# Water & Global climate change:

## Potential Impacts on U.S. Water Resources

**Prepared for the Pew Center on Global Climate Change**

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## **Foreword** *Eileen Claussen, Executive Director, Pew Center on Global Climate Change*

Availability of an adequate, safe water supply is critical to the health, economy, and environment of any nation and its people. The United States, on average, is well-endowed with water. However, this year's spring floods and summer droughts illlustrate the importance of wide seasonal fluctuations in precipitation. Further, the growing conflicts over environmental and developmental water uses are an indication that water is becoming increasingly scarce.

Current scientific research shows that climate change will have major effects on precipitation, evapotranspiration, and runoff — and ultimately on the nation's water supply. Climate-induced changes in the water cycle likely will affect the magnitude, frequency, and costs of extreme weather events as well as the availability of water to meet growing demand. Recent reports, including the Pew Center report, "The Science of Climate Change," show that climate change is likely to increase the number of days of intense precipitation and the frequency of floods in northern latitudes and snowmelt-driven basins. The frequency and severity of droughts could also increase as a result of a decrease in total rainfall, as well as more frequent dry spells and greater evapotranspiration.

Because of uncertainties about changes in precipitation, many uncertainties exist in predicting specific regional impacts of large-scale changes. Still, some consistent impacts can be identified. In the arid and semiarid western United States, relatively modest changes in precipitation can have proportionally large impacts on water supplies. And in mountainous watersheds, higher temperatures will increase the ratio of rain to snow, accelerate the rate of spring snowmelt, and shorten the overall snowfall season, leading to more rapid, earlier, and greater spring runoff.

"Water and Global Climate Change" is the third in a series examining the potential impacts of climate change on the environment and society. This report identifies impacts not only to the quantity, but also to the quality of the water supply. Changes in stream flows, increased storm surges, and higher water temperatures all could negatively affect the health of the nation's water supply. An increase in the number of days of intense precipitation also could increase the agricultural and urban pollutants washed into streams and lakes. The resulting rise in sea level would contribute to saltwater intrusion into rivers, estuaries, and coastal aquifers.

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## Executive Summary

The availability of freshwater to meet the demands of a growing and increasingly affluent population while sustaining a healthy environment has emerged as one of the nation's primary resource issues. Concerns about water are based in part on uncertainties over the availability of supplies stemming from the vicissitudes of the hydrologic cycle, growing populations, and the prospect that greenhouse gas-induced climate changes will alter the cycle in uncertain ways.

Global climatic changes will have major effects on precipitation, evapotranspiration, and runoff. But estimating the nature, timing, and even the direction of the impacts at the regional and local scales of primary interest to water planners involves many uncertainties. While specific regional impacts will depend on future climate changes as well as uncertain economic, institutional, and structural conditions, some consistent and robust results can be described.

In the relatively arid and semiarid western United States, modest changes in precipitation can have proportionally large impacts on water supplies. In mountainous watersheds, higher temperatures will increase the ratio of rain to snow, accelerate the rate of spring snowmelt, and shorten the overall snowfall season, leading to more rapid, earlier, and greater spring runoff. Because the temperature projections of climate models are less speculative than the projections of precipitation, temperature-induced shifts in the relative amounts of rain and snow and in the timing of snowmelt in mountainous areas are considered likely. Coping strategies should now be explored.

Where extensive water systems have been built, there are untapped opportunities for rethinking operating and management rules. At the same time, where water systems are already under stress because of limited supplies or water-quality problems, climatic changes may impose different and greater stresses than those already anticipated by water planners.

Climate-induced changes in hydrology will affect the magnitude, frequency, and costs of extreme events, which produce the greatest economic and social costs to humans. Flooding, the nation's most costly and destructive natural disaster, could become more common and extreme. Recent reports of the Intergovernmental Panel on Climate Change (IPCC) suggest that a greenhouse warming is likely to increase the number of intense precipitation days and flood frequencies in northern latitudes and snowmelt-driven basins. These reports also suggest that the frequency and severity of droughts could increase in some areas as a result of a decrease in total rainfall, more frequent dry spells, and greater evapotranspiration.

Many different general circulation models (GCMs) have been developed and improved over the past decades to understand the implications of increased concentrations of greenhouse gases on the climate. The ongoing National Assessment of the impacts of climate change on the United States is evaluating the implications of two different models — the Hadley and Canadian GCMs. Estimates of the impact of climate change on runoff within the water resource basins and subbasins in the conterminous United States using the outputs of these two general circulation models show similarities and sharp differences. For both models, temperatures and potential evapotranspiration rise significantly by 2100. But the uncertainties about the implications of climate change for water resources are illustrated by the contrasting projections of runoff based on these models. Estimates based on the Hadley model indicate flooding could increase in much of the country, while those based on the Canadian climate model indicate increased water scarcity would pervade much of the country. Both scenarios could result in sharply higher socioeconomic costs. Results based on these GCM outputs as well as more detailed regional studies emphasize two points: the detailed regional impacts of a greenhouse warming on future water supplies are uncertain, and runoff is sensitive to changes in temperature and precipitation.

Climatic changes will affect the demand as well as the supply of water. These changes may influence a wide range of water-system components, including reservoir operations, water quality, hydroelectric generation, and navigation. Irrigation, the largest consumer of U.S. water, is particularly sensitive to climate conditions; demand for irrigation water tends to increase as conditions become hotter and drier. Instream water uses such as hydroelectric power generation, navigation, recreation, and ecosystem maintenance are also sensitive to changes in the quantity, quality, and timing of runoff stemming from greenhouse warming.

Water is becoming increasingly scarce and expensive independent of climate change. Water demands are growing with population, incomes, and an appreciation for the values of instream ecological and recreational uses. Increased withdrawals of water for domestic, industrial, and agricultural uses, however, are limited by high economic costs and by the limited opportunities for increasing withdrawals from rivers or streams without adversely impacting instream uses. Improving the efficiency of our water use is rapidly becoming the primary means of balancing limited water supplies with growing demands. But as more people become dependent on a given water supply, vulnerability to drought can increase. Moreover, the capacity to store water to protect against floods and droughts and deal with the uncertainties of climate change appears to be declining because reservoir storage losses due to sedimentation have exceeded additions through new construction in recent years.

The impacts of climate change on water quality have received less attention than the impacts on quantity, but current research raises several concerns. Potential negative implications of climate change include reductions in dilution flows, increased storm surges, and higher water temperatures. Low flows in many western rivers will lead to increases in salinity levels to downstream water users; higher flows could help reduce some water quality concerns. Warmer water could threaten aquatic life directly as cool-water habitats disappear and indirectly as dissolved oxygen levels decline with higher temperatures. An increase in days with more intense precipitation could increase the agricultural and urban pollutants washed into streams and lakes, further reducing oxygen levels. Heavy rainfall is primarily responsible for soil erosion, leaching of agricultural chemicals, and runoff of urban and livestock wastes and nutrients into water bodies. Sea-level rise would contribute to saltwater intrusion into rivers and coastal aquifers.

The socioeconomic implications of both climate and non-climate impacts on water supply and demand will depend in large part on both the ability to adapt to change and on whether water managers and planners take action. Current laws and policies affecting water use, management, and development are often inefficient and unresponsive to changing conditions. The costs of these inefficiencies will likely rise if water becomes scarcer and supply and demand conditions change. There are four promising opportunities for reducing the costs and conflicts of supplying future water demands and adapting to future climate variability: (1) establishing incentives for using, conserving, and protecting supplies; (2) providing opportunities for transferring water among competing uses in response to changing conditions; (3) influencing how water is managed within and among basins; and (4) re-evaluating the operations of the existing infrastructure to address climate and non-climate changes.

All water-supply systems were designed and are operated on the assumption that future climate will look like past climate. Additional dams, reservoirs, aqueducts, levees, and other structures may eventually be needed to help adapt to climate change. But, when possible, costly and irreversible decisions to build water-related infrastructure should be postponed in anticipation of obtaining better information about the likely consequences and costs of a greenhouse warming. Water managers already have a wide variety of tools available for dealing with risk and uncertainty. One view holds that nothing different needs to be done now to cope with future climate changes as these tools will prove sufficient for dealing with future climate changes. But regional modeling studies suggest that even modest changes in climate can lead to changes in water availability outside the range of historical hydrologic variability. It is unclear whether some climate changes will be so rapid or of such large magnitude as to overwhelm existing systems before current management approaches can react. These uncertainties suggest the wisdom of re-examining design assumptions, operating rules, and contingency planning for a wider range of climate conditions than traditionally used. Maintaining options and building in flexibility are important for designing efficient water programs in the context of climate change.

## I. Introduction

*Water is critical to a society's welfare: it is vital for agriculture and industry, the healthy functioning of natural ecosystems on which humans depend, the production of energy, transportation, recreation, and the disposal of wastes.* Natural variability in water supply also affects society: too much water results in floods and too little results in drought, with potentially large socioeconomic costs.

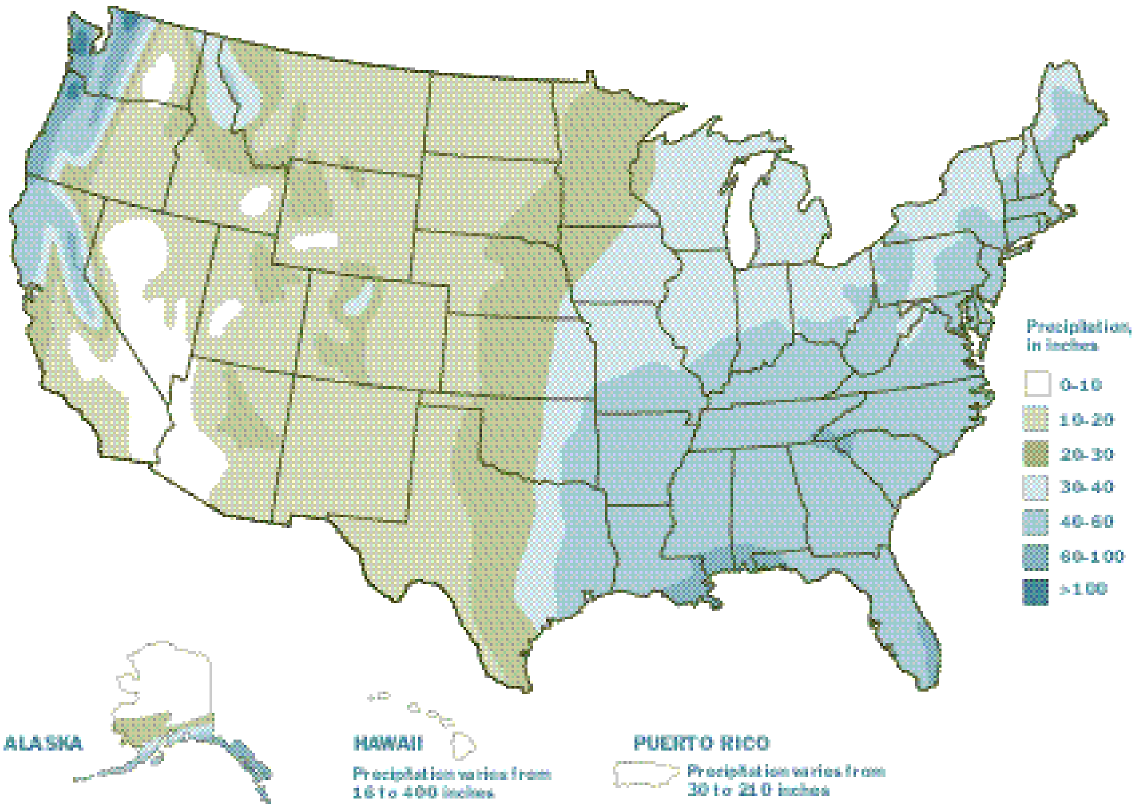
The United States, on average, is well-endowed with water. Annual precipitation averages nearly 30 inches, or 4,200 billion gallons per day (bgd), throughout the conterminous 48 states. While two-thirds of this precipitation quickly evaporates or transpires back to the atmosphere, the remaining one-third provides a renewable supply that is nearly 15 times larger than current consumptive use — water withdrawn from but not returned to a water source in a usable form. In addition, water stored in lakes, reservoirs, and groundwater aquifers within 2,500 feet of the surface is equivalent to more than 50 years of renewable supply (U.S. Water Resources Council, 1978).

But these averages hide important regional and temporal problems with distribution. Figures 1 and 2 show regional variations in average annual precipitation and runoff. Despite its apparent abundance and renewability, freshwater can be a scarce resource virtually everywhere in the United States at some time, especially in the arid and semiarid West. Moreover, the availability of water to meet the demands of a growing and increasingly affluent population — while sustaining a healthy, natural environment — has emerged as one of the nation's primary resource issues. These concerns are based in part on uncertainties about the availability of supplies stemming from the vicissitudes of the hydrologic cycle, growing populations, and, more recently, the prospect that greenhouse-induced climate changes will alter the cycle in uncertain ways.

The hydrologic cycle naturally consists of large seasonal, annual, and regional variations in supplies. A vast infrastructure of dams, reservoirs, canals, pumps, and levees collects, controls, and contains surplus flows and distributes water on demand during low-flow and high-flow periods.

*Figure 1*

Average **Annual Precipitation** in the United States and Puerto Rico

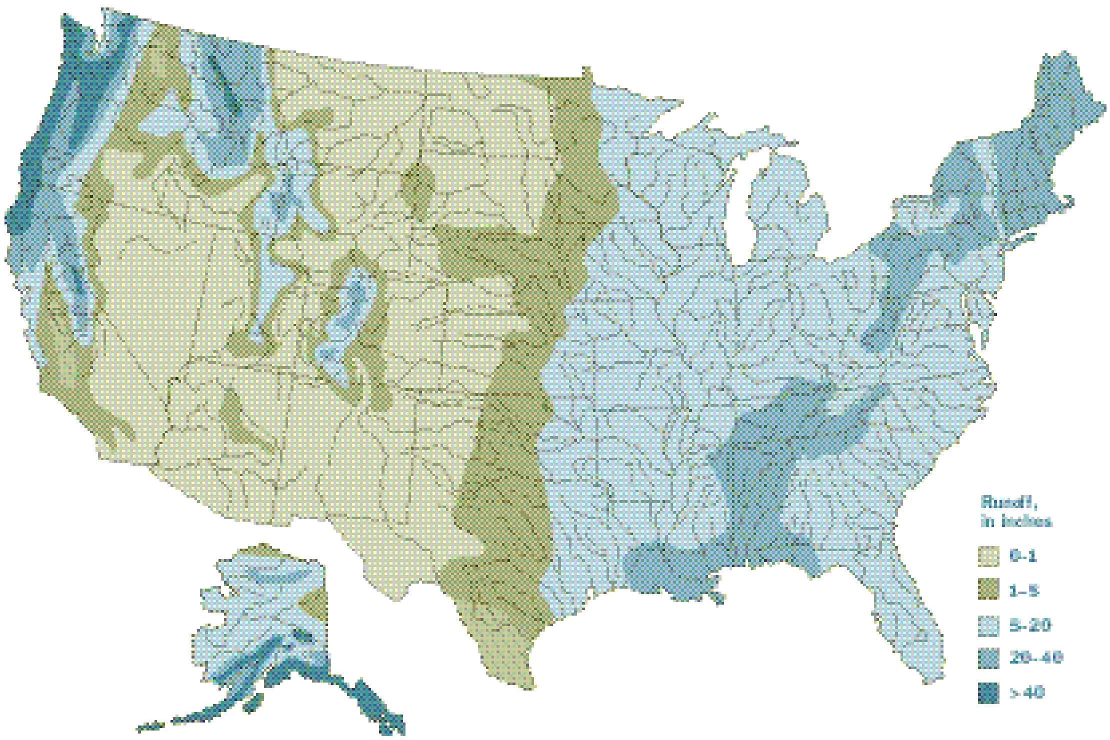



Source: U.S. Water Resources Council, 1978.

Current water-use patterns and the infrastructure to regulate and allocate supplies are the results of past hydrologic conditions. Even today, the design and evaluation of water investments and management strategies assume that future precipitation and runoff can be adequately described, assuming that the future will continue to look like the past. The increasing likelihood that a human-induced greenhouse warming could affect the variability and availability of water quality and supplies, as well as the demand for water, raises doubts about these assumptions and the most appropriate water policies for the future.

*Figure 2*

Average **Annual Runoff** in the Conterminous United States and Alaska




Source: U.S. Water Resources Council, 1978.

This paper reviews what is known about the potential impacts of a greenhouse warming on the supply and demand for water and the resulting economic and ecological implications. A tremendous amount has been written about the impacts of climate change on U.S. water resources. This paper reviews the most critical information and identifies the most important gaps.[1]

## II. Climate Change and its Potential Impacts on Hydrology and Water Supplies

### A. Impacts on the Hydrologic System

*The hydrologic system is an integrated component of the earth's geophysical system and both affects and is affected by climatic conditions.* Water vapor is the main greenhouse gas, and changes in climate affect all aspects of the hydrologic cycle. As the atmosphere warms due to human-induced greenhouse gas emissions, water vapor increases, further enhancing the warming. Changes in temperature affect evapotranspiration rates, cloud characteristics, 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 alter cloud formation and extent, vegetation patterns and growth rates, and soil conditions. On a larger scale, climatic changes can affect major regional atmospheric circulation patterns and storm frequencies and intensities. All of these factors are, in turn, very important for water planning and management decisions.

There are significant limitations in the ability of global models, including the most complex representations, the general circulation models (GCMs), to incorporate and reproduce important aspects of the hydrologic cycle. Many important hydrologic processes such as the formation and distribution of clouds and rain-generating storms occur on a spatial scale far smaller than most models are able to resolve. We thus know less about how the water cycle will change than is necessary to make informed 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 climatic changes and how we might strive to cope with these changes (AWWA, 1997; Frederick et al., 1997; Boland, 1998; Frederick, 1998; Gleick, 1998a; Steiner, 1998).

The ongoing National Assessment[2] of the impacts of climate change in the United States is using two current GCMs, the Canadian Global Climate Model (CGCM) and the British Hadley2 (HADCM2) model (Doherty and Mearns, 1999). For the continental United States, both the Canadian and British climate models show warming by 2090 of at least 4ºC (7.2ºF) over most of the North American continent in all seasons. Much of Canada and the United States show strong winter warming above 9ºC (16.2ºF) in the CGCM. Winter temperature increases in the HADCM2 are more modest, but still reach 1–5ºC (1.8–9.0°F) over the United States in all seasons (Doherty and Mearns, 1999). Changes of this magnitude will have dramatic consequences for snowfall and snowmelt conditions, evaporation regimes, runoff patterns, and water-system operation and management.

The models also show significant changes in precipitation patterns. The Canadian and Hadley models show decreases in winter precipitation over much of North America by 2030, with bands of increased precipitation off the West Coast of the United States and around the Caribbean coast extending northeastward. By 2090, both simulations show increases in precipitation over the West Coast of 5–7 millimeters per day (mm/day) in winter. Greater and more extensive drying occurs in the Canadian model for parts of the Great Plains, southeastern United States, and Mexico in winter, spring, and summer. In sum, both models are similar in their predictions of increases in precipitation over the West Coast. The Hadley model shows greater and more extensive drying in the southern latitudes, while the Canadian model shows drying farther northward in the southeastern United States and Mexico (Doherty and Mearns, 1999).

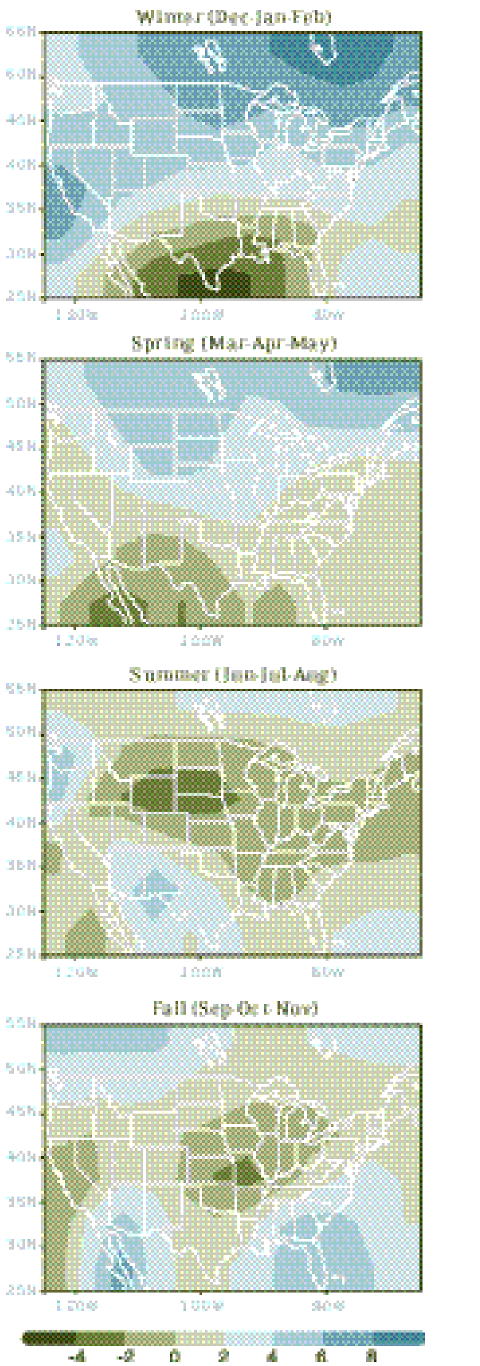
As noted earlier, many different climate models have been developed and run. Looking at a broader range of climate models can reveal important similarities and differences in their precipitation and temperature projections. In another assessment prepared for this series, Wigley (1999) reports the precipitation results from 15 different GCMs. Figure 3 plots the model-average changes in precipitation relative to global-annual-mean temperature changes for the continental United States. This figure shows some mid-continental precipitation decreases, as well as increases in precipitation, especially in winter, in northern latitudes. These increases are common to many models.

The effects of a greenhouse warming on water systems will be varied in both space and time, and many uncertainties about precise impacts remain. Nevertheless, considerable effort has been made at evaluating these impacts, and general and specific conclusions can be drawn. Some of these conclusions, which are based on the most recent reports of the Intergovernmental Panel on Climate Change (IPCC, 1996a, 1996b), are summarized in Box 1.

*Figure 3*

**Relative Precipitation Changes**

(%/°C) Mean of 15 Models




Model-average precipitation changes (percent) relative to the global-annual-mean temperature change for the effect of greenhouse gas increases (i.e., percent change per 1°C global-mean warming).

Source: Wigley, 1999, Figure 10.

As these findings suggest, a greenhouse warming would have major effects on precipitation, evapotranspiration, and runoff. But estimating the nature, timing, and even the direction of the impacts at the regional and local scales of primary interest to water planners involves a sequence of models that produces a cascade of uncertainties (Gleick, 1989; Frederick et al., 1997; Wood et al., 1997). These uncertainties should be kept in mind when expensive or long-term water projects are considered.

- The sequence begins with predictions of regional atmospheric or surface variables such as temperature and precipitation derived from a long-term GCM simulation. Biases of several degrees centigrade are not uncommon in attempts to reproduce seasonal temperature variations, and there is little agreement among the GCMs as to the regional details of future direction, magnitude, and timing of changes in precipitation.
- The second step in the sequence involves going from the large scale of the GCMs, which typically have grid cells of about 40,000 $km^2$ (roughly the area of Connecticut, Massachusetts, and Rhode Island combined) to the river-basin scale. Downscaling requires new assumptions and introduces additional uncertainties.
- The third step involves using hydrologic models to estimate the implications of the downscaled temperature and precipitation projections for streamflow patterns. The hydrologic modeling errors are likely to be modest relative to those introduced by the GCM simulations and downscaling, as long as the differences between the historical and the projected climate are small compared to the observed annual and seasonal variations in the hydrologic record.

- The fourth step in analyzing the impacts of climate change involves running a water resources simulation model with streamflow sequences corresponding to the various climate scenarios and evaluating the differences in system performance. Applying the climate-adjusted hydrology to water-resource system models calibrated and designed to operate with historical streamflows introduces additional uncertainties.
- Finally, actual impacts will depend on the changes in water policy and operations, and on changing demographics in a region. Such changes can help systems cope with greenhouse warming or they can make systems more vulnerable.

***Box 1***

## Summary of IPCC Findings on Precipitation and Water Resources

- The timing and regional patterns of precipitation will change and more intense precipitation days are likely in some regions.
- GCMs used to forecast climate change with higher concentrations of greenhouse gases suggest that a 1.5–4.5ºC rise in global mean temperature would increase global mean precipitation about 3–15%.
- Detailed changes in the regional distribution of precipitation are uncertain, but precipitation is expected to increase in higher latitudes, particularly in winter. This conclusion extends to the middle latitudes in most GCM results.
- Potential evapotranspiration — water evaporated from the surface and transpired from plants — rises with air temperature. Consequently, even in areas with increased precipitation, higher evapotranspiration rates may lead to decreases in runoff and a possible reduction in renewable water supplies.
- Increases in annual runoff caused by greater precipitation are likely in the high latitudes.
- Flood frequencies in some areas are likely to change. In northern latitudes and snowmelt-driven basins, floods may become more frequent, although the increase in flooding for any given climate scenario is uncertain and impacts will vary among basins.
- The frequency and severity of droughts could increase in some areas as a result of a decrease in total rainfall, more frequent dry spells, and greater evapotranspiration.
- Seasonal disruptions might occur in the water supplies of mountainous areas if the ratio of rain to snow increases and if the length of the snow storage season is reduced. A shift in the relative amounts of snow and rain and in the timing of snowmelt and runoff could increase the likelihood of flooding early in the year and reduce the availability of water during periods of peak demand. Basins in the western United States are particularly vulnerable to such shifts.
- Water quality problems may increase where there is less flow to dilute contaminants introduced from natural and human sources.
- Higher sea levels (associated with thermal expansion of the oceans and increased melting of glaciers and land ice) and more storm surges could push saltwater farther inland in rivers, deltas, and coastal aquifers. Such advances would adversely affect the quality and quantity of freshwater supplies in many coastal areas.
- More atmospheric carbon dioxide ($CO_2$) will affect the use of water by vegetation. Controlled experiments suggest that increasing $CO_2$ can reduce the rate of transpiration from plants, which would tend to increase runoff. On the other hand, rising $CO_2$ concentrations also contribute to plant growth, leading to a larger area of transpiring tissue and a corresponding increase in transpiration. The net effect of these opposing influences on water supplies will depend on the type of vegetation and other interacting factors such as soil type and climate.

Source: IPCC 1996a, 1996b.

## B. Impacts on Regional Water Resources

*A greenhouse warming could have major but highly uncertain impacts on a region's water resources.* In spite of their inevitable uncertainties, it is instructive to review the results of past efforts to project the impacts climate change might have on regional water supplies. A wide variety of regional and watershed assessments have been done around the United States. While specific regional impacts will depend on both the future climatic changes as well as the economic, institutional, and structural conditions in any region, a few broad general results can be described (see Box 2).

In the arid and semiarid western United States, relatively modest changes in precipitation can have disproportionally large impacts on runoff, which provides much of the region's renewable water supply. 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 (Rind et al., 1990; Nash and Gleick, 1991, 1993). In such cases, increases in precipitation would be required to maintain runoff at historical levels.

An even more significant finding is that higher temperatures can lead to dramatic changes in the snowfall and snowmelt dynamics in mountainous watersheds. This effect was identified in the mid-1980s for watersheds in California (Gleick, 1986, 1987a, 1987b). Modeling studies have now shown that all watersheds with significant snow dynamics are likely to be affected (see, for example,

***Box 2***

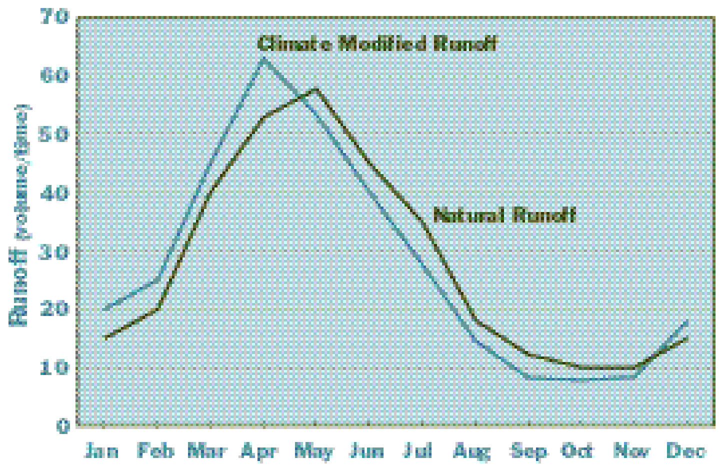
### General Observations about Regional Hydrologic Impacts in the United States

- Regions with snowfall, such as the Rocky Mountains and Sierra Nevada, California, will experience seasonal shifts in runoff, with increases in winter and early spring runoff, decreases in late spring and summer runoff, and possible increased flood intensities.
- Higher latitudes are more likely to receive increases in precipitation and runoff; lower latitudes are more likely to see decreases in runoff.
- In regions where water quality problems are related to average temperatures or flows, problems could be exacerbated by warming.
- Coastal freshwater aquifers in places such as Cape Cod, Long Island, and Florida will be at greater risk of saltwater intrusion due to rising sea level.
- Midcontinental regions, particularly the semiarid and arid western United States, may experience drying of soils during the growing season or more variability in water availability.

Lettenmaier and Gan, 1990; Cooley et al., 1992; Martinec et al., 1992; Miller et al., 1992; IPCC, 1996b; Leung and Wigmosta, 1999). Higher temperatures will have three major effects: they will increase the ratio of rain to snow, accelerate the rate of spring snowmelt, and shorten the overall snowfall season, leading to more rapid, earlier, and greater spring runoff. Figure 4 shows a hypothetical monthly hydrograph from a snowmelt basin with and without climate change.

*Figure 4*

Natural and Modified **Hypothetical Hydrograph** for Basins with Snowfall and Snowmelt




Source: Gleick and Chalecki, 1999.

Results from two approaches to forecasting the impacts of climate change on regional water supply are presented below. The first approach follows the first three steps in the sequence described above to evaluate large regional impacts of GCM-generated climatic conditions. The second uses more detailed regional hydrologic models to evaluate the sensitivities of specific watersheds to hypothetical climate changes. Both approaches have advantages and limitations and have been widely used in the United States.

A recent general assessment by the U.S. Geological Survey (USGS) (Wolock and McCabe, 1999) starts with outputs of the Canadian and the Hadley climate models. This assessment estimates the impact of climate change on runoff for the official water-resource basins (Figure 5) in the United States. Table 1 indicates the percentage changes in mean annual runoff for the 18 major water resource regions in the conterminous United States from 1990 to 2030 and from 1990 to 2090 using the outputs of the two GCMs. The runoff forecasts are based on a geographic downscaling and a water-balance model developed by Wolock and McCabe (1999).

*Figure 5*

### Map of the 21 Major **Water Resource Regions** of the United States


**MAPLEGEND**

| | |
|---|---|
| 1 | New England |
| 2 | Mid-Atlantic |
| 3 | South Atlantic-Gulf |
| 4 | Great Lakes |
| 5 | Ohio |
| 6 | Tennessee |
| 7 | Upper Mississippi |
| 8 | Lower Mississippi |
| 9 | Souris-Red-Rainy |
| 10 | Missouri |
| 11 | Arkansas-White-Red |
| 12 | Texas-Gulf |
| 13 | Rio Grande |
| 14 | Upper Colorado |
| 15 | Lower Colorado |
| 16 | Great Basin |
| 17 | Pacific Northwest |
| 18 | California |
| 19 | Alaska |
| 20 | Hawaii |
| 21 | Caribbean |

Source: U.S. Water Resources Council, 1978.

The differences in runoff derived from the two GCMs are striking. With the exception of the California region (which is projected to receive about 26 percent more runoff in 2030) and the Souris-Red-Rainy region (which is projected to receive 18-24 percent less runoff), the runoff projections for 2030 derived from the two climate models suggest very different scenarios. The Canadian model suggests runoff would decline in all regions except California. In 12 of the 18 regions, runoff declines by more than 20 percent, an outcome that would have serious adverse impacts. In contrast, the Hadley model projects increases in average runoff in most regions; the majority of the nation's arid and semiarid regions would have significantly more water, reducing problems of water scarcity but perhaps increasing the threat of floods. By 2090, most of the United States is projected to be even wetter under the Hadley model; the Canadian model suggests some further drying in the East but an increase in water supplies in much of the West.

Several different conclusions can be drawn from these results and the climate projections underlying them. First, significantly higher temperatures (even with more precipitation) can still lead to large reductions in regional runoff, while smaller temperature increases and large increases in precipitation can lead to much greater runoff. Second, runoff is extremely sensitive to climatic conditions, so any significant change in climate may lead to important water management problems. Third, far more work is needed on a regional scale to understand how climate will affect water resources. Finally, the great differences in results show the difficulty of making accurate predictions of future runoff. These results should be viewed with considerable caution. Until the GCMs can provide better and more consistent projections of regional changes in temperature and precipitation, this approach is of limited value to water planners. They would like more specific information about the direction and magnitude of the climate-induced changes in water supplies.

***Table 1***

**Projected Changes in Average Annual Runoff under Two Climate Models by Water Resource Region, 1990–2030 and 1990–2090 (in percent)**

| Water Resource Region | Canadian Climate Model 1990–2030 | Canadian Climate Model 1990–2090 | Hadley Climate Model 1990–2030 | Hadley Climate Model 1990–2090 |
|---|---|---|---|---|
| New England | –8 | –19 | 9 | 28 |
| Mid-Atlantic | –13 | –25 | 10 | 33 |
| South Atlantic-Gulf | –61 | –73 | 0 | 31 |
| Great Lakes | –12 | –10 | 20 | 55 |
| Ohio | –21 | –23 | 6 | 42 |
| Tennessee | –33 | –37 | 4 | 40 |
| Upper Mississippi | –23 | 17 | 20 | 60 |
| Lower Mississippi | –33 | –17 | 5 | 41 |
| Souris-Red-Rainy | –24 | –80 | –18 | 79 |
| Missouri | –25 | 48 | 18 | 45 |
| Arkansas-White-Red | –46 | 8 | 0 | 45 |
| Texas-Gulf | –87 | –34 | –10 | -8 |
| Rio Grande | –63 | –56 | –3 | 60 |
| Upper Colorado | –36 | 5 | 7 | 66 |
| Lower Colorado | –38 | 3 | 23 | 151 |
| Great Basin | –7 | 75 | 21 | 138 |
| Pacific Northwest | –2 | 19 | 15 | 13 |
| California | 26 | 139 | 27 | 118 |

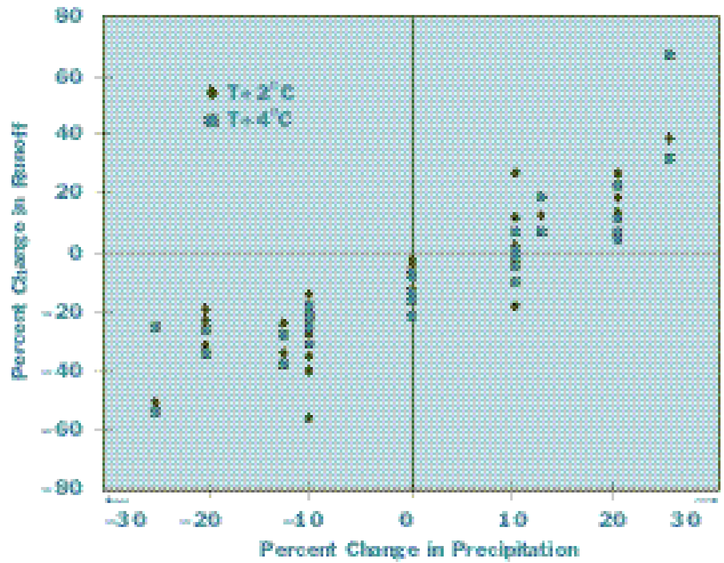
Source: Wolock and McCabe, 1999.

In fact, some more detailed regional work has been done over the past two decades. 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, and many more. Many of these studies show big possible changes in future hydrologic conditions relative to historical conditions. Table 2 and Figure 6 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.

The results of the simulation studies summarized in Table 2 support the conclusion that runoff is sensitive to changes in temperature and precipitation. In studies with an increase in temperature and no change in precipitation, runoff decreases. With no change in precipitation, estimated runoff declines by 2–12 percent with a 2ºC (3.6ºF) increase in temperature and by 4–21 percent with a 4ºC (7.2ºF) increase in temperature. A 10 percent reduction in precipitation and a 2ºC (3.6ºF) increase in temperature reduce estimated runoff by between 14 percent and 40 percent in most studies. A 4ºC (7.2ºF) increase in temperature leads to even larger reductions in runoff. These results are not comprehensive, but do suggest the possible magnitude and uncertainty surrounding the hydrologic implications of a greenhouse warming.

*Figure 6*

**Changes in Runoff** from Hypothetical Climate Changes in Western Mountainous River Basins




Source: See Table 2.

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. Dozens of studies show increases in winter runoff, decreases in spring and summer runoff, and higher peak flows (see, for example, Gleick, 1987b; Lettenmaier and Gan, 1990; Nash and Gleick, 1991, 1993; Jeton et al., 1996; Leung and Wigmosta, 1999). Because the temperature projections of the GCMs are less speculative than the impacts on precipitation, temperature-induced shifts in the relative amounts of rain and snow and in the timing of snowmelt in mountainous areas are considered likely. Coping strategies should now be explored.

*Table 2*

## Impacts on Mean Annual Runoff

### from Hypothetical Climate Changes in Mountainous River Basins (in percent)

| Precipitation Change | River Basin | Temperature Change +2°C | Temperature Change +4°C |
|---|---|---|---|
| –25 | Carson[7] | –25 | –25 |
| | American[7] | –51 | –54 |
| –20 | Upper Colorado[3] | — | –41 |
| | Animas River[3] | –26 | –32 |
| | White River[3] | –23 | –26 |
| | East River[3] | –19 | –25 |
| | East River[8] | — | –30 |
| | Sacramento[2] | –31 | –34 |
| –12.5 | Carson[7] | –24 | –28 |
| | American[7] | –34 | –38 |
| –10 | Great Basin Rivers[1] | –17 to –28 | — |
| | Sacramento River[2] | –18 | –21 |
| | Inflow to Lake Powell[3] | –23 | –31 |
| | White River[3] | –14 | –18 |
| | East River[3] | –19 | –25 |
| | Upper Colorado[4] | –35 | — |
| | Lower Colorado[4] | –56 | — |
| | Colorado River[5] | –40 | — |
| | Animas River[3] | –17 | –23 |
| 0 | Sacramento River[2] | –3 | –7 |
| | Inflow to Lake Powell[3] | –12 | –21 |
| | White River[3] | –4 | –8 |
| | East River[3] | –9 | –16 |
| | East River[8] | — | –4 |
| | Animas River[3] | –7 | –14 |
| | Animas River[6] | –2 | — |
| +10 | Great Basin Rivers[1] | +20 to +35 | — |
| | Sacramento River[2] | +12 | +7 |
| | Inflow to Lake Powell[3] | +1 | –10 |
| | White River[3] | +7 | +1 |
| | East River[3] | +1 | –3 |
| | Colorado River[5] | –18 | — |
| | Animas River[3] | +3 | –5 |
| +12.5 | Carson[7] | +13 | +7 |
| | American[7] | +20 | +19 |
| +20 | Upper Colorado[3] | — | +2 |
| | Animas River[3] | +14 | +5 |
| | East River[3] | +12 | +7 |
| | East River[8] | — | +23 |
| | White River[3] | +19 | +12 |
| | Sacramento[2] | +27 | +23 |
| +25 | Carson[7] | +39 | +32 |
| | American[7] | +67 | +67 |

Notes: Some of these models also evaluated the impacts of climate changes from general circulation models. Refer to the original references for details.

Sources:
[1] All Great Basin Rivers results from Flaschka, et al., 1987.
[2] All Sacramento River results from Gleick, 1986, 1987a, 1987b.
[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) results from Duell, 1992, 1994.
[8] McCabe and Hay, 1995.

The level of atmospheric $CO_2$ may affect water availability through its influence on vegetation and evapotranspiration rates. Higher $CO_2$ levels have been shown to increase plant growth. A larger area of transpiring tissue and the corresponding increase in transpiration would tend to reduce the runoff associated with a given level of precipitation. On the other hand, higher $CO_2$ levels increase the resistance of plant stomata to water vapor transport, resulting in decreased transpiration per plant unit. The net effect on water supplies is uncertain but would depend on factors such as vegetation, soil type, and climate. One study suggests that water resources in the Delaware River Basin are sufficiently sensitive to changes in stomatal resistance that the effects of higher temperatures and lower precipitation could be offset to some extent (Lins et al., 1997). A study of the effect of $CO_2$ enrichment on boreal ecosystems suggests that improved water economy of the plants did not increase runoff, probably because of a compensatory increase in evapotranspiration (Beerling, 1999).

This discussion and the model results highlight many of the uncertainties surrounding the implications of climate change for overall water availability.

## III. Evidence of Temperature and Hydrologic Trends

*Recent research shows that changes and variations in the hydrologic cycle of the earth may already be occurring.* A number of these changes are statistically significant; that is, they are sufficiently different from the past record to be the result of something other than just natural variability. Gaps in data, inadequate monitoring records, and biases in instrumental readings still need to be corrected, however. Only more time and analysis will confirm or refute whether these changes are directly related to intensification of the greenhouse effect.

The change that has received the most attention is the increase in average global temperature. Data from a network of ground- and ocean-based sites and satellites suggest that the average surface temperature of the earth has increased by nearly a degree over the past century. The 14 warmest years in this century have all occurred since 1980. Indeed, in a study released in March 1999, researchers report that the 1990s have been the warmest decade of the entire millennium, and 1998 the warmest year (Mann and Bradley, 1999). The higher latitudes have warmed more than the equatorial regions, in agreement with climate model projections for greenhouse warming (IPCC, 1996a; OSTP, 1997).

Precipitation patterns are also showing trends. 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). According to a recent analysis of data from 1900 to 1988, precipitation over land has increased by 2.4 mm per decade and global mean rainfall has risen by more than 2 percent (Dai et al., 1997a, 1997b). Consistent with the upward trend in global precipitation, the average mean interval between two drier-than-average months increased by about 28 percent from 1900–1944 to 1945–1988. Similar results are being seen in the United States. The percentage of wet areas over the United States has more than doubled (from about 12 percent to greater than 24 percent) since the 1970s, while the percentage of dry areas has decreased by a similar amount since the 1940s. 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 more precipitation in the conterminous United States, due primarily to an increase in heavy and extreme daily precipitation events — a worrisome trend in regions where flooding is a problem. By analyzing long-term precipitation trends in the United States, they determined the following:

- Precipitation over the conterminous United States has increased by about 10 percent since 1910.
- Increases in total precipitation are strongly affected by increases in both the frequency and the intensity of heavy and extreme precipitation events.
- The probability of precipitation on any given day has grown.
- The intensity of precipitation has increased only for very heavy and extreme precipitation days.
- The proportion of total precipitation from heavy precipitation events has grown at the expense of moderate precipitation events.
- An increase in the frequency and magnitude of extreme precipitation events would have enormous ramifications for water management, system operation, and water-related disasters.

Total annual snowfall in the far northern latitudes seems to be increasing, consistent with the observed increases in northern latitude precipitation. At the same time, snow and ice cover seem to be decreasing and melting earlier. Snow cover over the Northern Hemisphere land surface has been consistently below the 21-year average (1974–1994) since 1988 (Robinson et al., 1993; Groisman et al., 1994), with a decrease of about 10 percent over both North America and Asia. These changes are linked to higher temperatures. Other observed 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).

River runoff is considered to be an excellent integrator of climatic factors, and some efforts have been made to look at long-term runoff records to see if any trends can be detected. One difficulty, however, is that although long records of runoff are essential to determining whether runoff is changing over time, very few rivers have reliable records longer than several decades. Records longer than a century are extremely rare. Moreover, human interventions in the form of water withdrawals, the construction of dams and reservoirs, and land-use changes in watersheds have already caused significant changes in runoff regimes, greatly complicating the use of past runoff records to detect climate changes or even trends in natural variability.

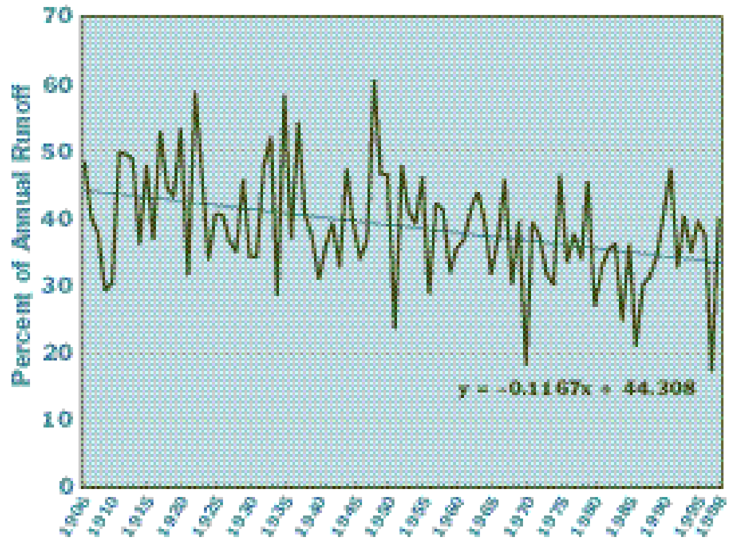
Some studies, however, have begun to see trends that cannot be explained by natural variability and that are consistent with modeling projections. Three studies published in 1994 all found evidence that certain rivers are exhibiting runoff trends consistent with the effects of global warming. Burn (1994) found a statistically significant trend toward earlier spring runoff in several rivers in western Canada — a finding predicted in model studies involving snowmelt described above. Lins and Michaels (1994) also reported statistically significant increases in autumn and winter streamflow in North America between 1944 and 1988. They related these regional and seasonal increases to global warming. Lettenmaier et al. (1994) detected clear increases in winter and spring streamflow across much of the United States between 1948 and 1988.

Lins and Slack (1999) used the USGS's Hydro-Climatic Data Network, a climate-sensitive network of stream gauges located in areas where runoff is affected little by human development, to examine daily streamflows observed in the United States from annual minimum to maximum through 1993. Their results show a broad pattern toward increasing lower and middle range annual streamflows across the conterminous United States during the twentieth century. However, they detect no broad trend in annual maximum streamflows and no continental-scale seasonal shift in peak discharges. Further analysis is needed to reconcile the Lins and Slack finding that the United States seems to be getting wetter but with no increase in peak flows with the Karl and Knight analysis that the increase in precipitation has been due primarily to an increase in heavy and extreme precipitation events.

One last piece of intriguing evidence is appearing. In some western watersheds, runoff timing appears to be shifting from spring to winter, suggesting a change in snowfall and snowmelt dynamics. In the Sacramento River basin, for example, the fraction of annual runoff that occurs in the April to July snowmelt season has been decreasing steadily over the past century (see Figure 7) (Gleick and Chalecki, in press). While this may not be due to human-induced climate change, it is precisely the kind of effect seen in the regional hydrologic climate-change studies done for these regions.

*Figure 7*

**Sacramento River Runoff** April to July Runoff (as percent of Annual Runoff)




Source: Gleick and Chalecki, 1999.
Note: Four-River Index

Further insights may emerge as updated runoff data become available. As Arnell (1996) states: "The evidence for global warming having a noticeable effect on hydrological behavior is not yet convincing, but it does seem to be accumulating."

## IV. Implications of Climate Change for Managed Water-Resource Systems

*Climatic changes may affect a wide range of water-system components, including reservoir operations, water quality, hydro-electric generation, and navigation.* While there is a rapidly growing literature about climate effects, the research has barely scratched the surface of the potential range of impacts and possible responses. Far more research is needed.

Precipitation, temperature, and carbon dioxide levels affect the demand for water as well as the supply. Yet, the impacts of climate on water use have received very little attention. Current withdrawal and consumptive uses (see Figure 8) and the potential impacts of the climate on water use are discussed below. Consumptive use is the portion of water withdrawn that evaporates, transpires, is incorporated into products or crops, or runs off to a sink where it is unavailable for further use (Solley et al., 1998).

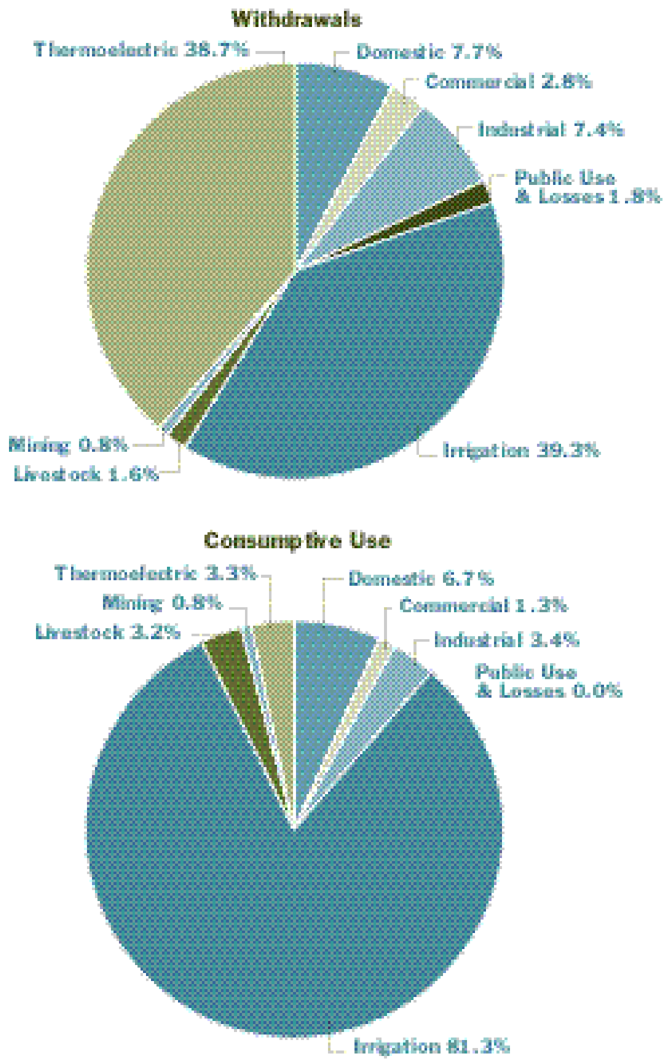
Irrigation, which accounts for 39 percent of all U.S. water withdrawals and 81 percent of consumptive use, is particularly sensitive to climatic conditions. Irrigation becomes more critical for crop production as conditions become hotter and drier. Consequently, in areas with available and affordable water supplies, these conditions would increase both the area under irrigation and the amount of water applied per irrigated acre. However, any increases in water-use efficiency attributable to higher atmospheric $CO_2$ levels would tend to counter the tendency to apply more water as temperatures rise. The net effect of these opposing forces on the demand for irrigation water is uncertain.

Water for household purposes — drinking, preparing food, bathing, washing clothes and dishes, flushing toilets, and watering lawns and gardens — accounts for 8 percent of withdrawals and 7 percent of consumptive use in the United States (Solley et al., 1998). Gardening, lawn sprinkling, and showering are the most sensitive of these uses to climate conditions. While indoor domestic water use is not very sensitive to temperature and precipitation, outdoor uses for gardens and parks depend on climate. In some regions of the United States, particularly the arid and semiarid West, climate-induced changes in domestic demand can aggravate the problems of balancing supply and demand.

Industrial use, which includes water for purposes such as processing, washing, and cooling in manufacturing facilities, accounts for 7 percent of withdrawals and 3 percent of consumptive use in the United States. Thermoelectric power use in the United States (which includes water for cooling to condense the steam that drives turbines that generate electric power with fossil fuel, nuclear, or geothermal energy) accounts for 39 percent of all withdrawals but only 3 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 reduce plant outputs, force shutdowns due to environmental constraints, or limit the amount of water available for safety systems. In a study of the possible impacts on the Tennessee Valley Authority (TVA) system, Miller (1993) noted that temperature-induced load reductions in hot, dry years could significantly affect the power supply system and reduce system reliability.

*Figure 8*

**Fresh Water Use** by Category, 1995 (in percent)




Source: Solley et al., 1998.

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

Changes in the quantity, quality, and timing of runoff stemming from greenhouse warming would affect instream water uses such as hydroelectric power generation, navigation, recreation, and maintenance of ecosystems. During a recent multi-year drought in California, hydropower generation dropped substantially, leading to increases in fossil-fuel combustion. Between 1987 and 1991, these changes cost ratepayers more than $3 billion and increased greenhouse gas emissions (Gleick and Nash, 1993). A comprehensive study of the impacts of climate change on the Colorado River suggested that modest decreases in average runoff would lead to very dramatic decreases in hydroelectric generation and reservoir levels, assuming no changes to the formal "law of the river" (the collection of statutes, contracts, and court decrees that apportion and regulate use of the water). On the other hand, modest increases in average runoff would lead to major increases in hydroelectricity generation and a risk of larger and more frequent floods (Nash and Gleick, 1993).

A warming could lengthen the navigation season on some northern lakes and rivers that typically freeze in winter, increasing the demand for water to facilitate navigation during the extended ice-free period. Similarly, seasonal water demands associated with recreational uses such as swimming, boating, and fishing might rise.

One consistent finding is that water-supply systems are sensitive to changes in inflows and demands. 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 numerous regions (McMahon et al., 1989; Cole et al., 1991; Mimikou et al., 1991; Nash and Gleick, 1993). The extent to which changes in operations might reduce these sensitivities and at what cost needs to be studied. This gap in knowledge contributes to the debate (discussed in Section VIII) on whether current management practices designed to deal with hydrologic variability are likely to be sufficient to deal with climate change.

## V. Ecological Impacts

*Ecosystems are fundamentally dependent on water resources: healthy ecosystems depend on receiving appropriate amounts of water of a certain quality at certain times.* Humans, in turn, are dependent on ecosystem processes. For example, primary productivity and inputs from watersheds support food webs, yielding fish for commercial and recreational purposes, while decomposition and biological uptakes remove organic materials and nutrients, purifying water. Ecosystem processes are affected by temperature and flow regimes and will be affected by changes in climatic conditions.

Previous assessments have identified a wide range of possible impacts, 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, and altered nutrient exchanges and food web structure (see, for example, the special issue of *Hydrological Processes*, 1997). More recently, papers prepared for the water sector of the National Assessment offer a good overview of both uncertainties and critical concerns (see, for example, Meyer et al., 1999; Hostetler and Small, 1999; Stefan and Fang, 1999; and Kusler and Burkett, 1999).

Actual impacts will depend on the nature of the climatic changes, the regional characteristics of the ecosystems, and the nature and scope of intentional interventions by humans. The following examples give a sense of the range of possible impacts identified to date.

Work across the United States suggests a wide range of serious concerns for ecosystems, with 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 (Eaton et al., 1996; Covich et al., 1997; Hauer et al., 1997; Meyer, 1997; Schindler, 1997). Recent research suggests that lake levels, water residence time, and mixing regimes will change, with profound effects on ecosystems. Dissolved oxygen concentrations and ice cover are predicted to decrease (Hostetler and Small, 1999; Stefan and Fang, 1999). Warm-water fish populations will increase, while cold-water species and wetlands will be disrupted and possibly lost (Meyer et al., 1999). Heavy rainfall, which could become more common in some regions, is primarily responsible for soil erosion, leaching of agricultural chemicals, and runoff of urban and livestock wastes and nutrients into water bodies (Adams et al., 1999; U.S. EPA, 1998).

Impacts in northern latitudes may be particularly severe. Studies for Alaska indicate dramatic decreases in permafrost, draining of existing lakes, creation of new ones, and alteration of nutrient exchanges and food web structures. The Rocky Mountain and Sierra Nevada regions would see greater fragmentation of cold-water habitats, shorter duration of ice cover for lakes, and a greater likelihood of late summer channel drying. Changes in the southeastern United States could include increased rates of production and nutrient cycling, more extensive summer deoxygenation, more drying of coastal wetland soils resulting in greater fire threat, and expansion of subtropical species northward (Meyer et al., 1999; Hostetler and Small, 1999; Kusler and Burkett, 1999). Some impacts may help ecosystems: riverine, lake fringe, and other wetland areas may benefit from increased precipitation; vegetation biomass may increase due to rising $CO_2$ levels; and lower lake levels may permit colonization by wetland vegetation (Kusler and Burkett, 1999). But these same researchers note their concern for the lack of practical options for protecting wetlands and other aquatic ecosystems from uncertain but potentially large changes.

Researchers also express concern not only about the actual impacts of climate change, but also about the limited ability of natural ecosystems to adapt to or cope with those changes over the short time frame in which the impacts are likely to occur. This limited ability to adapt may lead to irreversible impacts such as species extinction. Another concern is the lack of formal water rights held by ecosystems. As a result, competition for water in the past has often come at the expense of aquatic systems. While legal and institutional efforts are already underway to guarantee some minimum water level for sensitive ecosystems, they remain particularly sensitive to the vagaries of climatic fluctuations. While some research has been done on these issues, far more is needed.

## VI. Socioeconomic Costs of Extreme Hydrological Events

*Hydrological fluctuations impose several costs on society.* These include the economic and environmental costs of building and managing infrastructure to provide more even and reliable flows, and the costs of floods and droughts that occur despite these investments. The United States has constructed more than 80,000 dams and reservoirs to control floodwaters and increase available supplies. 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.

### A. Floods

*Flooding is the nation's most costly and destructive natural disaster and the cause, at least in part, of most federal disaster declarations.* Floodplains occupy about 160 million acres, or 7 percent, of U.S. land (Schilling, 1987). The proximity of these lands to water for navigation, recreation, power, and municipal and industrial uses makes them attractive for settlement. Floodplain development also has been encouraged by the dams, reservoirs, and levees that have been built to control floodwaters. Since the Flood Control Act of 1936 established flood control as a federal activity, the federal government has spent about $100 billion (in 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.

Flood damages, which vary widely from year to year, averaged nearly $5.7 billion (in constant 1997 dollars) and 98 deaths annually from 1990 to 1997. Dollar damages have increased about 1 percent yearly and flood-related deaths have risen 1.5 percent yearly on average since 1945 (National Weather Service, 1999). These damage estimates include only direct costs such as repairs to buildings, roads, and bridges attributable to flooding from rainfall and snowmelt. These estimates exclude damages attributable to wind (such as hurricanes), and indirect damages such as lost wages, crop and business losses, or the costs of temporarily evacuating homes for higher ground.

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), which was 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" (p. 8). The damages would have been $19.1 billion higher without the dams, reservoirs, and levees available to control floodwaters, according to estimates of the U.S. Army Corps of Engineers (Interagency Floodplain Management Review Committee, 1994). On the other hand, these facilities contributed indirectly to some of the damages that did occur by encouraging settlement and development in the floodplain. Floodplain development not only places more people and property at risk, it also reduces a basin's capacity to moderate flood flows naturally.

Future flood damages will depend on many factors. Among the most important are the rate of development in the floodplains, which has grown about 2 percent yearly (Schilling, 1987), and climate-induced changes in hydrological conditions, sea levels, and storm surges. As noted above, regional and local changes in hydrological conditions attributable to a greenhouse warming are uncertain. If future runoff is best characterized by the results based on the Hadley climate model (see Table 1), more frequent and extreme flooding would result. Events such as the 1993 Midwest flood that are now viewed as rare could become common. Under such a scenario, future riverine flood damages 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.

## B. Droughts

*Drought in the nineteenth century and again in the 1930s in the United States led to large-scale migrations and many deaths.* While the country is now better able to adapt, an extended drought still results in substantial adverse economic and social impacts. If the Canadian climate model provides the more accurate projection of the future (see Table 1), droughts and chronic water shortages rather than floods would become more widespread and intense.

Quantifying the socioeconomic impacts of a drought is difficult, and damage estimates are available for only a few drought events. 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. Agricultural losses during California's six-year drought from 1987 to 1992 were limited by temporarily removing land from production, 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 $250 million, less than 2 percent of the state's total agricultural revenues (U.S. Army Corps of Engineers, 1994).

A prolonged drought affects virtually all sectors of the economy. Urban users in California paid more for water and were subject to both voluntary and mandatory conservation programs. Investments as well as jobs were lost in landscaping and gardening. Electricity costs to consumers, as described in Section IV, rose more than $3 billion because of a reduction in the production of inexpensive hydropower. Recreation was adversely impacted. Visits to state parks declined by 20 percent between 1987 and 1991, and water-based activities such as skiing and reservoir fishing declined. But the state's environmental resources may have suffered the most severe impacts of the drought. Most major fisheries suffered sharp declines, and many trees were weakened or killed by the lack of precipitation, increasing the risk of forest fires (Nash, 1993; U.S. Army Corps of Engineers, 1994).

The net national economic costs of a drought are likely to be less than the costs suffered within the drought-impacted 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 from one area to another 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 level. For example, a U.S. Army Corps of Engineers (1991, 1994) analysis of the agricultural impacts of California's drought concluded that in 1991, the national costs were less than 30 percent of the state impacts.

Conservation, which has been encouraged by efforts to mitigate drought costs, can have mixed implications for vulnerability to future droughts. The availability of low-value uses such as washing sidewalks and irrigating pastures that can be reduced relatively easily provides opportunities for mitigating the socioeconomic impacts of drought. If these uses are eliminated and the conserved water is stored for use during drought, vulnerability decreases. But if the conserved water is used to add more customers to a supply system, vulnerability may increase (U.S. Army Corps of Engineers, 1995).

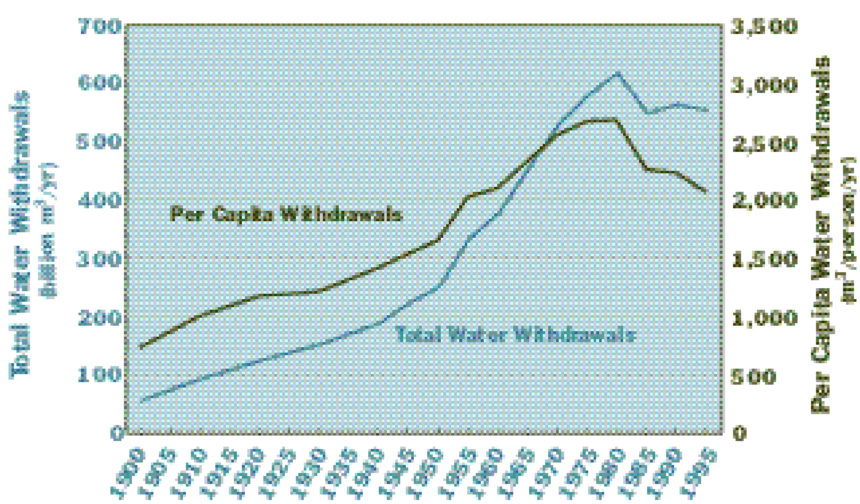
## VII. Socioeconomic Costs of Changes in Water Supply and Demand

*Offstream water use rose more than tenfold from 1900 to 1975, driven largely by population and economic growth; a willingness to ignore the adverse impacts of withdrawals on streamflows; and planners who sought to provide households, farmers, and businesses with virtually unlimited supplies at low prices (see Figure 9) (Brown, 1999; Frederick, 1991).*

Water demands have continued to grow since 1975 with population and incomes. For the past 25 years, however, water use has been constrained by high costs, environmental concerns, and scarcity. Conservation has become the principal means of balancing demand with supply. The combination of price incentives, water transfers, technology, and regulations has eliminated some inefficient and low-value water uses and encouraged the development and adoption of more water-efficient practices. These changes are reflected in national water use trends. Per capita water withdrawals peaked in 1975 and declined 29 percent in the following two decades. Total withdrawals peaked in 1980 and have declined 9 percent since. Total consumptive water use was unchanged between 1980 and 1995. But on a per capita basis, consumptive use fell 14 percent over those 15 years (Solley et al., 1998).

*Figure 9*

U.S. Total and Per Capita Water Withdrawals




Source: Gleick, 1998b.

The emphasis on more efficient water use is due in part to the high costs and limited opportunities for increasing offstream water use without adversely impacting instream uses. 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. From 1961 to 1970, more than 19,000 dams and reservoirs with more than 250 million acre-feet (maf) of storage were completed. In contrast, only 1,044 dams and 4.7 maf of storage were completed from 1991 to 1995 (U.S. Army Corps of Engineers, 1996). At this rate, the capacity to store water to protect against floods and droughts appears to be declining. Guldin (1989) estimated storage losses to sedimentation at 1.4 to 1.5 maf per year, or about 0.5 maf more than recent average annual additions to storage from new construction.

Proposed new large dam projects are often characterized by high costs, diminishing returns in a dam's ability to increase a water system's safe yield, and environmental 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 were the first to be developed, subsequent increases in storage require ever larger investments. There are also diminishing returns in the safe yield produced by successive increases in reservoir capacity within a basin. And the social 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).

For the first 75 years of the twentieth century, dams, reservoirs, and other water infrastructure were designed with a focus on extreme events such as the expected duration of severe droughts or the probable maximum flood (Hanchey et al., undated). This strategy of building redundancy into large water systems provided a cushion to deal with uncertainties such as climate change (Matalas and Fiering, 1977). However, the high costs and environmental concerns that now make it difficult to get a new project approved also make it likely that the projects that are undertaken will have less redundancy built into their water supply and control facilities (Frederick, 1991).

Alternatives for increasing freshwater supplies include recycling wastewater, desalting brackish water and seawater, weather modification to increase precipitation, and managing vegetation. 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).

Other 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 their quality, 36 percent of the nation's surveyed rivers and streams and 39 percent of the surveyed lakes, reservoirs, and ponds are impaired for one or more of their designated uses (U.S. EPA, 1998). Non-point pollutants are now the principal sources of surface water contamination and effective means of curbing many of these pollutants have yet to be developed or widely adopted. Threats to future water quality also include millions of underground tanks containing hazardous substances, landfills, abandoned waste sites, oil and gas brine pits, and the chemicals applied annually to the nation's croplands.

Climate change is also likely to affect water quality. Low streamflow conditions, storm surges, and water temperatures affect water quality and are susceptible to changes in the climate. Stream quality is often defined by conditions during critical low-flow periods when there is less water to dilute pollutant discharges, maintain dissolved oxygen levels, and support aquatic life. But current understanding of the hydrological impacts is insufficient to determine whether climate change would improve or worsen low-flow conditions. Likewise, the direction as well as the magnitude of the climate impacts on lake quality from changes in precipitation and evaporation rates is uncertain. However, climate-induced changes in storm surges and water temperatures are likely to have a negative impact on water quality. As noted above, a greenhouse warming may result in days with more intense precipitation in some regions, an outcome that is likely to increase the amount of agricultural and urban wastes washed by storm flows into rivers and lakes. Aquatic life could be threatened as these wastes degrade and reduce oxygen levels. Dissolved oxygen levels also tend to decline as temperatures rise because warmer water holds less oxygen. Although the environmental implications are not well understood, seasonal changes in air temperature and wind could alter the dynamics of temperature stratification and seasonal overturn of lakes and the extent of ice covering over some of the nation's northern lakes (Jacoby, 1990).

Groundwater accounted for 22 percent of total U.S. freshwater withdrawals in 1995 (Solley et al., 1998). In some areas, current levels of groundwater use are unsustainable. For example, declining aquifer levels, higher pumping lifts, and falling well yields have increased water costs in western Texas, causing farmers to take several million acres out of irrigation in recent decades. In California, groundwater overdrafts averaged nearly 1.5 maf yearly, equivalent to 4 percent of the state's total agricultural and urban use in 1995 (California Department of Water Resources, 1998). And pumping from coastal aquifers in California, Cape Cod, Long Island, New Jersey, and Florida has exceeded natural recharge, resulting in saltwater intrusion into the aquifers. Climate change could affect both the rate of groundwater withdrawals and the rate of aquifer recharge. For example, hotter and drier conditions would most likely increase withdrawals and decrease recharge, increasing the rate at which saltwater infiltrates into coastal aquifers. Sea-level rise associated with a greenhouse warming would also contribute to saltwater intrusion into coastal aquifers.

The socioeconomic impacts of a greenhouse warming look very different depending on whether the changed climate brings more water as projected by the Hadley climate model or less water as projected by the Canadian climate model. While the non-climate-related changes in water demand could be significant in some areas (as noted above), they may be overwhelmed by changes in water supplies as large as those indicated in Tables 1 and 2. But the regional supply-side uncertainties are huge. Some water-scarce regions could benefit from increased precipitation and runoff while others would be forced to adjust to less water.

On balance, hydrological change might be expected to have negative impacts, at least in the short term. Because current water-use patterns, infrastructure, and management practices are based on past hydrological conditions, changes in these conditions are likely to result in at least short-term adaptation costs.

## VIII. Adapting to Changing Supply and Demand Conditions

### A. Pressures on Water Resources

*Climate is just one of many factors challenging future water planners and managers.* Indeed, changes in population, economic conditions, technology, policies, and the relative value society places on alternative water uses may be more important determinants of future supply and demand conditions than those attributable to climate change (IPCC, 1996b; Frederick and Major, 1997). Climate changes will be imposed on top of these other long-term changes. Thus, even if the magnitude of climate change is less than the combined non-climate impacts — which is by no means certain — the marginal effect could be substantial and costly. Some recent work exploring these issues suggests that changes in flood risks from climate change are likely to be greater than the impacts caused by realistic land-use changes over the same period (Reynard et al., in press). Vulnerability, or the sensitivity and potential magnitude of damage associated with climate changes, may also be greatest for regions where current stress on water resources is high. Some recent efforts to develop vulnerability indicators are described below.

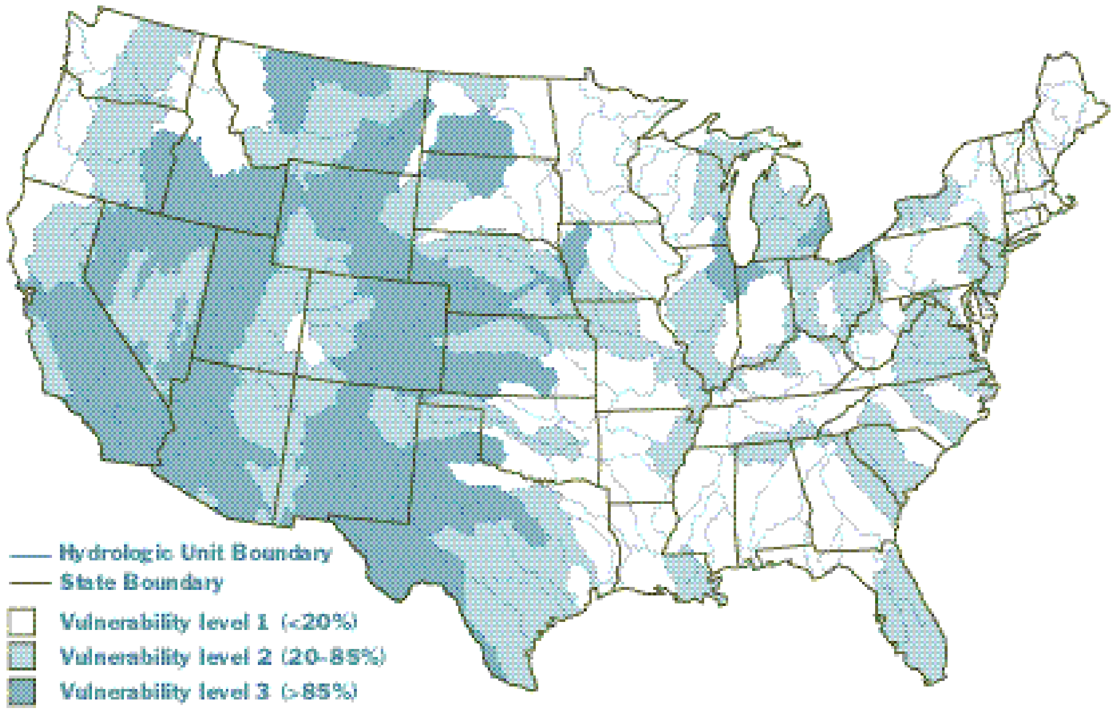
Climate change can be expected to affect a variety of human and ecological systems and cause changes in water supply and quality for drinking and irrigation; instream flows that support aquatic ecosystems, recreational uses, hydropower, navigation, and wastewater assimilation; wetland extent and productivity; and the frequency and severity of floods and droughts. Identifying regions where water resources are likely to be vulnerable to changes in climate will help water managers plan and prepare for such changes.

A variety of studies [e.g., Gleick (1990), Hurd et al. (1999), and Lane et al. (in press)] have examined indicators of regional water resource vulnerability. Figure 10 illustrates results for one of these indicators, termed Level of Water Development, which measures the ratio of current water use to mean annual unregulated streamflow. This indicator shows the interplay between resource scarcity and competing demands. Regions where water use is high relative to streamflow are potentially at risk to shifts in long-term climatic conditions. The results suggest that regions of the greatest vulnerability, as mea-

***Figure 10***

Level of **Water Development**

(share of available stream flow withdrawn for use)




Source: Hurd et al, 1999.

sured by this particular indicator, are clustered in the western United States. These regions, covering 20 percent of the United States, include the high irrigation areas along the eastern drainage of the Rocky Mountains, the Central Valley of California, and southern California. These regions withdraw more than 85 percent of their available streamflow and depend on storage to manage intra- and interannual variability.

As part of the U.S. Forest Service's periodic assessment of long-term resource supply and demand conditions, Brown (1999) has estimated water use for ten-year intervals to the year 2040 for 20 major 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 anticipated continued improvements in water-use efficiency encouraged by rising water costs. Under the middle population growth projection, total water use increases only 7 percent by 2040 despite a 41 percent increase in population. The implied reduction in per-capita withdrawals is largely attributable to two factors: continued improvements in water-use efficiency in municipal, industrial, and thermoelectric uses; and an 8 percent increase in total irrigated acreage with a relative geographic shift from west to east where less water is applied per acre (Brown, 1999). Even these relatively modest increases in withdrawals imply growing pressures on instream flows, especially if groundwater use is reduced to sustainable levels.

A greenhouse warming would alter both the water supply and demand conditions underlying Brown's projections. The socioeconomic implications of both climate and non-climate impacts on the supply and demand for water will depend in large part on society's ability to adapt to change and to eliminate current inefficiencies in the management and allocation of the resource.

## B. Adaptation

*The socioeconomic impacts of floods, droughts, and climate and non-climate factors affecting the supply and demand for water will depend in large part on how society adapts.* However, there is no strong consensus yet about the effectiveness of different coping and adaptation approaches to deal with future climate changes. One view holds that little needs to be done now because climate changes are highly uncertain; will manifest themselves slowly; and will be swamped by the many demographic, economic, and societal changes that will occur during the same period. This view also notes that a wide variety of tools are already available to water managers for dealing with risk and uncertainty, and that these tools will prove sufficient for coping with plausible impacts from future climate changes (Schilling and Stakhiv, 1998).

There is merit to this position, but some problems as well. The first problem is that along with the many remaining uncertainties about the details of climate change come potentially large risks. We are uncertain whether some climate changes will be rapid or whether some will be of such a large magnitude that they will overwhelm existing systems before current management approaches can react. As noted above, regional modeling studies suggest that even modest changes in climate can lead to changes in water availability outside the range of historical hydrologic variability. Because all of our water-supply systems were designed on the assumption that future climate would look like past climate, we cannot be certain that our existing systems and management methods will be adequate to deal with these changes. Another problem is that even if adaptation to different climatic conditions is possible, it may be very costly. Because these changes will be imposed on top of non-climatic changes, marginal costs may be very high. Finally, water managers have shown themselves reluctant to tackle this problem. They tend to be reactive, not proactive. As Schilling and Stakhiv (1998) note, water managers are technical and empirical pragmatists. They are trained to react to real events, and their tools of choice are physical rather than economic or institutional. The real uncertainties about future climate are significant barriers to action.

Despite the optimism of many water managers that existing systems will be adequate to deal with the risks imposed by climate change, current policies affecting water use, management, and development are often unresponsive to changing conditions. In the absence of institutional changes, the costs of these inefficiencies most likely will rise as water becomes scarcer and supply and demand conditions change.

Progress is being made. The American Water Works Association (AWWA), the nation's largest organization of water utilities, published a list of common-sense recommendations for water managers. Among other things, AWWA called for a re-examination of design assumptions, operating rules, and contingency planning for a wider range of climatic conditions than traditionally used (AWWA, 1997) (see Box 3). Isolated examples exist of water agencies or river basin commissions actually evaluating their vulnerabilities to possible future climatic changes [see, for example, Boland (1998) and Steiner (1998)]. But these examples are the exception rather than the norm.

There are opportunities for reducing the costs and conflicts of supplying future water demands and adapting to climate variability and change. Of particular promise are (1) establishing incentives for using, conserving, and protecting supplies; (2) providing opportunities for transferring water among competing uses in response to changing supply and demand conditions; (3) influencing how water is managed within and among basins; and (4) evaluating how "reoperating" existing infrastructure can help address possible changes. The potential to reduce costs and conflicts and move toward a more sustainable water future through non-structural economic, institutional, and technological changes has been documented in a recent study directed by Owens-Viani and others (1999) of 40 California water success stories.

*Box 3*

### Summary of Recommendations for Water Managers from the AWWA's Public Advisory Committee

- 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 climatic conditions than traditionally used.
- Water agencies and providers should explore the vulnerability of both structural and non-structural water systems to plausible future climate changes, not just past climatic variability.
- Governments at all levels should re-evaluate legal, technical, and economic approaches for managing water resources in the light of possible climate changes.
- Water agencies should cooperate with leading scientific organizations to facilitate the exchange of information on the state-of-the-art thinking about climatic 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.

Source: AWWA, 1997.

Water-use efficiency improvements are increasingly seen as a major — if not the major — tool for meeting future water needs in water-scarce regions where extensive infrastructure already exists. Such improvements can be made faster and more cheaply, with fewer environmental and ecological impacts, than continued investment in new supply. Some studies have recently begun to explore how effective such improvements 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 impacts of climate change on regional water supplies.

Prices and markets are also increasingly important for balancing supply and demand. Prices provide incentives to use less and produce more, and markets enable resources to move from lower- to higher-value uses as conditions change. In spite of their potential advantages, prices and markets have been slow to develop as tools for adapting to changing supply and demand conditions. Water remains underpriced and market transfers have been inhibited by institutional factors.

Water marketing, the voluntary transfer of water rights to new uses and users, has great potential to increase water-use efficiency (National Research Council, 1992; Western Water Policy Review Advisory Commission, 1998). However, both the nature of the resource and the institutions established to control it have inhibited water marketing. Efficient markets require that buyers and sellers bear the full costs and benefits of transfers. But when water is transferred, third parties are likely to be affected. The 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). Providing water for uses such as fish and wildlife habitats where the benefits accrue to the public at large rather than to individuals is another area in need of some form of government intervention. The federal government as well as some state governments have been acquiring water for environmental purposes such as preserving endangered species (Simon, 1998).

In spite of the obstacles, the potential gains to transfers are breaking down many of the barriers 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 1991, 1992, and 1994 helped mitigate the impacts of a prolonged drought by facilitating water transfers among willing buyers and sellers. 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 sustained changes in climate. At some point, the historical allocation of water becomes sufficiently imbalanced to warrant a permanent transfer of water rights. The prospect that neighboring watersheds and states will be affected 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 and other constraints to moving water across hydrologic and political boundaries remains slow, costly, and contentious.

As institutional mechanisms for marketing or trading water are explored, the other major coping strategy will be to re-evaluate the ability of our existing infrastructure to reduce climate-related risks. The United States has an enormous investment in dams, reservoirs, aqueducts, water treatment facilities, and other structures. Managers are beginning to explore how different operating rules and regimes might reduce future climate risks. But until the science can provide better information as to the timing and nature of the changes at the geographic scales of interest to water managers, climate change will have little impact on operations. These uncertainties are also obstacles to introducing climate impacts into investment decisions. Maintaining options and building in dynamic flexibility are important for designing efficient water programs in the context of climate change. New dams and other water-related infrastructure may eventually be needed to help adapt to climate change. However, when possible, costly and irreversible decisions to build new infrastructure should be postponed in anticipation of obtaining better information about the likely impacts of a greenhouse warming. It is also important to note that climate impacts and potential responses for the United States may be very different for other parts of the world (see Box 4).

***Box 4***

## Some Observations about Impacts and Responses for Other Parts of the World

- Climate impacts will vary enormously in different parts of the world. Precipitation and temperature patterns must be evaluated separately on a regional basis.
- The only way to evaluate the impacts of climate changes on floods, droughts, and water systems is to do specific regional modeling and assessment.
- Climate impacts and responses will depend not only on how climate dynamics change but also on a host of economic, social, and political conditions.
- The effectiveness of various adaptation and mitigation methods depends critically upon the intellectual and economic capital available and the nature of physical infrastructures in a region. Strong scientific and engineering capacity will be a great advantage. But regions with little or no existing water infrastructure will be more sensitive to climatic changes and altered variability and will have fewer alternatives for responding.

## IX. Conclusions

*1. Global climatic changes will have major effects on precipitation, evapotranspiration, and runoff.* Estimating the nature, timing, and even the direction of the impacts at the regional and local scales of primary interest to water planners and managers involves many uncertainties.

*2. Among the most significant uncertainties are the changes in precipitation and runoff projected by large-scale general circulation models.* Looking at the output from the GCMs being evaluated for the National Assessment, the Canadian and Hadley GCMs, shows that the two models give very different answers. Results based on these kinds of GCM outputs as well as more detailed regional studies emphasize two points: the impacts of climatic changes on future water supplies are uncertain, and runoff is sensitive to changes in temperature and precipitation.

*3. Uncertainties also exist in translating large-scale climatic changes into specific regional impacts because of problems with models and data, and because many of the human impacts will depend on economic, technological, and institutional factors that help define our water system.*

*4. In spite of the many uncertainties, some consistent robust results can be described.* In the arid and semiarid western United States, relatively modest changes in precipitation can have disproportionally large impacts on water supplies. In mountainous watersheds, higher temperatures will increase the ratio of rain to snow, accelerate the rate of spring snowmelt, and shorten the overall snowfall season, leading to more rapid, earlier, and greater spring runoff.

*5. Climate change will affect the demand as well as the supply of water and may influence a wide range of water-system components, including reservoir operations, water quality, hydroelectric generation, and navigation.* Irrigation, the largest consumer of U.S. water, is particularly sensitive to climate conditions. Instream water uses such as hydroelectric power generation, navigation, recreation, and ecosystem maintenance are also sensitive to changes in the quantity, quality, and timing of runoff likely to result from climatic changes.

*6. Climate-induced changes in hydrological conditions will affect the magnitude, frequency, and costs of future extreme events.* Recent reports suggest that climate changes are likely to increase the number of intense precipitation days and flood frequencies in northern latitudes and snowmelt-driven basins. On the other hand, the frequency and severity of droughts could increase in some areas as a result of a decrease in total rainfall, more frequent dry spells, and greater evapotranspiration.

*7. Potential negative implications of climate change for water quality include reductions in streamflows, increased storm surges, and higher water temperatures.* An increase in intense precipitation days could increase the agricultural and urban pollutants washed into streams and lakes, and sea-level rise would contribute to saltwater intrusion into rivers, estuaries, and coastal aquifers.

*8. The socioeconomic implications of both climate and non-climate impacts on the supply and demand for water will depend in large part on the ability of water-management systems to adapt to change and to eliminate current inefficiencies in managing and allocating the resource.*

*9. Data and modeling uncertainties are not justifications for delays in taking specific actions and for planning for altered climatologic conditions. Water managers already have a wide variety of tools available for dealing with hydrologic risk and uncertainty.* It is unclear whether some climate changes will be rapid or of such large magnitude as to overwhelm existing systems before current management approaches can react. These uncertainties suggest the wisdom of re-examining design assumptions, operating rules, and contingency planning for a wider range of climate conditions than traditionally used. Maintaining options and building in dynamic flexibility are important for designing efficient water programs in the context of climate change. New dams and other water-related infrastructure may eventually be needed to help adapt to climate change. However, when possible, costly and irreversible decisions on new infrastructure should be postponed in anticipation of obtaining better information about the likely impacts of the greenhouse effect.

## Endnotes

1. A searchable, comprehensive bibliography of the literature is available at www.pacinst.org (see also Chalecki and Gleick, in press).

2. For general information about the National Assessment of the Impacts of Climate Change and Variability on the United States, visit www.nacc.usgcrp.gov. More detailed information about the impacts of climate change on water resources of the United States will be available when the water sector report of the National Assessment is completed in early 2000.

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