investments. The United States has constructed more than 80,000 dams and reservoirs mostly to control flood waters and increase available supplies during dry periods. Yet floods and droughts continue to impose significant costs, and some of these costs have been rising over time. Climate-induced changes in hydrological conditions will affect the magnitude, frequency, and costs of future extreme hydrological events.

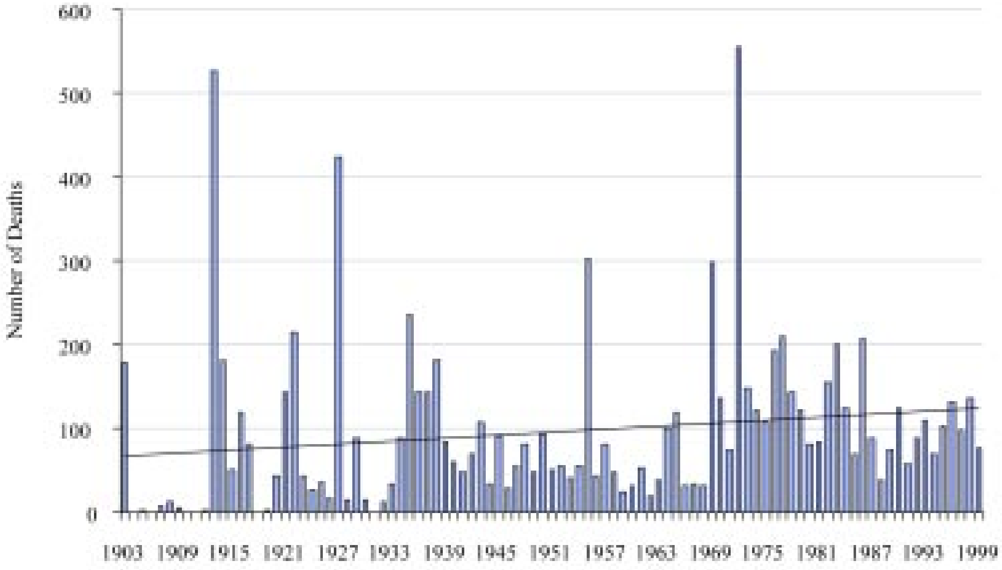
In a worst case, some regions could be subjected to both increases in droughts and increases in floods if climate becomes more variable. Even without increases in variability, both problems may occur in the same region. In the western United States, for example, where winter precipitation falls largely as snow, higher temperatures will increase the ratio of rain to snow (as described elsewhere), shifting peak runoff toward the period of time when flood risk is already highest. The actual magnitude of peak runoff could go up or down, depending on the extent of the shift and what happens with overall precipitation (Hay et al. 2000). At the same time, summer and dry-season runoff will decrease because of a decline in snowpack and accelerated spring melting.

Floods

The area of floodplains in the United States has been estimated at about 160 million acres or seven percent of U.S. land (Schilling 1987). These lands are often close to recreational opportunities, agricultural regions, and municipal and industrial developments, which makes them attractive for settlement. Federal and state efforts to control floods through the construction of dams, reservoirs, and levees have also led to floodplain development. Since the Flood Control Act of 1936 established flood control as a federal responsibility, the federal government has spent about $100 billion (1996 dollars) to construct, operate, and maintain flood-control structures (U.S. Army Corps of Engineers 1998). These facilities include approximately 400 major lake and reservoir projects, over 8,500 miles of levees and dikes, and hundreds of smaller local flood-protection projects. The U.S. Army Corps of Engineers estimates that these facilities have prevented nearly $500 billion in flood damages since 1950 (U.S. Army Corps of Engineers 1998).

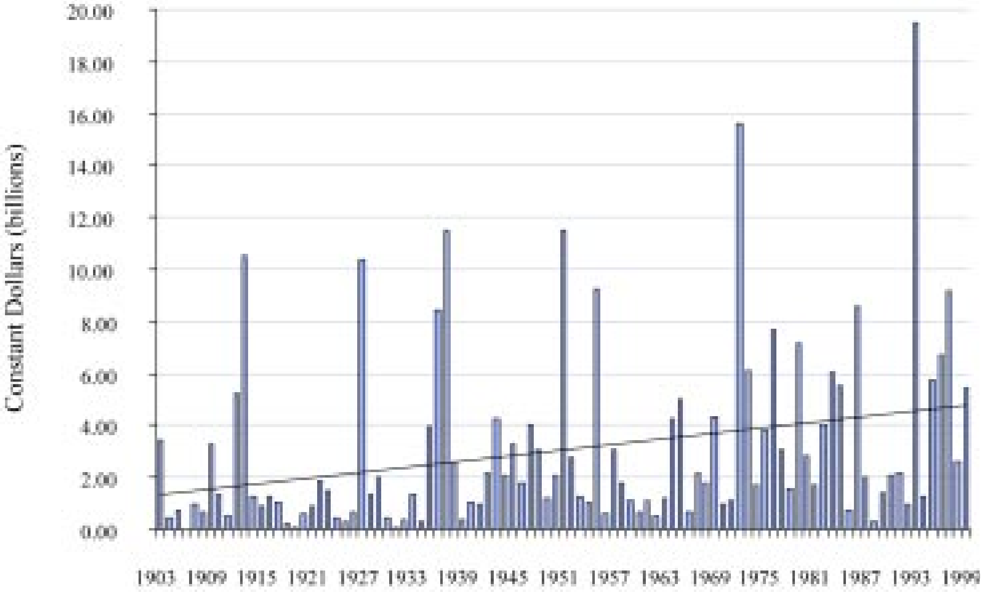
Despite these expenditures, flooding remains the nation's most costly and destructive natural disaster and the cause, at least in part, of most federally declared disaster declarations. A change in flood risks is therefore one of the potential effects of climate change with the greatest implications for human well-being. Few studies have looked explicitly at the implications of climate change for flood frequency, in large part because of

Figure 33:
Flood-Related Deaths in the United States, 1903 to Present



Source: http://www.nws.noaa.gov/oh/hic/flood_stats/recent_individ

Figure 34:
Flood-Related Damages in the United States (Constant 1997 Dollars)



Source: http://www.nws.noaa.gov/oh/hic/flood_stats/Flood_loss_ti the difficulty of getting detailed regional precipitation information from climate models and because of the substantial influence of both human settlement patterns and water-management choices on overall flood risk.

Floods already cause extensive loss of life and damage to property, particularly hurricane-induced flooding. Flood damages, which vary widely from year to year, averaged $4 billion and caused more than 100 deaths annually over the past 50 years (National Weather Service 1999, http://www.nws.noaa.gov/om/reachout/floods.htm). Dollar damages have increased about one percent per year and flood-related deaths rose one and one-half percent per year on average since 1945 (National Weather Service 1999, http://www.nws.noaa.gov/oh/hic/flood_stats/index.html). Figures 33 and 34 show estimated flood deaths and damages in the United States since the early 1900s. These estimates include only directly reported deaths and economic costs such as repairs to buildings, roads, and bridges attributable to flooding from rainfall and snowmelt. Excluded are damages attributable to wind such as hurricane storm surges and indirect damages such as lost wages due to business closures or the social costs of temporarily evacuating homes for higher ground.

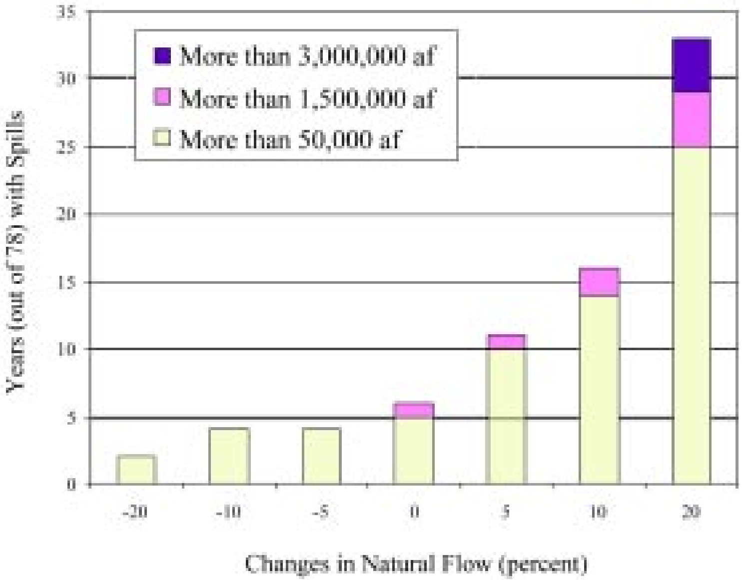
In a particularly dramatic example of the costs of flooding, the 1993 floods in the upper Mississippi and Missouri rivers resulted in economic damages estimated at between $12 billion and $16 billion. The Interagency Floodplain Management Review Committee (1994) established to determine the major causes and consequences of the flood concluded: "The flood of 1993 in the Midwest was a hydrometeorological event without precedent in modern times. In terms of precipitation amounts, record river levels, flood duration, area of flooding, and economic losses, it surpassed all previous floods in the United States." The U.S. Army Corps of Engineers, responsible for flood protection in the region, estimated that the damages would have been $19 billion higher without the dams, reservoirs, and levees available to control flood waters (Interagency Floodplain Management Review Committee 1994). These facilities also contributed indirectly to some of the damages that did occur by encouraging settlement and development in the floodplain. Floodplain development places more people and property at risk and it reduces a basin's capacity to naturally absorb flood flows.

Future flood damages will depend on many factors. Among the most important are the rate and style of development in the floodplains, the level and type of flood protection, and the nature of climate-induced changes in hydrological conditions, sea levels, and storm surges. As noted earlier, regional and local changes in hydrological conditions attributable to a greenhouse warming are uncertain but research to date suggests that there is a risk of increased flooding in parts of the United States that experience large increases in precipitation. The authors of the second IPCC impacts report (IPCC 1996b) concluded that: "the flood-related consequences of climate change may be as serious and widely distributed as the adverse impacts of droughts" and "there is more evidence now that flooding is likely to become a larger problem in many temperate regions, requiring adaptations not only to droughts and chronic water shortages, but also to floods and associated damages, raising concerns about dam and levee failure."

A study was done on the Colorado River Basin looking explicitly at flood risks and probabilities under conditions of climate change (Nash and Gleick 1991, 1993). This study looked at a series of climate change scenarios (including hypothetical scenarios and GCM equilibrium and transient scenarios). Using a basin-scale hydrologic model to evaluate changes in flow due to changes in climate, they evaluated the implications of the changes in flow for flood risk, assuming that the system of reservoirs would be operated using existing rule curves and water rights. They noted that even modest long-term changes in runoff overwhelm the existing reservoir system unless operating rules were changed. Within a few years of reduced flows under existing operations, the large reservoirs went dry trying to meet contracted water deliveries. Conversely, when average runoff increased, significant and non-linear flood risks rose in terms of the numbers of years when floods would be expected and the size of those floods (see Figure 35). This assessment showed that managers should not assume that existing reservoir systems, even when they are large and sophisticated, would automatically be able to deal with plausible climate change. The report also concluded that operators must begin evaluating whether or not changes in operations rules can help with climate change, a conclusion later adopted by the American Water Works Association in recommendations to water managers (AWWA 1997).

If future runoff were best characterized by the results based on the Hadley climate model (see Table 6), more frequent and extreme flooding would result. Events such as the 1993 Midwest flood that are now viewed as rare could become more common. Under such a scenario, future flood damages likely would rise significantly, even with advances in the ability to anticipate flood flows and remove people and property from the flood path. In addition, the combination of higher sea levels and the possibility of increased storm surges would threaten property and lives in coastal areas. If future runoff was best characterized by the results of the Canadian model, which is drier than the Hadley model (see Table 6), flood risks could decrease. In both cases, impacts on flooding depend not only on average precipitation but on the timing and intensity of precipitation – two characteristics not well modeled at present.

Figure 35:
Frequency and Volume of Uncontrolled Spills in the Upper Colorado River Basin Under Climate Change



Source: Nash and Gleick (1993).

Sidebar 3:
Ensemble Streamflow Predictions and Reservoir Management

Streamflow forecasting is critical for reservoir management. Reliable forecasts could help operators balance energy generation, mitigate severe droughts, and provide reliable flood protection. However, forecast benefits depend on the skill of the forecasting models, the way in which forecast information is presented, and whether the forecasts can be (and are) used by water managers. An ensemble streamflow prediction (ESP) consists of equally likely traces of future streamflows. The methodology is based on the premise that precipitation and temperature forcing of historical years are likely to occur in the future (Carpenter and Georgakakos 2000). ESP is most suitable for catchments with (a) strong seasonal cycles of atmospheric forcing and (b) significant persistence in soil moisture. Using this approach, a hydrologic watershed model is forced with observed precipitation and temperature up to the forecast preparation time to estimate the soil-moisture conditions at the spatial scale of the model. The model is then integrated forward in time using these soil-moisture estimates as initial conditions and the precipitation and temperature record of each historical year as input. The integration begins from the month and day corresponding to the forecast preparation time and extends out to the maximum forecast period. The result is an ensemble of equally likely streamflow traces pertaining to the forecast horizon. The ESP traces reflect the uncertainty of the atmospheric inputs but do not reflect the uncertainty of the model parameters. To incorporate this second uncertainty source, the ESP process should be repeated with different model parameters consistent with the respective parameter distributions, and the streamflow forecast ensemble should be expanded to include all generated streamflow traces.

The ESP approach has the potential to fully characterize the uncertainty of future streamflows. However, this information may or may not be utilized, depending on the nature of the management system. If, for example, reservoir operating policies are derived by deterministic management models (as are most current reservoir operating rules relating water level to release), the streamflow ensemble is usually reduced to a single time sequence such as the median or average trace, and the uncertainty implied by the ensemble is ignored. To fully utilize the streamflow forecast ensemble, the management model should be explicitly stochastic. It has been shown that ignoring forecast uncertainty in the management process can result in significant flood damage, less energy generation, and higher drought risk (Yao and Georgakakos 2000).

Source: Carpenter and Georgakakos (2000), and Yao and Georgakakos (2000).

In Lettenmaier et al. (1999), flood risks increased for many of the climate change scenarios, at all of the sites except for the Columbia River basin. For the Savannah River and the Tacoma system, flood risks rose substantially. Carpenter and Georgakakos (2000) and Yao and Georgakakos (2000) investigated the response of Lake Folsom on the American River in central California to potential climate and management scenarios. Folsom's main water uses are flood control, energy generation, water supply, and maintenance of low flows for environmental quality. The modeling approach used a decision-support system that included forecast uncertainty characterization, downscaling of GCM information, ensemble hydrologic forecasting, and dynamic reservoir management in the presence of uncertainty. The assessment was based on two climate scenarios. In the first scenario, CO_2 was assumed constant, equal to its present atmospheric concentration level. In the second scenario, based on the Canadian climate model, CO_2 was assumed to increase by one percent per year.

The Canadian GCM suggests that central California will experience wetter and more variable climate under a CO_2 increase. These climate changes cause Folsom's annual energy generation and revenues (based on present energy prices) to increase by around \$15 million (an increase of 24%), spillage (defined as water released above turbine capacity) to increase by 80%, and potential flood damage to increase by \$219 million (using present damage cost curves). Furthermore, the study clearly demonstrates that characterizing forecast uncertainty and using it to develop adaptive management policies can drastically improve system response from disastrous to desirable. Sidebar 3 describes the approach of using ensemble streamflow projections for reservoir management. For Lake Folsom, using a median deterministic forecast sequence (rather than the full forecast ensemble) under the Canadian one percent CO_2 increase scenario would cause flood damage on the order of \$4.3 billion, 20 times higher than that of the full forecast ensemble (\$219 million). By contrast, an improved forecast ensemble would reduce flood damage to \$26 million, a 10-fold decrease. Energy generation is not adversely affected by the added flood protection, but it actually increases, as indicated by the results of Table 14. To establish an upper performance bound, a run was also conducted with "perfect" streamflow forecasts. In this case, flood damages can be completely eliminated, energy generation attains a maximum value, and spillage is minimized. These findings show that climate change impacts could be mitigated by changes in the way systems are modeled, managed, and operated. Under a changing climate, traditional operating rules become ineffective, while adaptive forecast-control management schemes can provide reliable coping strategies. This assessment also clearly corroborates the value of improved short term and seasonal projections.

Droughts

Water managers must also be concerned about the risks of droughts. Drought in the 19th century and again in the 1930s led to large-scale migrations and much social hardship, and extended droughts can still result in substantial adverse economic and social impacts. Droughts vary in their spatial and temporal dimensions and are highly dependent on local management conditions and the perceptions of local water users. No single definition of drought applies in all circumstances; thus, determining changes in drought frequency or intensity that might be expected to result from climate changes is complicated. Most past studies have focused on evaluating changes in low-flow conditions and probabilities.

Several studies have shown that changes in low-flow measures tend to be proportionally greater than changes in annual, seasonal, or monthly flows (Dvorak et al. 1997, Arnell 1999).

Quantifying the socioeconomic impacts of a drought is difficult, and comprehensive damage estimates are rarely available. Agriculture, the economic sector most susceptible to water shortages, is likely to suffer reduced crop production, soil losses due to dust storms, and higher water costs during a drought. But non-climate factors can play an important role in limiting, or worsening, the impacts of climate. Agricultural losses during California's six-year drought from 1987-1992 were reduced by temporarily fallowing some land, pumping more groundwater, concentrating water supplies on the most productive soils and higher value crops, and purchasing water in spot markets to prevent the loss of tree crops. Direct economic losses to California's irrigated agriculture in 1991 were estimated at only $250 million, less than two percent of the state's total agricultural revenues (Nash 1993, U.S. Army Corps of Engineers 1994).

A prolonged drought affects virtually all sectors of the economy. Between 1987 and 1991, urban users in California paid more for water and were subject to both voluntary and mandatory conservation programs. Landscaping and gardening investments and jobs were lost. Electricity costs, as described above, rose more than $3 billion because of reduced hydropower power production. Recreation was adversely impacted. Visits to California state parks declined by 20%, and water-based activities such as skiing and reservoir fishing declined (Gleick and Nash 1991).

These kinds of impacts can be evaluated, and explicit costs can sometimes be assigned to them. However, not all of the impacts of drought are so readily quantified. During the 1987-1992 California drought, the state's environmental resources may have suffered the most severe impacts. Most major fisheries suffered sharp declines and many trees were weakened or killed by the lack of precipitation, increasing the subsequent risk of forest fires (Nash 1993, Brumbaugh et al. 1994). These kinds of ecosystem impacts are rarely monetized or quantified.

Table 14:
Assessment of Lake Folsom Response Using an Integrated Forecast-Management System and the Canadian Climate Scenario

Cases	Energy (GWH)	Energy Value (M$)	Spillage (bcf)	Max. Damage ($)	Inflows (bcf)	Max. Daily Flow(cfs)
Baseline (Present)	678.878	61.595	10.368	0	116.4	81700
CO2 Increase (Future)	839.477	76.077	18.064	219,895,000	150.3	149736
CO2 Increase; IFE	843.841	76.417	16.807	26,040,400	150.3	149736
CO2 Increase; Perfect	868.915	78.766	15.091	0	150.3	149736

IFE: Improved Forecast Ensemble; bcf. Billion cubic feet; cfs. Cubic feet per second. All changes are annual averages unless otherwise labeled.
Sources: Yao and Georgakakos (2000), Carpenter and Georgakakos (2000).

The net national economic costs of a drought are likely to be less than the costs suffered within the drought-affected area because some groups benefit from the hardships of others. For example, drought-induced agricultural losses increase the prices farmers unaffected by the drought receive for their crops and a decline in hydropower production increases the demand and price for alternative sources of energy. Including income transfers reduces the costs of drought as the scale of the impact assessment increases. Thus, drought events that are costly at the local level may be lessened at the regional level and negligible at the national levels. For example, analysis of the agricultural impacts of California's drought concluded that in 1991 the national economic costs were less than 30% of the state impacts (U.S. Army Corps of Engineers 1991, 1995, Brumbaugh et al. 1994, Frederick and Gleick 1999).

Socioeconomic Costs and Benefits of Changes in Water Supply and Demand

All of the physical and ecological impacts of climate change will entail social and economic costs and benefits. On top of the uncertainties described above in evaluating both climate changes and potential impacts, evaluating the economic implications of the diverse impacts is fraught with difficulties, and few efforts to quantify them have been made. Ultimately, however, comprehensive efforts to evaluate costs will be necessary in order to help policymakers and the public understand the implications of both taking and not taking actions to either reduce the impacts of climate change or adapt to the changes that are unavoidable.

Several steps are needed to evaluate socioeconomic effects of climate change. First, estimates of the nature and magnitude of the impacts of climate change are necessary. Second, these impacts need to be put into common units, typically monetary, with a comprehensive discussion of the limitations of doing so. Among these limitations is the fact that many impacts may never be quantifiable in economic terms. Third, the costs of taking various actions must be evaluated, together with the effects of options to reduce expected impacts.

The socioeconomic impacts of a greenhouse warming look very different depending on which projections are used and on the methods and assumptions adopted by the researchers. The results published to date are a valuable guide for future assessments but policymakers should have low confidence in specific quantitative estimates. Some researchers have argued that the effects of climate change on municipal and industrial water use will generally be small compared with the expected rates of growth of water use, but in the United States new research is beginning to suggest the opposite may be true – that the impacts of climate change could exceed, sometimes significantly, impacts due to population growth and economic changes in some sectors and for some kinds of impacts (see, for example, Frederick and Schwarz 1999). While climate impacts on water use could be large in some areas, research to date indicates that climate-induced changes in demands would mostly be modest compared to changes in water supplies. Some water-scarce regions could benefit from increased precipitation and runoff while others are forced to adjust to less water. Water abundant areas might suffer from further increases in runoff but benefit from reductions.

The costs of water supply and protection from floods and droughts have been rising for much of this century and they are likely to continue rising even in the absence of climate change. Future water costs will depend on the costs of developing new supplies, implementing conservation options, foregoing desired water uses, meeting water quality standards, and protecting natural aquatic ecosystems. Additional factors likely to contribute to higher future costs of water are the threats to existing supplies posed by contamination and groundwater depletion. Although billions of dollars have been spent in recent decades to improve water quality, 36% of the nation's surveyed rivers and streams and 39% of the surveyed lakes, reservoirs, and ponds are still impaired for one or more of their designated uses (USEPA 1996, see also http://www.epa.gov/iwi/national/index.html). Non-point source pollutants, such as agricultural chemicals applied to farmland and runoff from urban areas, are now the principal sources of surface water contamination, and effective means of curbing these pollutants have yet to be developed. Threats to water quality are also continuing to come from underground tanks containing hazardous substances, old mines, landfills, abandoned waste sites, and oil and gas brine pits.

Few studies have attempted to evaluate the economic consequences of the impacts of climate change on U.S. water resources. Most of these studies are "back of the envelope" computations that make relatively simple assumptions about both climate change and consequences for overall water systems. As a result, policymakers should have little confidence in specific results, some of which are described here. Cline (1992) assumed that climate change would cause a 10% decrease in water availability across the country. Assuming average values for water in different sectors, he estimated that this simple impact would cause economic damages of approximately $7 billion annually, ignoring ecological impacts, effects on water quality, flood risks, and many other factors. Titus (1992) estimated changes in water supply and demand for each state under simple climate change scenarios and concluded that annual damages to water resources in the nation would be between $21 and $60 billion, with the majority of costs resulting from increased costs of controlling water pollution. Neither of these studies included economic models that integrate water supply and demand functions, producer or consumer surplus, or constraints on water systems.

Hurd et al. (1998) integrated climate scenarios, simple hydrologic models, and an economic model that allocates water to different activities to maximize economic welfare, one relatively narrow measure of overall well-being. While actual water-supply systems rarely attempt to maximize economic welfare, this approach offers a more detailed insight into possible economic impacts than earlier general assessments. The study assessed possible economic costs and benefits from climate change for four major water regions and for the nation as a whole, focusing on five aspects of water: water quality, lost hydropower, flooding, navigation, and water supply. The results varied depending on region and the nature of the climate change. For the Colorado River basin, welfare declines by $102 million annually for the "central case" of a 2.5^o C warming and a seven percent drop in precipitation; for the Missouri basin, welfare declines by $519 million; for the Delaware basin, welfare falls by only $22 million; and for the Apalachicola, Flint, Chattahoochee (AFC) basin total damages for the central case are $15 million. For the national analysis, welfare losses associated with the central case are estimated to be $9.4 billion annually. Of this amount, over $5 billion are associated with water-quality damages and $2.8 billion with hydroelectric losses (Hurd et al. 1998). If average temperatures rise 5^o C with no change in average precipitation, national welfare losses are projected to rise to $43 billion annually. Most of the economic losses are imposed on nonconsumptive water users such as hydropower rather than consumptive water users such as irrigators. Furthermore, most of the impacts will be in the western part of the United States. The authors note the uncertainties and assumptions in their analysis and call for further improvements and efforts in this area. In particular, the methods of putting dollar values on flood damages, ecological damages, and all of the "costs" of water scarcity are poorly developed.

Another study recently found the potential for much more severe economic costs for the United States. Frederick and Schwarz (1999) evaluated the impacts of the Canadian and Hadley climate models, described earlier, on water scarcity in the nation's water resource regions. Unlike previous studies, they also attempted to evaluate how population and economic changes would affect U.S. water resources in the absence of climate change.

They also evaluated the socioeconomic impacts of the changes in water scarcity under alternative water-management scenarios, where “scarcity” was defined as the adequacy of water supplies to meet consumptive use plus “desired” or “critical” instream uses on a sustainable basis. Desired instream use is defined as the flow required to maintain fish and wildlife populations estimated for the Second National Water Assessment (USWRC 1978). Critical instream use is defined as 50% of desired flow.

Water-scarcity indices were developed for the 1995 historical baseline and for the year 2030 both with and without climate change. Under current conditions, average annual renewable water supplies already fail to meet estimated desired use (the sum of consumptive use and desired instream flow) in the Rio Grande, Lower Colorado, and Great Basin regions. Mean renewable supplies in the Lower Colorado do not even meet the much lower flows needed to provide critical instream use. Dry condition renewable supplies (flows exceeded 80% of the time) fall short of critical needs in these three basins and in the Texas-Gulf region.

The 2030 scenario without climate change assumes renewable supplies and desired instream use are unchanged from the 1995 baseline. Consumptive use is projected to increase about eight percent by 2030 based on projections by Brown (1999). This increase in consumptive use, which is substantially smaller than the projected increases in population and economic growth, anticipates improvements in water-use efficiency as well as a shift in irrigation from the western to eastern United States. These assumptions lead to a modest increase in water scarcity in the absence of climate change. Frederick and Schwarz (1999) estimate the annual costs of the changes in water use between 1995 and 2030 without climate change to be just under $14 billion. This figure is based on the costs of the changes in water withdrawals, development of new supplies, conservation, reductions in irrigation, and instream flows implied in Brown’s (1999) projections of water use. The costs are based on estimates of the current costs of developing supplies for offstream use and conservation opportunities, with allowance for future technological and managerial advances and changes in energy prices.

The economic impacts of different scenarios of climate-induced changes in water supplies are calculated as the changes in the annual costs of maintaining the projected no-climate change, non-irrigation offstream water uses with the climate-altered supplies. Scenarios were developed using both the Hadley and Canadian climate models, and the authors note that different climate models would lead to different results. The options for maintaining offstream water uses include (a) removing land from irrigation, (b) investing in water conservation, (c) developing new supplies, and (d) changing instream flows. The benefits and costs of the climate-induced changes in water supplies are estimated under three alternative management scenarios that differ in the level of protection provided for instream flows and irrigation.

The increased annual costs for the conterminous United States attributable to the sharp decline in water supplies implied by the drier Canadian climate model range from $105 billion under the “efficient” management scenario to $251 billion under the scenario that provides the greatest protection for instream flows. “Efficient” management permits streamflows to fall to critical levels for ecosystems. Most of the damages occur in the South Atlantic-Gulf, Lower Mississippi, and Texas-Gulf regions. In contrast to the cost increases estimated with the Canadian climate scenarios, the increases in water supplies under the wetter Hadley climate scenarios reduce annual water costs by nearly $5 billion relative to the no-climate-change case. The benefits are attributed to the projected increase in instream flows (Frederick and Schwarz 1999). The analysis does not consider flooding costs or the benefits of reduced flooding. In the case of the Hadley scenario, increases in water supplies could be accompanied by increases in damaging floods; for the Canadian scenarios, flood risks could drop. Nijssen et al. (2000) note that the Frederick and Schwartz damages, which used annual runoff changes, could be underestimated in regions where seasonal changes in runoff are important, such as the Pacific Northwest.

The results of the Frederick and Schwarz analysis support several general conclusions. First, given the uncertainties in future climate projections, the range of plausible outcomes is very wide, but a greenhouse warming could have major impacts on the costs of balancing future water supplies and demands. Under some scenarios, the additional costs imposed by climate change are extremely large: ten to twenty times larger than the additional costs imposed by future population growth, industrial changes, and changing agricultural water demands. Indeed, the upper end of the changes described above is on the order of 0.5 percent of the nation's total gross domestic product. Second, the contrasting hydrologic implications of the two climate models used indicate the magnitudes as well as the direction of these impacts are uncertain and likely to vary among water resources regions. Third, there are many opportunities to adapt to changing hydrologic conditions, and the net costs are particularly sensitive to the institutions that determine how the resource is managed and allocated among users. Far more effort is required to expand upon this kind of analysis, to reduce uncertainties, and to incorporate the kinds of economic costs and benefits these studies were not able to include.

Coping and Adaptation

Climate change is just one of a number of factors putting pressure on the hydrological system and water resources of the United States. Population growth, changes in land use, restructuring of the industrial sector, and demands for ecosystem protection and restoration are all occurring simultaneously. Current laws and policies affecting water use, management, and development are often contradictory, inefficient, or unresponsive to changing conditions. In the absence of explicit efforts to address these issues, the societal costs of water problems are likely to rise as competition for water grows and supply and demand conditions change.

There are many opportunities for reducing the risks of climate variability and change for U.S. water resources. We note the applicability here of the precautionary approach taken in many international agreements, including the United Nations Framework Convention on Climate Change:

> "Parties should take precautionary measures to anticipate, prevent or minimize the causes of climate change and mitigate its adverse effects. Where there are threats of serious or irreversible damage, lack of full scientific certainty should not be used as a reason for postponing such measures, taking into account that policies and measures … should be cost-effective so as to ensure global benefits at the lowest possible cost" (UNFCCC 1992).

The nation's water systems are highly developed and water managers have a long history of adapting to changes in supply and demand. Their efforts have largely focused on minimizing the risks of natural variability and maximizing system reliability. Many of the approaches for effectively dealing with climate change are little different than the approaches already available to manage risks associated with existing variability. Tools for reducing these risks have traditionally included supply-side options such as new dams, reservoirs, and pipelines, and more recently, demand-management options, such as improving efficiency, modifying demand, altering water-use processes, and changing land-use patterns in floodplains. This work is going on largely independently of the issue of climate change, but it will have important implications for the ultimate severity of climate impacts. Among the new tools water agencies and managers are exploring are (1) incentives for conserving and protecting supplies, (2) opportunities for transferring water among competing uses in response to changing supply and demand conditions, (3) economic changes in how water is managed within and among basins, (4) evaluating how "re-operating" existing infrastructure can help address possible changes, and (5) new technology to reduce the intensity of water use to meet specific goals.

The lessons from existing efforts need to be evaluated in order to understand how they might mitigate (or worsen) the impacts of climate change. During the 20th century dams, reservoirs, and other water infrastructure were designed with a focus on extreme events such as the critical drought periods or the probable maximum flood. This approach provided a cushion to deal with uncertainties such as climate change (Matalas and Fiering 1977). In recent years, however, the high costs and environmental concerns that now make it difficult to get a new project approved also make it possible that the projects that are undertaken will have less redundancy built into their water supply and control facilities than the projects built earlier (Frederick 1991).

Few studies have evaluated how to integrate climate change into regional or local planning, how water-system managers view climate change, or how to best bring water planners, designers, and system managers into the discussion about future climate change (see, for example, Waggoner 1990, AWWA 1997, O'Conner et al. 1999). Even fewer efforts to take pro-active measures have been initiated. In part this reflects a split in opinion among water analysts and policymakers. Some believe that water managers already have the tools necessary to deal with plausible climate change. Schilling and Stakhiv (1998), for example, comment on the apparent lack of concern or awareness of the issue of climate change among water managers and operators and argue that the key response of water managers to climate change should be virtually the same as that to existing climate variability: to upgrade and intensify introduction of innovative and cost effective supply-side and demand-side management measures and to create institutions that are flexible in adapting to both social and environmental changes (see also Stakhiv and Schilling 1998). They note that the apparent indifference of water professionals should not be interpreted to mean that they are oblivious to the potentially serious consequences of climate change. Rather it may stem from their belief that the approaches for effectively dealing with climate change are little different than the approaches already available to manage existing variability.

Others believe that this approach ignores some critical concerns: first, climate change could produce hydrologic conditions and extremes of a *different nature* than current systems were designed to manage; second, it may produce similar kinds of variability but *outside of the range* for which current infrastructure was designed; third, it assumes that sufficient time and information will be available before the onset of large or irreversible climate impacts to permit managers to respond appropriately; fourth, it assumes that no special efforts or plans are required to protect against surprises or uncertainties. The first situation could require that completely new approaches or technologies be developed. The second could require that efforts above and beyond those currently planned or anticipated be taken early. Moreover, complacency on the part of water managers may lead to the failure to anticipate impacts that could be mitigated or prevented by actions taken now. Schilling and Stakhiv (1998) and Stakhiv and Schilling (1998) urge the active solicitation of the views of the water-management community and point to examples where water agencies, river commissions, or utilities have begun to act on the kinds of recommendations noted above.

Another major complication exists: some major river basins in the United States are so heavily developed, with such complicated overlapping management layers, that their ability to adapt to changes in climate may be compromised. In a detailed analysis of the Columbia River Basin, for example, Miles et al. (2000) concluded that it is already impossible to meet all current water-resources objectives and that current institutional arrangements in the Basin preclude an organized and comprehensive management response. When they imposed climate change on the Basin, decreased spring and summer streamflows led to rapid decreases in the reliability of meeting some system objectives, including irrigation water supply and fishery protection target flows. Coupled with inefficient allocations resulting from western water law, the authors concluded that recreation, instream flow targets, agricultural diversions in the middle Snake River, and non-firm energy targets are all vulnerable to climate variability because of the lack of adaptability to low flows in the system.

Some options for coping or adapting to climate change impacts on U.S. water resources are described below. This section should be regularly revisited and expanded in later assessments.

Water Planning and Management

Decisions about long-term water planning, the design and construction of new water-supply infrastructure, the type and acreage of crops to be grown, urban water allocations and rate structures, reservoir operation, and water-supply management all depend on climate conditions and what humans do to respond and adapt to those conditions. In the past, these decisions relied on the assumption that future climate conditions would have the same characteristics and variability as past conditions, and U.S. water-supply systems were designed with this assumption in mind. Dams are sized and built using available information on existing flows in rivers and the size and frequency of expected floods and droughts. Reservoirs are operated for multiple purposes using the past hydrologic record to guide decisions. Irrigation systems are designed using historical information on temperature, water availability, and soil water requirements.

This reliance on the past record now may lead us to make incorrect – and potentially dangerous or expensive – decisions. Given that risk, one of the most important coping strategies must be to try to understand what the consequences of climate change will be for water resources and to begin planning for those changes. The academic community has advocated this position for a decade. An earlier two-year study by the Climate and Water Panel of the American Association for the Advancement of Science on the implications of global climate change for the water resources of the United States (Waggoner 1990) concluded:

> "Among the climatic changes that governments and other public bodies are likely to encounter are rising temperatures, increasing evapotranspiration, earlier melting of snowpacks, new seasonal cycles of runoff, altered frequency of extreme events, and rising sea level...*Governments at all levels should reevaluate legal, technical, and economic procedures for managing water resources in the light of climate changes that are highly likely.*" [Italics in original.]

The Second World Climate Conference concluded in 1991 that:

> "The design of many costly structures to store and convey water, from large dams to small drainage facilities, is based on analyses of past records of climatic and hydrologic parameters. Some of these structures are designed to last 50 to 100 years or even longer. *Records of past climate and hydrological conditions may no longer be a reliable guide to the future. The*

> *design and management of both structural and non-structural water resource systems should allow for the possible effects of climate change.*" (Italics added) (Jager and Ferguson 1991.)

Similarly, the IPCC (1996c) urged water managers to begin "a systematic reexamination of engineering design criteria, operating rules, contingency plans, and water allocation policies" and states with "high confidence" that "water demand management and institutional adaptation are the primary components for increasing system flexibility to meet uncertainties of climate change." This emphasis on planning and demand management rather than construction of new facilities marks a change in traditional water-management approaches, which in the past have relied on the construction of large and expensive infrastructure.

In 1997, the American Water Works Association, the largest professional association of water utilities and providers in the United States, published a set of recommendations from its Public Advisory Forum (AWWA 1997). Among the recommendations to water managers were the following:

- While water management systems are often flexible, adaptation to new hydrologic conditions may come at substantial economic costs. Water agencies should begin now to re-examine engineering design assumptions, operating rules, system optimization, and contingency planning for existing and planned water-management systems under a wider range of climate conditions than traditionally used.

- Water agencies and providers should explore the vulnerability of both structural and non-structural water systems to plausible future climate change, not just past climate variability.

- Governments at all levels should re-evaluate legal, technical, and economic approaches for managing water resources in the light of possible climate change.

- Cooperation of water agencies with the leading scientific organizations can facilitate the exchange of information on the state-of-the-art thinking about climate change and impacts on water resources.

- The timely flow of information from the scientific global change community to the public and the water-management community would be valuable. Such lines of communication need to be developed and expanded.

One of the main implications of climate change for water management is a shift toward improved decision-making under uncertainty and flexible management approaches.

Modifying Operation of Existing Systems

Many portions of the country have extensive and complex water supply and management systems, consisting of an intricate web of imported and local supplies, dams, reservoirs, aqueducts, pipelines, water treatment facilities, wastewater plants, and hydropower stations. Balancing water supply and demand while maintaining ecosystem health, even in the absence of climate change, is a daunting task. These systems must play a leading role in adapting to, and coping with any future climate change just as they now play a leading role in mitigating the impacts of existing climate variability.

There are two critical issues associated with using existing facilities to address future climate change: can they handle the kinds of changes that will occur; and at what economic and ecological cost? There have been few detailed analysis of either of these questions, in part because of the large remaining uncertainties about how the climate may actually change. Another issue that must be addressed is how to involve the public adequately in decisions about water supply and distribution. While the principle of local public participation is often espoused, even at the international water policy level, it is rarely successfully implemented. Without precise information on the characteristics of future climate, the best that water managers can hope to do may be to explore the sensitivity of their system to a wider-range of conditions than currently experienced and to develop methods or technologies that can improve operational water management. This kind of approach was first recommended by the Climate and Water Panel of the American Association for the Advancement of Science in the late 1980s. That panel, chaired by Roger Revelle and Paul Waggoner, recommended:

> During planning, managers should be alert for economical measures to increase flexibility and accommodate climatic variability, sea-level rise, and as we learn more about it, climatic change. They should exploit opportunities to retain or increase flexibility of systems, especially since such measures may be fairly inexpensive if put in an original design (Waggoner 1990, p. 5).

Georgakakos et al. (1998) explored the use of flexible reservoir management strategies to permit managers to reduce the uncertainties associated with climate variability. In a test of this approach, current reservoir practices for the Saylorville Reservoir in the upper Des Moines river basin were shown to be inadequate for accommodating historical variability, while alternative methods mitigated adverse effects of climate variability. This approach is also applicable for changes in conditions caused by the greenhouse effect.

Major (1998) also looked at how water systems might be managed under conditions of climate change. Among the techniques he discusses are how to integrate multiple systems to provide flexibility for changing conditions; the value of reallocating storage under new conditions; and the applicability of non-structural measures such as land-use planning, flood and storm warnings, and water pricing. In a study of how effective current operating rules are for addressing possible climate changes, Hotchkiss et al. (2000) evaluated the operation of six main dams on the Missouri River and concluded that if basin precipitation were to increase only 10%, the operating rules for the reservoirs will require modification to increase release rates. Miles et al. (2000) did an comprehensive assessment of the impacts of climate variability and change for the Columbia River Basin and concluded that the adaptability of the basin to the threat of floods is high, but that there is also high vulnerability to likely changes in seasonality of streamflow and reductions in spring and summer flows.

The work of Lettenmaier et al. (1999) and Georgakakos and Yao (2000a,b) reinforce the conclusion that effective operation of complex systems can reduce impacts of climate change, but only if implemented in a timely and dynamic manner. Lettenmaier et al. (1999) addressed this question of response to climate change for a series of water systems around the United States. They noted that reservoir systems buffer modest hydrologic changes through operational adaptations. As a result, the effects of climate change on the systems they studied tend to be smaller than the underlying changes in hydrologic variables. They concluded that significant changes in design or scale of water management systems might not be warranted to accommodate climate change alone, although this obviously depends on the ultimate size of the changes. They urged a concerted effort to adjust current operating rules or demand patterns to better balance the existing allocated purposes of reservoirs, which requires planning and participation by water managers.

O'Conner et al. (1999) examined the sensitivity and vulnerability of community water systems to climate change by surveying 506 managers. Water-system managers do not dismiss the issue of climate change, but they have been reluctant to consider it in their planning horizons until they perceive a greater degree of scientific certainty about regional impacts. Interestingly, most managers admit that they expect disruptions in daily operations caused by changes in climate variability. Experienced and full-time water managers were more likely to consider future climate scenarios in planning than inexperienced or part-time managers. O'Conner et al (1999) offered some conclusions and discussion of policy implications of their survey:

- Moving away from exclusive reliance on surface water by integrating surface and groundwater management reduced vulnerability to climate fluctuations;

- Continued efforts to improve research and to communicate the risk of climate change to water managers, especially at the local level, will be useful; and

- Local governments should consider creating more full-time water manager positions to attract top professionals capable of considering long-term issues and concerns in planning.

Chao et al. (1999) explored ways of managing the water level of Lake Erie under conditions of climate uncertainty in two workshops with managers, scientists, and water planners. Four different methods of including the issue of climate were explored and the authors concluded that large-scale modeling could help managers improve their understanding of how any particular system might be affected in the future and what management options might be appropriate to evaluate or consider. They also found that scenario analysis was useful for addressing climate change by permitting managers to explore unanticipated outcomes. Public planning sessions were found to be useful for eliciting ideas and opinions. They also recommended that more work be conducted to improve GCMs, to evaluate overall impacts, and to identify the most susceptible economic sectors.

New Supply Options

Traditional water-supply options, such as dams, reservoirs, and aqueducts may still have an important role to play in meeting water needs in parts of the United States. We note, however, the existing financial, environmental, and social difficulties now associated with such options. Because new infrastructure often has a long lifetime, it is vital that the issue of climate change be factored into decisions about design and operation.

While new supply options can be expensive and controversial, traditional and alternative forms of new supply will play a role in addressing changes in demands and supplies caused by climate change and variability. Options to be considered include wastewater reclamation and reuse, water marketing and transfers, and even limited desalination where less costly alternatives are not available and where water prices are high. None of these alternatives, however, are likely to alter the trend toward higher water costs. They are either expensive relative to traditional water costs or their potential contributions to supplies are too limited to make a significant impact on long-term supplies (Frederick 1993). Ultimately, the relative costs, environmental impacts, and social and institutional factors will determine the appropriate response to greenhouse-gas induced climate change.

Major (1998) notes that incremental construction can allow for adaptation but adds that planners must choose robust designs to permit satisfactory operation under a wider range of conditions than traditionally considered. Designing for extreme conditions, rather than simply maximizing the expected value of net benefits, should be considered. He also suggests postponement of irreversible or costly decisions.

Demand Management, Conservation, and Efficiency

As the economic and environmental costs of new water-supply options have risen, so has interest in exploring ways of improving the efficiency of both allocation and use of water resources. Improvements in the efficiency of end uses and sophisticated management of water demands are increasingly being considered as major tools for meeting future water needs, particularly in water-scarce regions where extensive infrastructure already exists (Vickers 1991, Postel 1997, Gleick 1998a, Dziegielewski 1999, Vickers 1999). Evidence is accumulating that such improvements can be made more quickly and more economically, with fewer environmental and ecological impacts, than further investments in new supplies (Gleick et al. 1995, Owens-Viani et al. 1999).

Industrial water withdrawals in the United States have declined significantly over the past twenty years because of the changing mix of the economy and improvements in the efficiency of water use. Making a ton of steel in the 1930s consumed 60 to 100 tons of water. Today that same steel can be produced with less than six tons of water. Yet producing a ton of aluminum today only requires one and a half tons of water (Gleick 1998a). Replacing old steel-making technology with new can thus reduce water needs. Replacing steel with aluminum, as has been happening for many years in the automobile industry for other reasons, also reduces water needs. Total industrial water use in California decreased 30% between 1980 and 1990 because of natural economic and technological changes. Over the same period, total gross industrial production rose 30% in real terms (CDOF 1994). In 1979, on an industry-wide level, it took an average of 13,500 cubic meters of water to produce a million dollars of industrial output. By 1990, this figure had dropped to under 7,400 cubic meters.

Water productivity can also be improved in outdoor gardens, municipal lawns, golf courses, and other urban landscapes. In some parts of the United States as much as half of all residential or institutional water demand goes to landscaping. Improvements in watering efficiency could reduce that demand substantially, as could changes in the composition of these gardens. Innovative garden designs, xeriscaping, the use of sprinkler controllers, moisture sensors, and drip technology can all reduce outdoor water use in homes, often by 25 to 50% or more depending on homeowner's preferences, the price of water, and the cost of alternatives (Gleick et al. 1995). In some regions, outdoor municipal and institutional landscape irrigation is being done with reclaimed water, completely eliminating the use of potable water for this purpose.

The largest single user of water is the agricultural sector and in some places a substantial fraction of this water is lost as it moves through leaky pipes and unlined aqueducts, as it is distributed to farmers, and as it is applied to grow crops. In water-short areas, new techniques and new technologies are already changing the face of irrigation. New sprinkler designs, such as low-energy precision application (LEPA) can increase sprinkler efficiencies from 60 to 70% to as high as 95% (Postel 1997). Drip irrigation has expanded worldwide. In California, more than 400,000 hectares of crops were watered using drip systems in the mid-1990s and more crops are being covered by such methods. Where high-valued crops are grown in relatively permanent settings such as orchards and vineyards, drip irrigation is now the dominant irrigation method. But even for row crops such as strawberries, asparagus, peppers, melons, tomatoes, cotton, and sugar cane, drip systems are becoming more common. Identifying technical and institutional ways of improving the efficiency of these systems in a cost-effective manner will go a long way toward increasing agricultural production without having to develop new supplies of water (Gleick 1998a).

Some studies have recently begun to explore how effective such improvements in water-use efficiency might be for addressing climate-related impacts. In an assessment of urban water use, Boland (1997, 1998) shows that water conservation measures such as education, industrial and commercial reuse, modern plumbing standards, and pricing policies can be extremely effective at mitigating the effects of climate change on regional water supplies. A number of water-system studies have begun to look at the effectiveness of reducing system demands for reducing the overall stresses on water supplies, both with and without climate change. As described earlier, Kirshen and Fennessey (1995) showed that supply deficits in the Boston water system caused by climate change could cost as much as $700 million to make up, but that these costs dropped to under $150 million if demand management options were implemented. Wood et al. (1997) and Lettenmaier et al. (1999) noted that long-term demand growth estimates had a greater impact on system performance than climate change in circumstances when long-term withdrawals are projected to grow substantially. Actions to reduce demands or to moderate the rate of increase in demand growth can therefore play a major role in reducing the impacts of climate change. Far more work is needed to evaluate the relative costs and benefits of demand management and water-use efficiency options in the context of a changing climate.

Economics, Pricing, and Markets

Prices and markets are also increasingly important tools for balancing supply and demand for water and hence for coping with climate-induced changes. Economists and others are beginning to advocate an end to the treatment of water as a free good. This can be accomplished in many different ways. Because new construction and new concrete projects are increasingly expensive, environmentally damaging, and socially controversial, new tools such as the reduction or elimination of subsidies, sophisticated pricing mechanisms, and smart markets provide incentives to use less water, produce more with existing resources, and reallocate water among different users. Water marketing is viewed by many as offering great potential to increase the efficiency of both water use and allocation (NRC 1992, Western Water Policy Review Advisory Commission 1998). As conditions change, markets can help resources move from lower- to higher-value uses.

The characteristics of water resources and the institutions established to control them have inhibited large-scale water marketing to date. Water remains underpriced and market transfers are constrained by institutional and legal issues. Efficient markets require that buyers and sellers bear the full costs and benefits of transfers. However, when water is transferred, third parties are likely to be affected. Where such externalities are ignored, the market transfers not only water, but also other benefits that water provides from a non-consenting third party to the parties to the transfer. A challenge for developing more effective water markets is to develop institutions that can expeditiously and efficiently take third-party impacts into account (Loh and Gomez 1996, Gomez and Steding 1998, Dellapenna 1999). As a result, despite their potential advantages, prices and markets have been slow to develop as tools for adapting to changing supply and demand conditions.

The potential gains are breaking down many of the barriers to transfers in the western United States. Temporary transfers are becoming increasingly common for responding to short-term supply and demand fluctuations. Water banks can provide a clearinghouse to facilitate the pooling of water rights for rental. The temporary nature of such a transfer blunts a principal third-party concern that a transfer will permanently undermine the economic and social viability of the water-exporting area. California's emergency Drought Water Banks in the early 1990s helped mitigate the impacts of a prolonged drought by facilitating water transfers among willing buyers and sellers. Dellapenna (1999) and others have noted, however, that the California Water Bank was not a true market, but rather a state-managed reallocation effort that moved water from small users to large users at a price set by the state, not a functioning market. More recent efforts to develop more functioning markets on a smaller scale have had some success (California Department of Water Resources, http://rubicon.water.ca.gov/b16098/v2txt/ch6e.html). Idaho and Texas have established permanent water banks and other states are considering establishing them as well.

Temporary transfers are particularly useful for adapting to short-term changes such as climate variability. They are less effective in dealing with long-term imbalances that might result from changing demographic and economic factors, social preferences, or climate. At some point, the historical allocation of water becomes sufficiently out of balance to warrant a permanent transfer of water rights. The prospect that neighboring basins and states will be impacted very differently by climate change could increase the potential benefits of interbasin and interstate transfers. Such transfers have occurred, but the process of resolving third-party issues remains slow, costly, and contentious (Gomez and Steding 1998).

While a private-property market system can be a good mechanism for allocated resources, such a system fails when there are significant barriers to the functioning of a market. Actual markets in water have been very rare in practice, and those that have been most successful have generally been for the transfer of small quantities of water, in narrow geographical regions, among similar types of users. Dellapenna (1999) argues that markets intended to bring about major changes in the time, place, or manner of use of water have only functioned through the strong intervention of central state authorities, and that such "markets" are rather most appropriately described as public management. At a broader level, various economic instruments can be useful in managing public property, but resort to these instruments should not obscure the difficulties in setting prices on a public good such as water where prices alone cannot capture the full value of the resource.

A related factor is the implications of climate change for environmental justice and equity. While almost no work has been done in this area, several concerns arise, including the possible impacts of changes in water availability for rate structures and the prices paid by the poor for water, the consequences of inequitable allocations of scarce supplies, and effects on rural water quality from water transfers from agricultural to urban users.

National and State Water Law

Water in its many different forms has been managed in different ways at different times, and in different places around the country, leading to complex and sometimes conflicting water laws. At the federal level, laws such as the Clean Water Act and the Safe Drinking Water Act have played a major role in how water is used, allocated, and treated. Yet these national tools, not to mention the many regional and local laws affecting water, were all designed without considering the possibilities of climate changes. Even without such changes, efforts are needed to update and improve legal tools for managing and allocating water resources. Dellapenna (1999) argues that the current fragmented approach is obsolete and that integrated water management at the basin level is required, both with and without climate changes. He further argues, however, that climate changes are likely to exacerbate the problems that already exist under inefficient management.

Two separate legal issues must be addressed. The first is the role of law in managing water resources within the United States, in different hydrologic conditions and under different management and legal structures of the states, counties, municipalities, irrigation districts, and other complex institutions with roles in water management. The second is the role of law in managing the water resources shared between the United States and its northern and southern neighbors. In this case, international water law plays a critical role (see the following section).

There are currently three major kinds of water rights in the United States: *appropriative rights* – which assigns rights to water on a first-come, first-served basis; *traditional riparian rights* – where water is treated as a common pool resource available to whoever is capable of accessing it; and *regulated riparianism* – which treats water as public property, managed by local or regional governments. Regulated riparian statutes may permit new access after a judicial or public review process.

Dellapenna (1999) argues that the last option, while not perfect, may be the best for managing the nation's water supply in the face of future environmental, economic, and population-driven stresses. The balance between community values and expert judgment can be guided by the principle of "subsidiarity," whereby decisions are to be made at the lowest level possible and higher-level decisions are subsidiary to lower-level ones.

International Water Management: Legal and Institutional Questions Relating to Climate Change and U.S. Border Regions

More than 260 river basins around the world are shared by more than one nation (Wolf et al. 1999). Internationally, this characteristic has led to both water-related conflicts as well as cooperation (Gleick 1998a, 2000). Customary international law has only been marginally effective in dealing with such matters. If conflict is to be avoided, new and effective legal instruments will have to be developed and implemented in many river basins around the world (Dellapenna 1994, 1996, 1997). Differences between surface water and groundwater laws may also be important, but such differences are not well understood.

There is a significant body of international law addressing transboundary water problems, and more addressing climate change-related activities that affect air quality, but very little law addressing climate change-related activities that affect water quality, quantity, or distribution. Ultimately, this will be of importance for the United States at both its northern and southern borders, where shared watersheds lead to local and regional political disputes. The United States has several treaties with its neighbors over water resources, including a major treaty with Mexico signed in 1944 over the Colorado River. International agreements also cover the protection and use of the Great Lakes, shared by the United States and Canada. These agreements include no provisions for explicitly addressing the risks of climate-induced changes in water availability or quality (Gleick 1988, Goldenman 1990).

A sizable body of international customary law regarding freshwater allocation and protection has developed over the last century. This body of law argues that riparian states have a legal right to use surface water, such as a river, absent agreement otherwise. Beyond that, upstream states sometimes argue their right to do what they want to a river that originates in their sovereign territory. In contrast, downstream states argue that upstream states can do nothing to alter historical flows and water quality of the river (Dellapenna 1999). The United Nations completed work in 1997 on a new convention reconciling these discordant claims in two principles now generally recognized and accepted even among states that have not ratified the convention:

- “equitable utilization” - each state is entitled to a fair share of the water, and is subject to an obligation to cooperate in negotiating those shares as well as cooperating to avoid harm to the shares of other states;

- “no harm” rule – states are not to cause substantial injury to the water resources in other states, subject to the need to accommodate the equitable utilization of the shared waters (United Nations 1997, articles 5, 7).

One other issue may cause international tensions in the future – international trade of water. Such trades are already causing tensions between parties in Canada and the United States as a result of tentative proposals to market and move Canadian water. In late 1999, Canada announced its intention to enact a ban on bulk exports of water to other countries. The Canadian proposal has uncertain implications for existing treaty arrangements with the United States, including the North American Free Trade

Agreement (NAFTA). The implications of climate change have not yet been adequately addressed for these issues.

Research Needs

To readers of this report who have come this far, it should be clear that there are important gaps in our understanding of how climate changes will affect the water resources of the United States. This report can only be a first step – regular assessments must be done in order to reduce the risks of making mistakes or missing critical impacts. New research is needed, new data need to be collected and analyzed, and new and existing solutions need to be assessed. Below are several recommendations for filling the gaps in our knowledge. Participation by all sectors of U.S. society is necessary, including hydrologists, civil engineers, public and private organizations, governments at all levels, water planners, and water managers.

- More work is needed to improve the ability of global climate models to provide information on water-resources availability, to evaluate overall hydrologic impacts, and to identify regional impacts.

- Substantial improvements in methods to downscale climate information are needed to improve our understanding of regional and small-scale processes that affect water resources and water systems.

- Information about how storm frequency and intensity has changed and will change is vitally important for determining impacts on water and water systems, yet such information is not reliably available. More research on how the severity of storms and other extreme hydrologic events might change is necessary.

- Increased and widespread hydrologic monitoring systems are needed. The current trend in the reduction of monitoring networks is disturbing (see http://water.usgs.gov/streamgaging).

- There should be a systematic reexamination of engineering design criteria and operating rules of existing dams and reservoirs under conditions of climate change.

- Information on economic sectors most susceptible to climate change is extremely weak, as are tools for assessing the socioeconomic costs of both impacts and responses in the water sector.

- More work is needed to evaluate the relative costs and benefits of non-structural management options, such as demand management and water-use efficiency, or prohibition on new floodplain development, in the context of a changing climate.

- Research is needed on the implications of climate change for international water law, U.S. treaties and agreements with Mexico and Canada, and international trade in water.

- Little information is available on how climate change might affect groundwater aquifers, including quality, recharge rates, and flow dynamics. New studies on these issues are needed.

- The legal allocation of water rights should be reviewed, even in the absence of climate change, to address inequities, environmental justice concerns, and inefficient use of water. The risks of climate change make such a review even more urgent.

Summary

As the new century begins, many challenging factors face the public, water planners and managers, and policymakers. Changes in population, economic conditions, technology, policies, and the relative values of society will be important determinants of future water supply and demand. On top of these complexities, human-induced changes in our basic climate conditions must also be taken into account. More than twenty years of research and more than a thousand peer-reviewed scientific papers have firmly established that a greenhouse warming will alter the supply and demand for water, the quality of water, and the health and functioning of aquatic ecosystems.

As noted throughout this report, the detailed nature of future climate change and its impacts remain uncertain. These uncertainties are obstacles to introducing climate impacts into investment or operational decisions, but they must not be used as an excuse to avoid taking certain actions now. The first line of defense for protecting the nation's water resources must be a strong and consistent research and monitoring program to continue to evaluate climate-related risks. Where climate change is minor or where other factors dominate, the impacts on our water resources may be low. In some regions and for some issues, climate change may even reduce the risks imposed by growing populations, industrialization, and land-use changes.

A growing body of evidence, however, shows that U.S. water resources are sensitive to both climate and to how these complex water systems are managed. In many cases and in many locations, there is compelling scientific evidence that climate change will pose serious challenges to our water systems. Of particular concern are climate changes that cause impacts that are larger than other expected changes, different in nature than expected changes, or imposed on top of existing long-term challenges. In these instances, the marginal economical, ecological, and social costs to society could be substantial. There is also a risk that climate impacts will not be felt equally across social or economic groups in the country.

The United States has invested hundreds of billions of dollars in dams, reservoirs, aqueducts, water treatment facilities, and other concrete structures. These systems were designed and are operated assuming that future climatic and hydrologic conditions will have the same characteristics as past conditions. We now understand that this is no longer a valid assumption. Some managers are beginning to explore how different operating rules and regimes might reduce future climate risks; this kind of evaluation should be encouraged. The relative socioeconomic and environmental impacts of both climate and non-climate impacts on the supply and demand for water will depend in large part on the ability to foresee major changes, to adapt to such changes, to be flexible in the face of probable surprises, and to be innovative in the management and allocation of the nation's water resources. Maintaining options and building in dynamic flexibility are important for designing and operating water systems that will continue to meet our needs in the coming decades.

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