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Water Resources and Climate Change

Kenneth Frederick ◆ June 1997

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WATER RESOURCES AND CLIMATE CHANGE

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INTRODUCTION

Human efforts to alter the hydrological cycle date back to ancient times. Prayer, dances, human and animal sacrifices, and other rituals have been tried to bring rain. Cloud seeding is a more scientific, but still uncertain, attempt to induce precipitation. Although it is questionable whether any of these *intentional* efforts have significantly altered precipitation patterns, the balance of evidence now suggests that humans are influencing the global climate and, thereby, altering the hydrological cycle, however *inadvertently*.

The most recent scientific assessment by the Intergovernmental Panel on Climate Change (IPCC) concludes that, since the late 19th century, anthropogenically induced emissions of gases such as carbon dioxide (CO_2) that trap heat in the atmosphere in the manner of a greenhouse have contributed to an increase in global mean surface air temperatures of about 0.3 to 0.6^{o}C. Moreover, based on the IPCC's mid-range scenario of future greenhouse gas emissions and aerosols and their best estimate of climate sensitivity, a further increase of 2^{o}C is expected by the year 2100. The purpose of this paper is to examine the likely impacts of a greenhouse warming on the supply and demand for water and the resulting socioeconomic implications.

CLIMATE IMPACTS ON WATER SUPPLIES

IPCC results

Hydrological changes associated with a greenhouse warming -- whether it will rain more or less, for instance -- are more speculative than temperature projections, especially at the regional and local geographic scales of interest to water planners. The most recent IPCC analysis suggests that a greenhouse warming will have the following effects on water supplies.

- The timing and regional patterns of precipitation will change, and more intense precipitation days are likely.

- General circulation models (GCMs) used to predict climate change suggest that a 1.5 to 4.5^{o}C rise in global mean temperature would increase global mean precipitation about 3 to 15 percent.

- Although the regional distribution is uncertain, precipitation is expected to increase in higher latitudes, particularly in winter. This conclusion extends to the mid-latitudes in most GCM results.

- Potential evapotranspiration (ET) -- water evaporated from the surface and transpired from plants -- rises with air temperature. Consequently, even in areas with increased precipitation, higher ET rates may lead to reduced runoff, implying a possible reduction in renewable water supplies.

- More annual runoff caused by increased precipitation is likely in the high latitudes. In contrast, some lower latitude basins may experience large reductions in runoff and increased water shortages as a result of a combination of increased evaporation and decreased precipitation.

- Flood frequencies are likely to increase in many areas, although the amount of increase for any given climate scenario is uncertain and impacts will vary among basins. Floods may become less frequent in some areas.

- 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 higher ET.

- The hydrology of arid and semiarid areas is particularly sensitive to climate variations. Relatively small changes in temperature and precipitation in these areas could result in large percentage changes in runoff, increasing the likelihood and severity of droughts and/or floods.

- Seasonal disruptions might occur in the water supplies of mountainous areas if more precipitation falls as rain than snow and if the length of the snow storage season is reduced.

- Water quality problems may increase where there is less flow to dilute contaminants introduced from natural and human sources.

Regional uncertainties

Even the direction of regional changes in precipitation and runoff are uncertain. The American Association for the Advancement of Science Panel on Climate Variability, Climate Change and the Planning and Management of US Water Resources estimated the range of regional equilibrium values (neglecting transient delays and adjustments) for an equivalent doubling of CO_2 from preindustrial levels as -3 to +10^{o}C for temperature, -20 to +20 percent for precipitation, -10 to +10 percent for evapotranspiration, and -50 to +50 percent for runoff. Subsequent advances in global climate modeling have done little to reduce the uncertainty regarding the impacts of increasing atmospheric greenhouse gases on regional water supplies.

Changes in runoff, the source of a region's renewable water supply, are the direct result of changes in precipitation and evaporation (which is strongly influenced by temperature). Studies simulating the effects of climate changes on hydrologic processes have been performed for a number of river basins and subbasins. While these studies estimate the impacts on water resources, they offer no guidance as to the likelihood that the assumptions underlying the modeling will be realized. Nevertheless, these studies are instructive as to the possible magnitude of, and the uncertainty surrounding, the hydrological implications of a greenhouse warming.

Estimates of the impacts of alternative temperature and precipitation changes on annual runoff in several semiarid rivers are presented in Table 1. These simulation studies suggest that relatively small changes in temperature and precipitation can have large effects on runoff. With no change at all in precipitation, estimated runoff declines by 3 to 12 percent with a 2^{o} C increase in temperature; with a 4^{o} C increase, runoff declines by 7 to 21 percent simply because of more evaporation. Although runoff is generally more sensitive to changes in precipitation than to temperature, a 10 percent increase in precipitation does not fully offset the negative impacts on runoff attributable to a 4^{o} C increase in temperature in three of the five rivers for which this climate scenario was studied.

The IPCC's review of climate impact studies suggests large differences in the vulnerability of water resource systems to climate variables. Isolated single-reservoir systems in arid and semiarid areas are extremely sensitive; they lack the flexibility to adapt to climate impacts that could vary from decreases in reservoir yields in excess of 50 percent at one extreme to increased seasonal flooding at the other. In contrast, highly integrated systems are inherently more robust. A set of studies undertaken largely in the United States and based on the most recent transient GCM simulations suggests that most of these integrated systems are sufficiently robust and resilient and possess adequate institutional capacity to adapt to likely changes not only in the climate but in such factors as economic and population growth. Much of the world's water, however, is managed through single-source, single-purpose systems.

Uncertainties as to how the climate and hydrology of a region will change in response to a global greenhouse warming are enormous. However, one of the more likely impacts involves areas where precipitation currently comes largely in the form of winter snowfall, and where streamflow comes largely from spring and summer snowmelt. A warming would likely result in a distinct shift in the relative amounts of snow and rain and in the timing of snowmelt and runoff. A shift from snow to rain could increase the likelihood of flooding early in the year and reduce the availability of water during periods of peak demand, especially for irrigation. Many of the basins in the western United States are vulnerable to such changes.

Table 1: Impacts of climatic changes on mean annual runoff in semiarid river basins

Precipitation Change		Temperature Change: T+2°C	T+4°C
		Change in Mean Annual Runoff	
-10%	Great Basin Rivers [1]	-17 to -28%	
	Sacramento River [2]	-18%	-21%
	Inflow to Lake Powell [3]	-24%	-32%
	White River	-13%	-17%
	East River	-19%	-25%
	Animas River	-17%	
0	Sacramento River	-3%	-7%
	Inflow to Lake Powell	-12%	-21%
	White River	-4%	-8%
	East River	-9%	-16%
	Animas River	-7%	-14%
+10%	Sacramento River	+12%	+7%
	Inflow to Lake Powell	+1%	-10%
	White River	+7%	+1%
	East River	+1%	-3%
	Animas River	+3%	-5%

Notes: [1] All Great Basin Rivers results from Flaschka, et al., 1987.
[2] All Sacramento River results from Gleick, 1986, 1987.
[3] All Lake Powell, White, East, and Animas River results from Nash and Gleick, 1993.

Source: Adapted from Nash and Gleick, 1993.

Sea level rise

Sea levels rising in response to thermal expansion of the oceans and increased melting of glaciers and land ice will also affect water availability. The global sea level increased about 18 cm (7 inches) during the past century. The most recent IPCC results suggest average sea level might rise another 15 to 95 cm (6 to 37 inches) by the year 2100, with a best guess of about 50 cm (20 inches).

Higher sea levels and increased storm surges could adversely affect freshwater supplies in coastal areas. Salt water in river mouths and deltas would advance inland and coastal aquifers would face an increased threat of saltwater intrusion, jeopardizing the quality of water for many domestic, industrial, and agricultural users. For example, sea level rise would aggravate water-supply problems in several coastal areas in the United States, including Long Island, Cape Cod, New Jersey shore communities, and the Florida cities of Miami, Tampa, and Jacksonville.

Rising sea level also threatens critical freshwater supplies in California. The Sacramento-San Joaquin Delta, for example, which is already under stress, is a major source of water for the farms and cities of southern California and the San Joaquin Valley. It is also the habitat for scores of fish species, several of which have been so weakened by the diversion and degradation of delta water that they have either been granted protection or are being considered for listing under the federal Endangered Species Act. Saltwater intrusion from San Francisco Bay threatens the delta’s ecology as well as its use as a freshwater source. Over the last century, sea level rise in conjunction with ground subsidence in the delta has exacerbated these water supply and environmental problems.

Limiting the intrusion of saltwater depends on sufficient freshwater flows from the delta to the bay and on maintaining the levees that protect the more than 500,000 acres of islands within the delta. These islands are now rich farmlands created out of the marshland that originally characterized much of the delta. Gradual compaction of the delta’s peat soils has caused many of the islands to fall well below sea level. When a levee breaks, as happens on average about twice a year, freshwater (that would otherwise help prevent saltwater from entering into the delta) floods onto the land. Any wide-scale failure of these levees thus would increase salinity levels, threatening the ecosystem and water for the farms and cities to the south. As the level of the sea rises, additional scarce freshwater supplies are required to prevent saltwater intrusion into the delta; maintaining the more than 1,100 miles of levees becomes increasingly difficult and expensive as well.

Carbon dioxide effects

A growing body of research suggests that atmospheric carbon dioxide levels may affect water availability through its influence on vegetation. Controlled experiments indicate that elevated CO_2 concentrations increase the resistance of plant “pores,” that is stomata, to water vapor transport. Experiments suggest that a doubling of CO_2 would increase stomatal resistance and reduce the rate of transpiration -- the passage of water vapor from plants -- by about 50 percent on average. The resulting decrease in transpiration would tend to increase runoff. On the other hand, CO_2 also has been demonstrated to increase plant growth, leading to a larger area of transpiring tissue and a corresponding increase in transpiration. Other factors that might offset increases in plant water-use efficiency associated with a CO_2-enriched atmosphere are a potential increase in leaf temperatures caused by reduced transpiration rates and species changes in vegetation communities. The net effect of opposing influences on water supplies would depend on the type of vegetation and other interacting factors, such as soil type and climate.

CLIMATE IMPACTS ON WATER DEMAND

Precipitation, temperature, and carbon dioxide levels can affect the demand for water as well as the supply.

Irrigation

Irrigation, the most climate-sensitive use of water, accounts for 41 percent of all water withdrawn from ground and surface sources in the United States and 81 percent of consumptive use (that part of the water withdrawn that is evaporated, transpired, incorporated into crops, or otherwise removed from the immediate water supply). In the seventeen water-scarce western states these percentages rise to 77 percent and 85 percent, respectively.

The yields and profitability of irrigated relative to dryland farming tend to increase as conditions become hotter and drier. Consequently, in areas with available and affordable water supplies, hotter and drier conditions would increase both the land under irrigation and the amount of water applied per irrigated acre. Increased water use efficiency attributable to higher atmospheric CO_2 levels would tend to counter the tendency to apply more water as temperatures rise.

Gregory McCabe and David Wolock of the U.S. Geological Survey used an irrigation model to simulate the effects of hypothetical changes in temperature, precipitation, and stomatal resistance (to illustrate the effects of changes in atmospheric CO_2 concentrations) on irrigation demand. Their results, which are based on annual plant water use in a humid-temperate climate, suggest that increases in mean annual irrigation demand are strongly associated with increases in temperature and less strongly associated with decreases in precipitation. When temperature and precipitation were the only changes, irrigation demand increased with a 2^{o} C warming, even with 20 percent more precipitation. Plant water use is even more sensitive to changes in stomatal resistance than to temperature. For instance, a

20 percent increase in stomatal resistance reduced irrigation demand with a 2° C warming and no change in precipitation.

Domestic use

Water for normal household purposes -- drinking, preparing food, bathing, washing clothes and dishes, flushing toilets, and watering lawns and gardens -- accounts for 8 percent of withdrawals and 6 percent of consumptive use in the United States. Water demands for gardening, lawn sprinkling, and showering are the most sensitive of these uses to climate changes.

Aggregate annual domestic water use is not very sensitive to changes in temperature and precipitation; estimates suggest that a 1 percent rise in temperature would increase use from 0.02 to 3.8 percent and a 1 percent decrease in precipitation would increase residential water use from 0.02 to 0.31 percent. Nevertheless, because they are likely to be greatest during the seasons and years when supplies are under the most stress, climate-induced increases in domestic demand can aggravate the problems of balancing supplies with demands during drought.

A study of urban water use in four mountainous counties of Utah illustrates how climate variables can increase domestic water demands when supplies are likely to be scarcest. This study found that potential evapotranspiration and rainfall best explain changes in residential water use attributable to the climate. Higher evapotranspiration attributable to a temperature rise of about 2.2° C (4° F) increased residential water demand by an estimated 2.8 percent during the summer season and by as much as 8 percent during the month of June, when supplies in the region are likely to be in short supply. A temperature increase of 4.4° C (8° F) increased demand by 5 percent in the summer and as much as 16 percent in June.

Industrial and thermoelectric power uses

Industrial use -- which includes water for purposes such as processing, washing, and cooling in facilities that manufacture products -- accounts for 7 percent of withdrawals and 4 percent of consumptive use in the United States. Thermoelectric power use -- which includes water for cooling to condense the steam that drives the turbines in the generation of electric power with fossil fuel, nuclear, or geothermal energy -- accounts for 39 percent of all withdrawals but only 4 percent of consumptive use in the United States.

A rise in water temperature would reduce the efficiency of cooling systems, contributing to an increased demand for cooling water. Since more than 95 percent of the freshwater withdrawn for industrial and thermoelectric power use is now returned to ground and surface water sources, this increased demand would not represent a major increase in consumptive use. But if aquatic ecosystems were threatened by higher water temperatures resulting from either a global warming or from warmed-up returnflows of water used for cooling, these uses might be subjected to more stringent environmental regulations.

Stricter regulations on returnflows might prompt a switch from once-through cooling systems to cooling towers and ponds that return little or no water to the source. Such a shift would reduce withdrawals and returnflows but have little effect on consumptive water use. Evaporative losses occur on site with cooling towers and ponds. In a once-through system more of the evaporation occurs off-site and is attributable to the increased temperature of the receiving water body.

Global warming would also have indirect effects on industrial and thermoelectric water use. For instance, summer energy use for air conditioning would rise, and winter demand for space heating would decline. Changes in the temporal and perhaps the spatial demand for energy would alter the demand for cooling water.

Instream uses

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. These changes might also affect instream water demands, directly or indirectly. For example, changes in streamflows would alter actual and potential hydroelectric power generation, which in turn would affect the demand for substitute sources of electricity. Since thermoelectric cooling is one of the largest withdrawal uses of water, shifts in hydroelectric power production could have a significant impact on the demand for water within a watershed.

A warming would increase the potential length of the navigation season on some northern lakes and rivers that typically freeze in winter. To the extent that lake depth and river flow are constraints on navigation, demand could increase 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.

During the last quarter century, public policy has shifted from one that encouraged withdrawal uses at the expense of aquatic ecosystems to one that has emphasized protecting instream flows and recovering some of the recreational and environmental benefits that had been sacrificed under the earlier policy. Aquatic ecosystems and the benefits they provide are vulnerable to hydrological shifts that could result from a greenhouse warming, especially if the major burden of adaptation falls on streamflows. Maintaining minimum instream flows to protect an endangered species or recreation benefits when supplies become scarcer requires major adjustments in the use of water. On the other hand, protecting offstream uses could threaten the sustainability of some aquatic ecosystems. Tradeoffs between instream and withdrawal water uses would increase if water supplies became scarcer or more variable as a result of climate change.

SOCIOECONOMIC IMPACTS AND POLICY IMPLICATIONS

Climate is only one of many factors influencing the future supply and demand for water. Indeed, population, technology, economic conditions, social and political factors, and the values society places on alternative water uses are likely to have more of an impact on the future availability and use of water than changes in the climate. Even in the absence of human-induced changes in the climate and hydrological cycle, there is cause for concern over the adequacy of water supplies. Demands are outpacing supplies, water costs are rising sharply, and current uses are depleting or contaminating some valued resources. Climate change has the potential to either aggravate or alleviate an area's water situation. On balance, however, the impacts are likely to be adverse because the existing water infrastructure and use are based on an area's past climate and hydrology.

During most of this century, dams, reservoirs, pumps, canals, and levees provided the primary means of adapting to climate and hydrological variability and meeting the growing demands for water. While the focus was on supply-side solutions, institutions that establish opportunities as well as incentives to use, abuse, conserve, or protect water resources were slow to adapt to the challenges of growing scarcity, rising instream values, and the vulnerability and variability of supplies. In recent decades, however, the high financial and environmental costs of water projects, along with limited opportunities for building additional dams and reservoirs to develop new water supplies, have shifted the focus away from new construction to improved management of existing supplies and facilities, and also toward demand management.

New infrastructure may, in some instances, eventually prove to be an appropriate response to climate-induced shifts in hydrological regimes and water demands. But it is difficult to plan for and justify expensive new projects when the magnitude, timing, and even the direction of the changes at the basin and regional levels are unknown. Narrowing the range of uncertainty for improved water planning depends on a better understanding of (1) the processes governing global and regional climates; (2) the links between climate and hydrology; (3) the impacts of the climate on unmanaged ecosystems; (4) the impacts of ecosystem changes on the quantity and quality of water; and (5) the impacts of increased atmospheric CO_2 on vegetation and runoff. In the meantime, the possibility that a warming could result in greater hydrological variability and storm extremes should be considered in evaluating margins of safety of long-lived structures such as dams and levees that are under consideration anyway. In particular, low-cost structural and managerial modifications that ensure against the possibility of a range of climate-induced impacts should be sought.

More importantly, the prospect that a global warming will alter in unknown ways local and regional supplies and demands reinforces the need for institutions that facilitate adaptation to whatever the future brings and promote more efficient water management and use. Unlike the structural supply-side approach, demand management that introduces incentives to conserve and opportunities to reallocate supplies as conditions change does not require long lead times, large financial commitments, or accurate information about the future climate.

Although likely to rise in the future, the magnitude and nature of water costs will be determined by the policies adopted to deal with all of these challenges. Critical determinants of future water costs will be the efficiency with which supplies are managed, how they are allocated among competing uses, and the effectiveness and costs of efforts to protect aquatic environments and drinking water quality. Integrated management of existing supplies and infrastructure at the river basin and watershed levels offers a potentially cost-effective means of increasing reliable supplies and resolving water conflicts in many regions. Providing appropriate incentives to conserve and protect the resource and opportunities to voluntarily reallocate supplies (subject to consideration of third-party impacts) in response to changing conditions would assure supplies to those purposes we value most highly. Measures required to achieve this objective include elimination of subsidies for the use of federally supplied irrigation water; pricing water at its social cost; establishing well-defined, transferable property rights in water; and creating water banks and other institutions to facilitate voluntary water transfers. While the prospect of climate change adds another element of uncertainty to the challenge of matching future supplies with demands, it does not alter what needs to be done to ensure that water is managed and apportioned wisely.

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FURTHER READING

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About RFF

Resources for the Future (RFF) is an independent, nonprofit research organization that aims to help people make better decisions about the conservation and use of their natural resources and the environment. For the past 45 years, researchers at RFF have conducted environmental economics research and policy analysis involving such issues as forests, water, energy, minerals, transportation, sustainable development, and air pollution. They also have examined, from a variety of perspectives, such topics as government regulation, risk, ecosystems and biodiversity, climate, hazardous waste management, technology, and outer space.

While many RFF staff members are economists by training, other researchers hold advanced degrees in ecology, city and regional planning, engineering, American government, and public policy and management. RFF neither lobbies nor takes positions on specific legislative or regulatory proposals. Its operating budget is derived in approximately equal amounts from three sources: investment income from a reserve fund; government grants; and contributions from corporations, foundations, and individuals (corporate support cannot be earmarked for specific research projects). Some 45 percent of RFF's total funding is unrestricted.

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About RFF's Climate Issues Briefs

As decisionmakers prepare for domestic policy debates and the ongoing international negotiations under the Framework Convention on Climate Change, RFF's climate issues briefs provide topical, timely, and non-technical information and analysis. They are intended to integrate the various aspects of climate change with critical reviews of existing literature and original research at RFF on climate policy, energy markets, water and forest resource management, technological change, air pollution, and sustainable development.

Forthcoming briefs will examine issues related to domestic emissions trading programs; the scheduling of emissions reductions over time; the potential for technical innovation to substantially lower the cost of limiting greenhouse gases; and different modeling approaches for assessing the economic costs of limiting emissions of greenhouse gases.

About RFF's Climate Economics and Policy Program

As international debate intensifies over possible agreements to limit emissions of greenhouse gases, Resources for the Future (RFF) launched its Climate Economics and Policy Program in October 1996 to increase understanding and knowledge of the complex issues that must be addressed to design appropriate domestic and international policies that are effective, reliable, and cost-efficient. The program responds to both the long-term debate about climate change, and the specific debates surrounding the negotiations being carried out under the United Nations Framework Convention on Climate Change.

The publication of the Second Assessment Report of the Intergovernmental Panel on Climate Change signaled the beginning of a broader agenda of research and debate on global climate change. While there is still scientific uncertainty about the magnitude of climate change risks, the world's policy makers are now shifting more of their attention to debating appropriate policy responses.

RFF brings a well recognized and respected reputation for objectivity to this debate. The Climate Economics and Policy Program integrates the many different aspects of climate change with ongoing basic and applied research at RFF involving energy markets, water and forest resource management, air pollution, environmental regulation, and sustainable development.

PROGRAM AREAS. Drawing on RFF's strengths in environmental and natural resource assessment, economic analysis, and policy design, the climate program focuses on five main areas:

- Economic and environmental consequences of climate change and policies to deal with climate change.
- Domestic and international policy design issues.
- Interactions between climate change and other policies.
- Equity, efficiency, and other criteria used in decisionmaking.
- Development of analytical tools.

PROGRAM OUTPUTS. RFF's climate program includes original basic and applied research, policy analysis, and educational outreach.

Research. Integrating basic and applied research on the economic implications of global climate change with ecological, engineering, scientific, environmental health, geographical, international, and other considerations, an initial set of research projects underway at RFF include:

- Bringing Uncertainty into the Equation When Calculating Climate Change Risks
- Discounting in Intergenerational Decisionmaking (workshop)
- Economic Analysis of Greenhouse Gas Emissions Trading
- Effective Environmental Policy in the Presence of Distorting Taxes
- Electricity Restructuring and the Costs of Controlling CO_2
- Environmental Consequences of Tax System Reform
- Impacts of Climate Change Mitigation on Other Environmental Problems
- Importance of Technical Change in the Economics of Carbon Policy (workshop)
- International Cooperation for Effective and Economic Greenhouse Gas Limitation
- Vulnerability of Low-Income Households to the Hydrologic Effects of Climate Change

Policy analysis. As a response to questions arising in the ongoing international negotiations, RFF will issue a series of short papers on a variety of issues related to policy in 1997. These studies will be based on original research combined with critical reviews of existing literature. Potential questions to be addressed include:

- How should the climate problem be thought about in general?
- How might a domestic emissions trading program be established?
- How does the performance of revenue-raising and non-revenue-raising policy instruments compare?
- How should emissions reductions be scheduled over time?
- What is the potential for technical innovation to substantially lower the cost of greenhouse gas limitations, and what government policies can tap that potential?
- What are the strengths and weaknesses of different modeling approaches for assessing the economic costs of greenhouse gas limitations?

Educational outreach. RFF regularly shares its climate change findings with members of the academic, business and environmental communities, and representatives of local, national and international governments by publishing and disseminating discussion papers and convening educational forums on selected topics. To support a well-informed public, RFF provides regular reports of its climate change activities to the news media, posts program updates and activities on RFF’s internet home page (http://www.rff.org), and will provide educational materials for lay audiences on the economics of climate change.

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