Global Climatic Changes: A Summary of Regional Hydrological Impacts

Since higher concentrations of CO_2 and trace gases alter the atmosphere's radiative balance, their effects on climate, hydrologic balance and water resources must be determined.

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Concern over global climatic changes caused by growing atmospheric concentrations of primarily carbon dioxide (CO_2) and other trace gases — such as nitrous oxide (N_2O), methane (CH_4) and chlorofluorocarbons (CFCs) — has increased in recent years as our understanding of atmospheric dynamics and global climate systems has improved. These gases can alter the heat balance of the earth by retaining longwave radiation that would otherwise be lost through the earth's atmosphere to space. This effect, known colloquially as the "greenhouse effect," gained widespread public attention in 1988 after a series of unusually warm years were attributed to rising concentrations of these greenhouse gases.[1]

Despite recent improvements in our understanding of atmospheric dynamics and large-scale climatic processes, the climatic effects of greenhouse gases are still only partially understood. One of the most important consequences of future changes in climate will be alterations in regional hydrologic cycles and the subsequent effects on the quantity and quality of regional water resources. However, the full effects of these consequences are poorly understood.

Most recent hydrological research suggests that climatic changes that are caused by increases in atmospheric trace-gas concentrations will alter the timing and the magnitude of runoff and soil moisture, change lake levels and groundwater availability, and affect water quality. Any or all of these effects could lead to environmental and socioeconomic dislocations, and they have widespread implications for future water resources planning and management.

Fundamental questions have yet to be answered about how greenhouse warming will alter regional precipitation patterns, and how water availability and quality will be affected. Very few watersheds have been studied in detail using appropriate models or methods. Little work has been done on the interactions among climate, vegetation responses and water resources. The role of management in mitigating the impacts on water resources has been inadequately assessed. Questions remain about the implications of climatic change for shared international rivers. And the role of international water law and water treaties in resolving climate-induced disputes is still unresolved. These issues are of great importance to society if critical impacts are to be identified and if concerted efforts are to be made in order to reduce the negative consequences of climatic changes.

Methods of Analysis

Novaky *et al.*[2] and Beran[3] distinguish between hydrology and water resources. Both sources consider hydrology to be the science of the hydrologic regime and water resources refers to the quantity and quality of water available at a particular time and place. Thus, hydrologists are interested in the effects of climatic changes on precipitation, runoff, soil moisture and the statistics of water availability, whereas water-resource planners are more interested in the effects of climatic changes on municipal water supplies, hydroelectricity production, reservoir design and management, reliable yield and irrigation requirements.

Three steps are required to evaluate the implications of climatic changes for water:

1. Develop quantitative scenarios of changes in major climatic variables such as temperature, precipitation and evapotranspiration.
2. Simulate the hydrologic cycle for a basin of interest, using the scenarios developed in the first step.
3. Assess the implications of the hydrologic variations identified in the second step for the performance of such water-resource systems as dams, aqueducts, reservoirs, groundwater-recharge basins, and so on.

Accurate quantitative estimates of the changes in major long-term climatic variables such as air temperature, precipitation, evapotranspiration and vegetation types and distributions are needed in order to provide accurate forecasts of water availability and quality. Unless reliable climate forecasts can be produced by climatologists, the predictive value of all hydrologic assessments are necessarily limited.

Development of Climate Scenarios

To assess the implications of the greenhouse effect for water resources, regional details of future changes are needed for temperature, precipitation, evaporation, wind speed, and other hydroclimatological variables. The ability to predict these details, however, is limited, and therefore climate scenarios must be employed. Such scenarios should be internally-consistent pictures of future conditions, and they can be constructed by a number of methods, including the direct use of general circulation models, paleoclimatic reconstructions, recent historical climate analogues, or purely hypothetical climatic scenarios.[4]

Direct Use of General Circulation Models

Much of the effort of trying to understand climate has focused on the development of computer models of the many intricate and intertwined phenomena that make up the climate. The most complex of these models, typically referred to as *general circulation models* or *global climate models* (GCMs), are detailed, time-dependent, three-dimensional numerical simulations that include atmospheric motions, heat exchanges and important land-ocean-ice interactions.[5–20]

General circulation models currently provide the best information on the response of the atmosphere to increasing concentrations of greenhouse gases. Data produced by using these models indicate, among other conditions, that:

- Global average temperatures will rise approximately 3°C for a doubling of carbon dioxide concentration;
- Global average precipitation will increase ten to 15 percent; and,
- Precipitation and temperature will both increase more toward the polar regions than toward the equatorial regions.

In theory, GCM estimates of changes in hydrologic variables such as runoff could be used directly to estimate changes in water resources. Manabe and Wetherald used the Geophysical Fluid Dynamics Laboratory (GFDL) general circulation model to examine soil moisture in the mid-continental, mid-latitude region of the United States, and concluded that significant drying may occur if the concentration of CO_2 is doubled in the earth's atmosphere.[21] Although the results from the various GCMs are not in complete agreement on the issue of mid-continental summer dryness,[22–24] more recent studies are beginning to confirm significant soil-moisture reductions.[18]

One other feature of GCM-computed hydrologic changes merits special attention: the decrease and earlier disappearance of the winter snowpack. Although estimates of the changes in precipitation patterns vary considerably from one GCM to another, all GCMs show shorter snowfall and snowmelt seasons due to increases in average temperatures. The change in snow conditions, in turn, leads to the earlier and significant increase of evaporation from bare soils which is, in turn, responsible for much of the summer soil-moisture effects. Similar alterations of snowfall and snowmelt conditions have now been identified in regional model studies.

GCM-generated hydrologic data suffer from two major limitations. First, the spatial resolution of GCMs is too coarse to provide hydrologic information on a scale typically of interest to hydrologists. GCM resolution is unlikely to dramatically improve for many years because of the extreme cost of high-speed computer time — a factor of two increase in resolution requires approximately a factor of eight increase in computer time.[25] With a typical model resolution of 4.5 degrees latitude by 7.5 degrees longitude and nine vertical layers in the atmosphere, computing one year of weather at 30-minute intervals takes ten hours of computer time on a Cray XMP supercomputer, which is one of the fastest computing machines in the world. Present resolutions are usually between 4 to 7.5 degrees latitude by 5 to 10 degrees longitude — these grid areas consist of hundreds of thousands of square kilometers. Yet, hydrologists are interested in climatic events that occur on the scale of tens or hundreds of square kilometers — a scale several orders of magnitude finer than current GCM resolution.

Second, hydrologic parameterizations in GCMs are very simple and often do not provide the detailed information necessary for water-resource planning.[4] The GCM soil-moisture budget, for example, is typically computed by the so-called "bucket method," in which the field capacity of the soil is assumed to be uniform everywhere.[6] Runoff occurs when the soil moisture exceeds this capacity, and the rate of evaporation is determined as a simple function of the soil moisture and the potential evaporation rate.[26] Efforts are being made to improve GCM hydrology predictions through such improvements as more accurate vegetation parameterizations and information on the behavior of soils. However, until such improvements occur, those interested in the implications of climatic changes for water resources must seek other, more reliable methods of evaluating hydrologic impacts.

Changes in climatological variables estimated by GCMs (such as changes in temperature and precipitation) are considered to be more reliable than GCM-predicted changes in runoff or soil moisture. As a result, there is a trend toward using temperature and precipitation estimates for a doubled-CO_2 environment as inputs to more detailed regional models.

Paleoclimate Analogues

Variations of climate and hydrologic conditions from one geological period to another, and from one millennium to another, are clearly evident in the geologic record. By looking at these variations and attempting to identify periods that may be similar to future green-

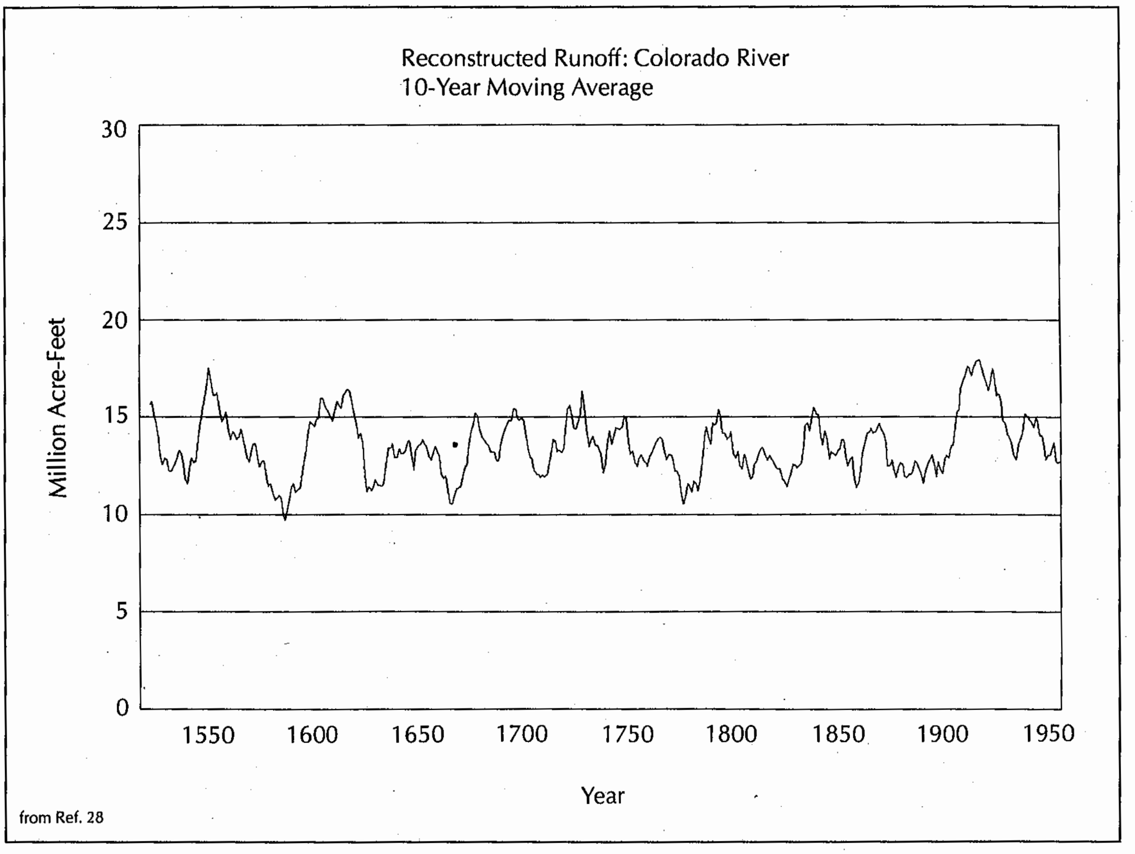

FIGURE 1. Four-hundred year runoff record in the Colorado River Basin reconstructed from tree rings and plotted as a ten-year moving average. Note the anomalously high runoff during the early 20th century that was used to determine allocations for the 1922 Colorado River Compact.

house conditions, where and what significant changes in water availability may be reasonably determined.

Paleoclimatic analogues are reconstructions of information on precipitation, temperature, evaporation or other climatic variables from a variety of long-term records such as tree rings, pollen deposits, vegetation or fossil types, the appearance or disappearance of civilizations, lacustrine (lake sediment) deposits, shoreline terraces, traces of dunes and other morphological features, and chemical isotope ratios in ice cores. Figures 1 and 2 show two such climate reconstructions. Such reconstructions can provide valuable information on both past climatic conditions and the vulnerability of existing water-resource systems to future changes. In a striking example, Stockton and Jacoby used tree rings to extend the runoff record in the Colorado River Basin back more than 400 years (see Figure 1).

This kind of study has direct water-management and policy implications. For example, the original 1922 Colorado River water allocation was based on the hydrologic record available at the time — this record spanned about 30 years from the late 1890s to the early 1920s. In 1976, when the historical record was reconstructed back to the mid-1500s using tree rings, the 1890-1920s period stood out as a time of abnormally high runoff (see Figure 1). The 400-year record now shows that more water was allocated to users than is likely to be available on a long-term average basis. If the long-term record had been available in 1922, the overallocation might not have occurred.

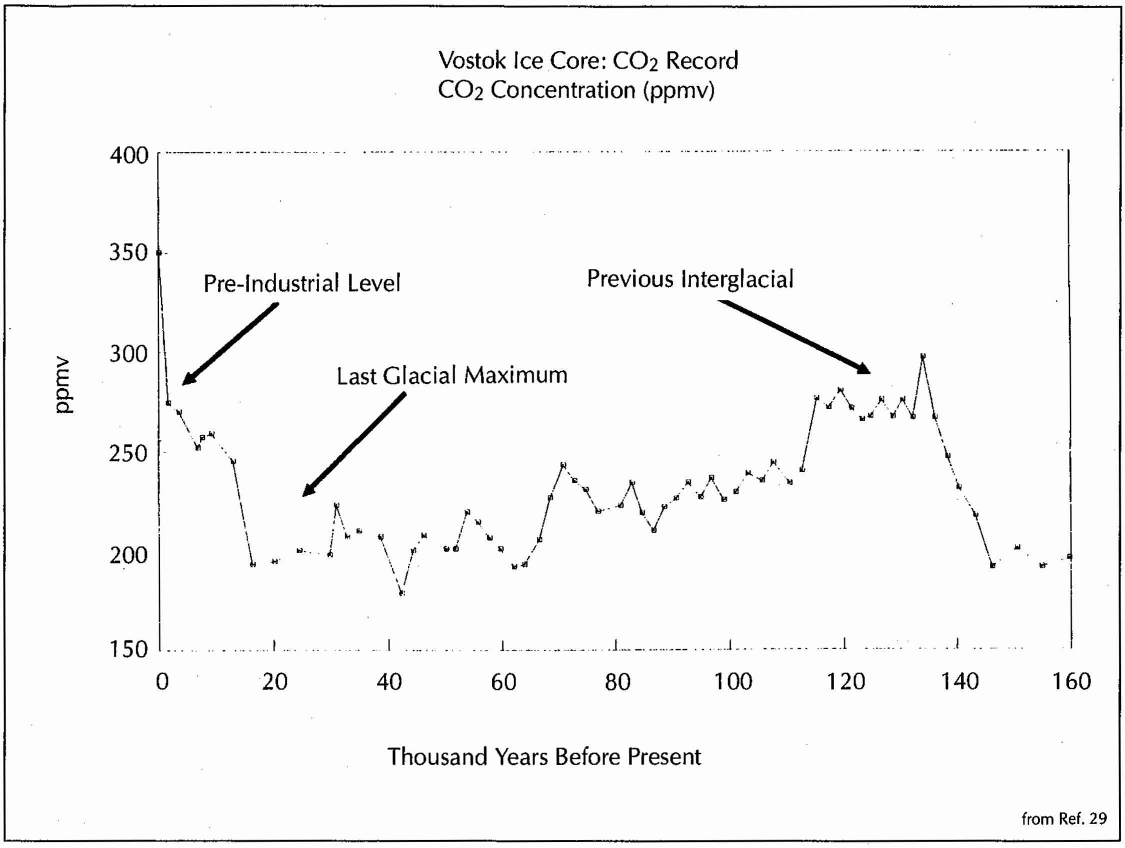

FIGURE 2. Atmospheric carbon dioxide concentration in parts per million by volume (ppmv) for the past 160,000 years, reconstructed from the Vostok ice core, Antarctica. Note the high CO_2 concentrations during the most recent interglacial period, the low CO_2 concentration during the most recent glacial maximum, the rise in CO_2 at the start of the current interglacial period (18,000 years ago) and the recent dramatic increase in CO_2 concentrations due to industrial activities.

Figure 2 shows an analysis of carbon dioxide and temperature from an ice core sample from the Vostok station in Antarctica.[29] This analysis extends the record of atmospheric CO_2 concentrations back 160,000 years.

Perhaps the most ambitious effort to use paleoclimatic data to evaluate future climatic impacts is the attempt of Soviet climatologists to develop information on past periods that are, in theory, comparable to future periods expected under conditions of greenhouse warming.[30] In this work, the Holocene optimum (about 6,000 to 5,000 years ago) is considered an analogue for a 1°C warming, the last interglacial (about 125,000 years ago) is considered an analogue for a 2 to 2.5°C warming and the Pliocene climatic optimum (about 3 to 4 million years ago) corresponds to a warming of 3 to 4°C. Although there are limits to the parallels that can be drawn between the past periods and future conditions, this type of activity can provide valuable insights into climate dynamics.

Several things limit the usefulness of paleoclimatic scenarios for evaluating the impacts of future climate changes on water resources. First, the farther we go back in time, the more difficult it becomes to recover hydrologic data. Thus, the evidence for developing such scenarios is limited in extent and scope. Second, the causes of climatic shifts over geologic time differ considerably from the anthropogenic changes now anticipated. And third, because these past changes typically predate human activity, we have no evidence for how they might affect society. Because of this last limitation, attention has lately turned to the use of more recent climatic extremes within the current period of instrumented record.

Recent Climate Analogues

Modern instrumental data can be used to develop climate scenarios. Long-term records can be analyzed for examples of climatic variability that offer insights into the vulnerability of water systems. Wigley *et al.* examined precipitation records in England and Wales for the period 1766 to 1980 in order to evaluate whether there had been a change in the frequency of wet and dry rainfall extremes.[31] Jones then employed these data in order to reconstruct riverflow volumes in order to study the effects of climate on water availability.[32] Similarly, Palutikof utilized scenarios constructed from the instrumented record to explore possible impacts on water resources in the United Kingdom in the early years of a climatic change.[33]

On a far larger scale, Bradley *et al.* compiled precipitation data from the mid-19th century, northern hemisphere land areas in an effort to look for trends.[34] In the last 30 to 40 years, significant increases have been observed in mid-latitude precipitation (35 to 50°N) and decreases in low-latitude precipitation (5 to 35°N). While these trends are consistent with GCM projections of precipitation changes associated with increasing concentrations of trace gases, they cannot be unambiguously attributed to this cause. Such analyses help to define natural large-scale hydrological variability and are useful in defining the longer-term perspective for identifying anthropogenic perturbations.

Finally, recent climatic anomalies can provide insights into the vulnerability of present society to future climatic changes. Many sources discuss regional water-resource impacts that are a function of past climatic variability.[35–40] These case studies provide information on how to avoid environmentally and economically costly climate impacts in the future.

The greatest advantage to using recent climate analogies or case scenarios is that they are based on human experience. Perhaps the greatest drawbacks to this approach are that anticipated greenhouse climatic changes have an anthropogenic cause unlike those that led to past climatic variability, and that the magnitude of the anticipated changes due to the greenhouse effect are larger than most historical natural variations. Thus, such analyses are often criticized on the grounds that the recent past is an unreliable guide to the future.

Hypothetical Climate Scenarios

Many hydrologists use purely hypothetical scenarios to assess the behavior of watersheds to future climatic conditions. Such scenarios (*e.g.*, +2, +3, +4°C increases or decreases of 10 and 20 percent in precipitation or evapotranspiration) permit the testing of wide ranges of hydrologic vulnerabilities. Although these scenarios are the easiest to develop, they are not particularly realistic and they often lack internal consistency. Care should be taken, therefore, in interpreting the results.

Table 1 lists the range of hypothetical scenarios used in a variety of studies. The values chosen typically reflect best estimates of the changes in important climatic variables, although extreme values are occasionally chosen to explore where a system might fail to perform as expected or designed. Thus, the practice of using hypothetical temperature increases of 1, 2, 3 or 4°C reflects the consensus that greenhouse warming will produce temperature rises in this range for an equivalent doubling of atmospheric carbon dioxide. Greater uncertainty about the magnitude, and even the direction, of regional precipitation changes is reflected in the choice of both increases and decreases in monthly or annual average rainfall.

Combining Climate Scenarios With Regional Hydrologic Models

Once scenarios of climate change are developed, hydrologic models can be employed to estimate the impacts on water resources. If accurate estimates of future water availability are to be calculated, regional

TABLE 1
Regional Studies Using Hypothetical Climate Scenarios

Study/Scenario	Temperature (degree C)	Evapotranspiration (percent)	Precipitation (percent)
Stockton & Boggess[41]	±2		±10
Nemec & Schaake[42]	+1, +3		±10, 25
Revelle & Waggoner[43]	+2, +4		-10
Flaschka *et al.*[44]	±2		±10, 25
Gleick[45,46,47]	+2, +4		±0, 10, 20
Fitzgerald & Walsh[48]		±5, 10, 15	±5, 10, 15, 20
Schaake[49]		±10	±10, 20

hydrologic evaluations need to incorporate the complexities of snowfall and snowmelt, topography, soil characteristics, natural and artificial storage, and monthly or seasonal variations.

The concept of employing hydrologic models for assessing the regional impacts of climatic changes has several attractive characteristics. First, diverse modeling techniques exist. This diversity permits flexibility in identifying and choosing the most appropriate approach to take to evaluate any specific region. Second, hydrologic models can be chosen to fit the characteristics of the available data. Third, regional-scale models require far fewer computer resources and are far easier to manipulate and modify than are general circulation models. Fourth, regional models can be used to evaluate the sensitivity of specific watersheds to both hypothetical changes in climate and to changes predicted by large-scale GCMs or climatic analogues. And finally, methods that incorporate both detailed regional characteristics and output from GCMs will be well-situated to take advantage of the continuing improvements in the resolution, regional geography, and hydrology of global climate models.

Many types of hydrologic-simulation models have been developed in recent years to help hydrologists study ecosystems, to aid in the engineering design of structures and to study the response of watersheds to different types of perturbations. Different classification schemes have been used to discriminate among these models, including physical and mathematical, continuous and discrete, dynamic and static, descriptive and conceptual, and stochastic and deterministic.[50,51] For the purpose of climate-impact assessment, an important distinction can be made between:

- Those models that rely primarily on empirical or statistical techniques for evaluating the hydrologic characteristics of a region or for extending the existing hydrologic record; and,[41,43,52]
- Those techniques that are physically-based mathematical descriptions of hydrologic phenomena — these techniques are the so-called deterministic or conceptual models.[42,44–47,53–56]

Stochastic hydrologic models were initially introduced to analyze reservoir design and operation. These models provide the means for estimating, among other things, the probability of sequences of future dry or wet years given past hydrologic data, and they are often easier to design and manipulate than deterministic models. But since stochastic hydrologic techniques assume that future hydrologic behavior will look statistically like the past, they are of limited use in evaluating the effects of climatic changes, which may alter the underlying distributions and physical relationships among hydrologic variables.

For that reason, considerable attention has been given to the wide range of deterministic, physically-based hydrologic models. Many deterministic models have been developed to analyze the different types of hydrologic phenomena. The models vary in their ability to represent or reproduce the small- and large-scale features of watersheds, from narrowly-focused models that study short time period, site-specific characteristics to general models capable of incorporating water balances in a large region. Each type of model has strengths and limitations, depending on the model design, data requirements and the objectives of the analyst.

Because of these varied strengths and limitations, it would be advisable that a set of criteria for using regional models to evaluate the hydrologic impacts of climatic changes be developed. Six important technical factors should be considered when selecting and using a regional hydrologic model to study the impacts of changes in climate on regional water resources:[47]

1. The inherent accuracy of the model.
2. The degree to which model parameters depend on the climatic conditions for which the model is calibrated.
3. The availability of input data, including comparative historical data.
4. The accuracy of the input data.
5. Model flexibility, ease of use and adaptability to diverse hydrologic conditions.
6. Compatibility with existing general circulation models.

Models designed to evaluate the impacts of climatic changes on runoff must be able to:

- Reproduce reasonably well the historical streamflow record; and,
- Simulate the streamflow under climatic conditions that are different from the conditions for which the model has been calibrated.

There are extensive discussions in the literature about the ways in which hydrologic models can be validated.[50,57–59] Almost all of these studies, however, deal with validating models under stationary climatic conditions. When the goal is to investigate the effects of climatic changes, additional effort must be made to extend the validation to conditions of non-stationary climates. Strictly speaking, this type of validation is not possible until the climatic changes actually occur and the "experiment is done." There are, however, tests that can be applied to provide at least some measure of confidence that the initial model calibration is still valid. Among these tests is the differential split-sample test, which is applied to a model when initial conditions are to be changed. In this case, two periods with different historical conditions are chosen, such as a period of high average precipitation and a period of low average precipitation. For example, if the climatic change to be modeled is a transition to a warmer, wetter scenario, the model should be calibrated on a dry, cool data set and then validated for the other extreme.[59] A variation on this test consists of calibrating the model on average conditions and verifying that the relative errors during the dry periods and wet periods are of similar distribution and magnitude.

Different methods have been used in the past few years to evaluate climate-induced changes in water availability, including both conceptual and stochastic models.[3,45,60,61] In one of the earliest comprehensive studies, Stockton and Boggess[41] used the empirical relationships derived by Langbein and others[62] to predict changes in runoff for the 18 water resource regions of the coterminous United States. Using only hypothetical annual-average changes, they conclude that warmer and drier shifts in climate would be the most problematic for water availability. Revelle and Waggoner also used the empirical relationships of Langbein to evaluate hypothetical climate change scenarios for the Colorado River Basin.[43] They concluded that annual runoff in that region is especially sensitive to changes in temperature. In one of the first regional studies, Nemec and Schaake used a more detailed deterministic approach to look at the impact of hypothetical temperature and precipitation scenarios in an arid and a humid watershed.[42]

TABLE 2
Hydrologic Studies Using GCM Output

Study	GISS	GFDL	NCAR	OSU
Gleick[47]	X	X	X	
Cohen[55]	X	X		
Mather & Feddema[54]	X	X		
Sanderson & Wong[64]	X			
Bultot *et al.*[56]	X			
U.S. EPA[63]	X	X		X

Note: Different GCM runs were used by different researchers. Thus, the results of each study must be reviewed individually. Please refer to the individual studies for details of the methodologies and basin-specific assumptions.

GISS = Goddard Institute for Space Studies, New York, New York
GFDL = Geophysical Fluid Dynamics Laboratory, Princeton, New Jersey
NCAR = National Center for Atmospheric Research, Boulder, Colorado
OSU = Oregon State University, Corvallis, Oregon

More recently, a number of studies have offered new insights into hydrologic vulnerabilities to greenhouse warming. These studies involve more accurate and comprehensive regional water-balance models and incorporate climate scenarios developed from general circulation models.[44–47,55,56,63] Table 2 lists some of those studies that used general circulation model scenarios of climate change as inputs to regional hydrologic models.

Cohen evaluated the implications of general circulation model temperature and precipitation scenarios for water levels in the Great Lakes.[55] The net basin water supply of the Great Lakes was predicted to decline in response to greenhouse warming over a wide range of climate scenarios, including some with large increases in precipitation, although the overall results were sensitive to changes in wind speed and other assumptions about variables that may alter lake evaporation rates. Using temperature and precipitation data from two GCMs (the Geophysical Fluid Dynamics Laboratory model and the Goddard Institute for Space Studies model), net basin supply decreased between 15 and 30 percent.

In a study of the Sacramento Basin in California, many hydrologic impacts were identified that were robust and consistent over a wide range of both hypothetical and GCM-generated climate-change scenarios.[45–47,53] These impacts include large decreases in summer soil-moisture levels, decreases in summer runoff volumes, major shifts in the timing of average-monthly runoff throughout the year and large increases in winter runoff volumes. Using eight different general circulation model temperature and precipitation scenarios, including both increases and decreases in average precipitation, summer runoff decreased by between 30 and 68 percent (see Figure 3), winter runoff increased 16 to 81 percent (see Figure 4) and summer soil moisture decreased 14 to 36 percent (see Figure 5). The principal mechanism driving these hydrologic effects is a dramatic change in snowfall and snowmelt conditions. Due to higher temperatures, a greater fraction of annual and seasonal precipitation falls as rain rather than as snow. This condition has the effect of reducing total annual snowpack. In addition, the precipitation that is received as snow begins to melt earlier in the spring and melts faster, leading to less spring and summer snowmelt runoff and decreases in summer soil moisture. This effect has now been noted in other regions,[56,63,65,66] and has been identified in GCM results.[4,18]

Two other results are particularly notewor-

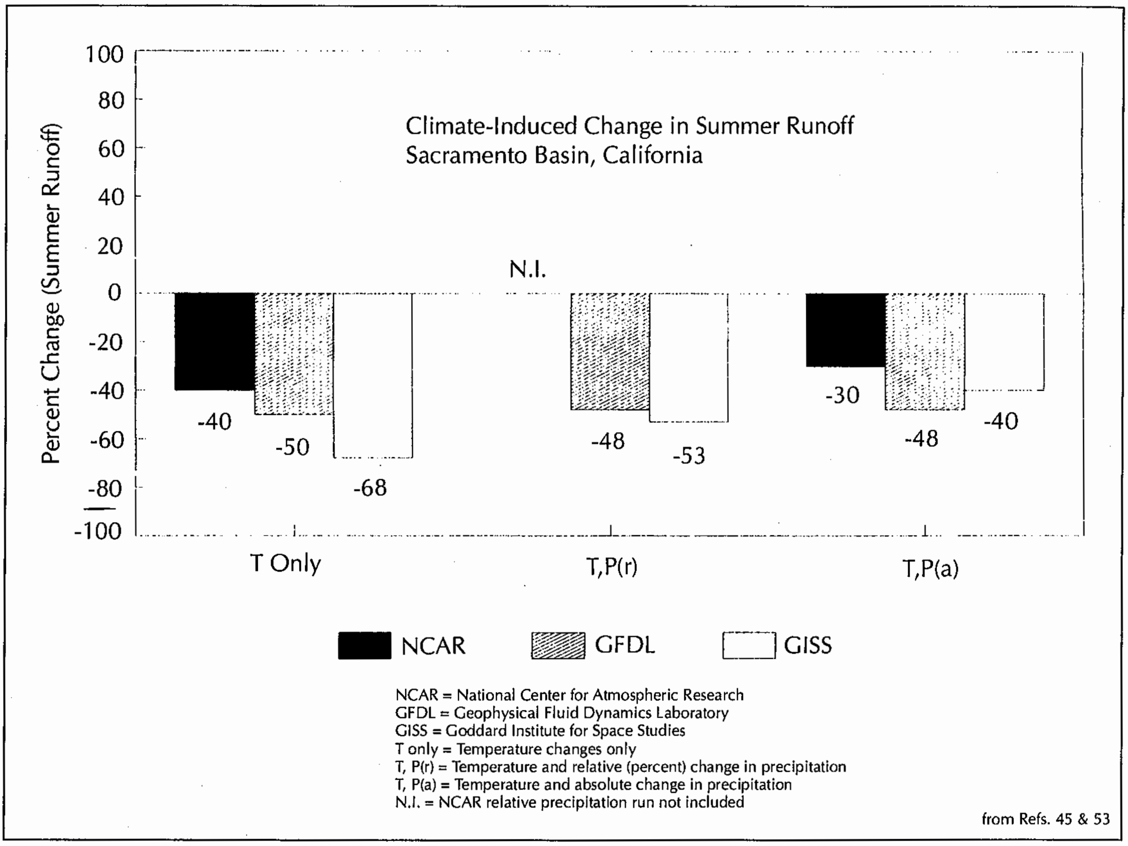

FIGURE 3. Percent change in average summer (June, July and August) runoff between the model historical run ("base case") and eight GCM-derived doubled carbon dioxide scenarios in the Sacramento Basin in California. Note that all scenarios show a decrease in summer runoff.

thy. First, *annual* runoff appears to be more sensitive to changes in precipitation than to changes in temperature,[40,44,47] an effect described theoretically by Wigley and Jones.[67] Second, in watersheds with a seasonal snowfall and snowmelt pattern, the seasonal *distribution* of runoff and soil moisture is more sensitive to temperature than to precipitation.[47,56,63] In these watersheds, higher temperatures reduce the ratio of snow to rain during the winter, hasten the onset of spring snowmelt and increase the rate of snowmelt runoff.

The results of these regional studies suggest that physically-based models are able to provide considerable information on the regional hydrologic effects of climatic changes, despite uncertainties about many regional details of future climate. Such information has important ramifications for long-range water resource planning, for agricultural water development and conservation, and for industrial water use over the next several decades.

Summary & Discussion

Ultimately, unless climate-induced changes can be converted into estimates of how the availability of freshwater resources may change, water managers and planners will be unwilling or unable to implement new management policies or to plan for changed conditions. Freshwater resources are critical for both ecological services and human development. Among the critical issues are the quality of drinking water, supply for industrial activities, agricultural water use, sewage treatment, navigation, hydroelectricity production

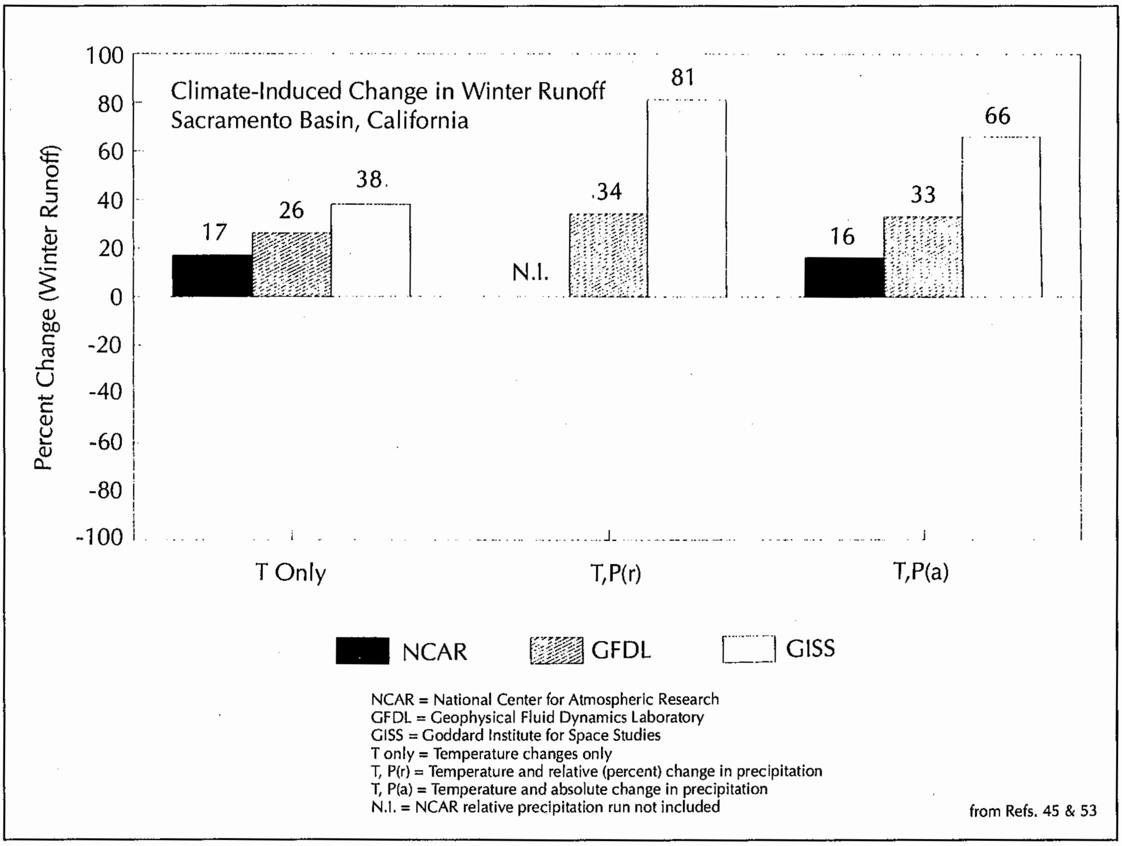

FIGURE 4. Percent change in average winter (December, January and February) runoff between the model historical run ("base case") and eight GCM-derived doubled carbon dioxide scenarios in the Sacramento Basin in California. Note that all scenarios show large increases in winter runoff.

and a wide range of environmental services such as fisheries, waterfowl habitat and wetlands preservation. Many other water resource problems will also arise, including impacts on groundwater withdrawal and recharge, and effects on islands dependent on shallow freshwater lenses and rainfall. Far more research into these questions is needed.

In the long run, large-scale general circulation models of the climate may be able to provide valuable information on detailed, regional impacts on water supplies. But waiting until such a capability is available means waiting until climate impacts unambiguously begin to appear. For that reason, hydrologists and water planners are relying on a variety of other methods to increase current understanding of climatic vulnerabilities, including reviewing the paleoclimate and the more recent instrumented records, and using regional hydrologic models to explore a wide range of climate-change scenarios. These techniques have identified a number of important problems that may soon face us.

Ultimately, if realistic estimates of changes in regional water availability are to be calculated, then a number of advances are needed. In order to be valuable to water resource planners, regional hydrologic assessments must include:

- A focus on short time-scales such as days or weeks, rather than annual or even monthly averages;
- The ability to incorporate into regional studies the increasingly detailed assess-

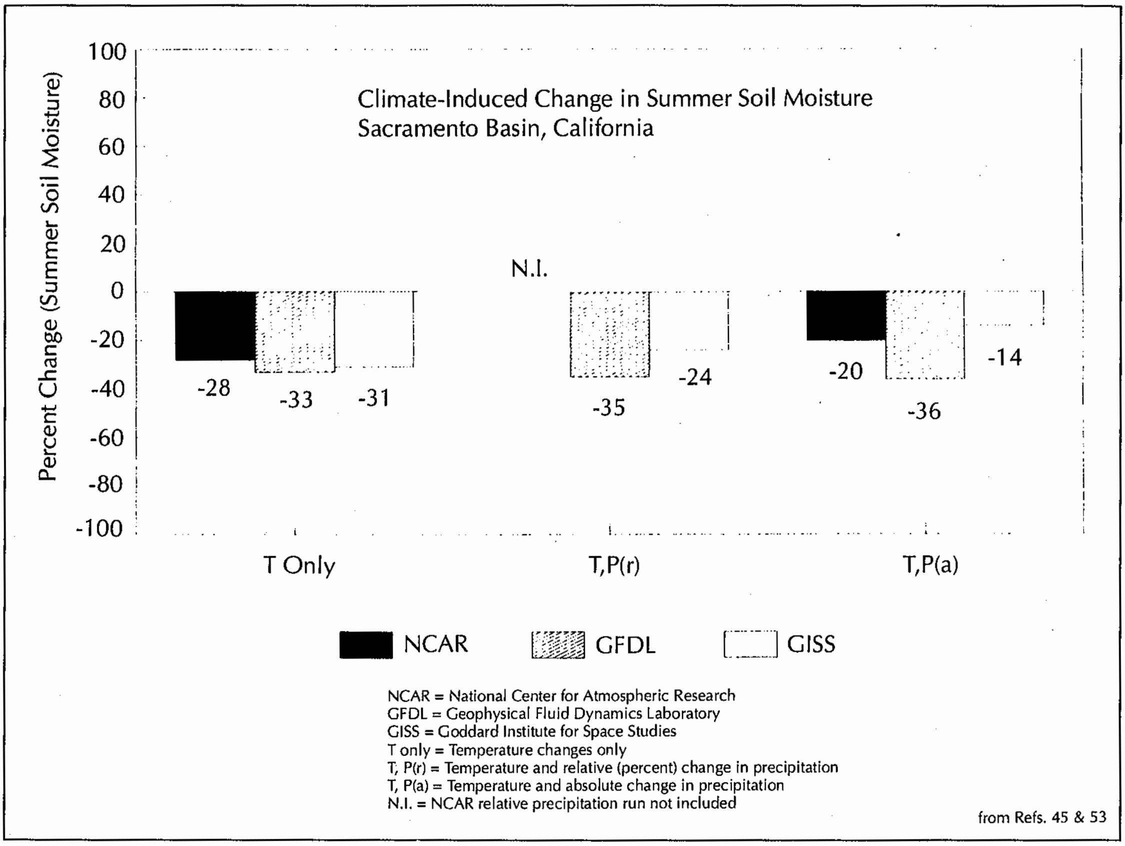

FIGURE 5. Percent change in average summer (June, July and August) soil moisture between the base case and eight GCM-derived scenarios. All of the scenarios reveal large decreases in summer soil moisture. These changes are driven by an increase in the ratio of rain to snow in winter, by a faster and earlier spring snowmelt as well as by increased summer evapotranspiration.

ments of changes produced by GCMs;

- The ability to produce information on hydrologically important variables, such as changes in runoff and available soil moisture; and,
- The ability to incorporate snowfall and snowmelt, vegetation changes, topography, soil characteristics, natural and artificial storage, and other regional complexities.

Finally, the long construction times and subsequent lifetimes of reservoirs, dams and water-transfer facilities means that planning should begin today for changes that may not become evident for years. Yet changes in water resources management and planning will only come if those responsible for water systems can be convinced that the problem of climatic change is sufficiently real and pressing to require their attention.

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REFERENCES

1. Hansen, J.E., "The Greenhouse Effect: Impact on Current Global Temperature and Regional Heat Waves," statement to the United States Senate, Committee on Energy and Natural Resources, June 23rd, 1988.

2. Novaky, B., Pachner, C., Szesztay, K., & Miller, D., "Water Resources," in Kates, R.W., Ausubel, J.H., & Berberian, M., eds., *Climate Impacts Assessment,* SCOPE 27, John Wiley and Sons, New York, 1985, pp. 187-214.

3. Beran, M., "The Water Resource Impact of Future Climate Change and Variability," in Titus, J.G., ed., *Effects of Changes in Stratospheric Ozone and Global Climate: Volume 1: Overview,* United States Environmental Protection Agency, Washington, D.C., 1986, pp. 299-330.

4. World Meteorological Organization (WMO), "Water Resources and Climatic Change: Sensitivity of Water-Resources Systems to Climate Change and Variability," World Meteorological Organization, WCAP-4, WMO/TD-No. 247, Geneva, Switzerland, 1987.

5. Manabe, S., "Climate and the Ocean Circulation I: The Atmospheric Circulation and the Hydrology of the Earth's Surface," *Monthly Weather Review,* Vol. 97, No. 11, 1969, pp. 739-774.

6. Manabe, S., "Climate and the Ocean Circulation II: The Atmospheric Circulation and the Effect of Heat Transfer by Ocean Currents," *Monthly Weather Review,* Vol. 97, No. 11, 1969, pp. 775-805.

7. Schlesinger, M.E., & Gates, W.L., "The January and July Performance of the OSU Two-Level Atmospheric General Circulation Model," *J. Atmos. Sci.,* Vol. 37, 1980, pp. 1911-1943.

8. Manabe, S., & Stouffer, R.J., "Sensitivity of a Global Climate Model to an Increase of CO_2 Concentration in the Atmosphere," *J. Geo. Res.,* Vol. 85, No. C10, 1980, pp. 5529-5554.

9. Manabe, S., & Wetherald, R.T., "On the Distribution of Climate Change Resulting From an Increase in CO_2-Content of the Atmosphere," *J. Atmos. Sci.,* Vol. 37, 1980, pp. 99-118.

10. Wetherald, R.T., & Manabe, S., "Influence of Seasonal Variation Upon the Sensitivity of a Model Climate," *J. Geophys. Res.,* Vol. 86, No. C2, 1981, pp. 1194-1204.

11. Ramanathan, V., "The Role of Ocean-Atmosphere Interactions in the CO_2 Climate Problem," *J. Atmos. Sci.,* Vol. 38, 1981, pp. 918-930.

12. Manabe, S., Wetherald, R.T., & Stouffer, R.J., "Summer Dryness Due to an Increase of Atmospheric CO_2 Concentration," *Climatic Change,* 3, 1981, pp. 347-386.

13. Hansen, J.E., Rind, D., Russell, G., Stone, P., Fung, I., Ruedy, R., & Lerner, J., "Climatic Sensitivity: Analysis of Feedback Mechanisms," in Hansen, J.E., & Takahashi, T., eds., *Climate Processes and Climate Sensitivity,* American Geophysical Union Monograph 29, Maurice Ewing Vol. 5, American Geophysical Union, Washington, D.C., 1984.

14. Hansen, J., Russell, G., Rind, D., Stone, P., Lacis, A., Lebedeff, S., Ruedy, R., & Travis, L., "Efficient Three-Dimensional Global Models for Climate Studies: Models I and II," *Monthly Weather Review,* Vol. 111, No. 4, 1983, pp. 609-662.

15. Hansen, J., Fung, I., Lacis, A., Rind, D., Lebedeff, S., Ruedy, R., Russell, G., & Stone, P., "Global Climate Changes as Forecast by Goddard Institute for Space Studies Three-Dimensional Model," *J. of Geophys. Res.,* 93, D8, 1988, pp. 9341-9364.

16. Washington, W.M., & Meehl, G.A., "General Circulation Model Experiments on the Climatic Effects Due to a Doubling and Quadrupling of Carbon Dioxide Concentration," *J. Geophys. Res.,* Vol. 88, No. C11, 1983, pp. 6600-6610.

17. Washington, W.M., & Meehl, G.A., "Seasonal Cycle Experiment on the Climate Sensitivity Due to a Doubling of CO_2 With an Atmospheric General Circulation Model Coupled to a Simple Mixed-Layer Ocean Model," *J. Geophys. Res.,* Vol. 89, No. D6, 1984, pp. 9475-9503.

18. Wilson, C.A., & Mitchell, J.F.B., "A Doubled CO_2 Climate Sensitivity Experiment With a Global Climate Model Including a Simple Ocean," *Journal of Geophysical Res.*, Vol. 92, No. D11, 1987, pp. 13315-13343.

19. Mearns, L., Gleick, P.H., & Schneider, S.H., "Climate Forecasting," in American Association for the Advancement of Sciences, Waggoner, P.E., ed., *Climate Change and U.S. Water Resources*, John Wiley and Sons, Inc., New York, 1990, pp. 87-138.

20. Schneider, S.H., Gleick, P.H., & Mearns, L., "Prospects for Climate Change," in American Association for the Advancement of Sciences, Waggoner, P.E., ed., *Climate Change and U.S. Water Resources*, John Wiley and Sons, Inc., New York, 1990, pp. 41-74.

21. Manabe, S., & Wetherald, R.T., "Reduction in Summer Soil Wetness Induced by an Increase in Atmospheric Carbon Dioxide," *Science*, Vol. 232, 1986, pp. 626-628.

22. Schlesinger, M.E., & Mitchell, J.F.B., "Model Projections of the Equilibrium Climatic Response to Increased Carbon Dioxide," in MacCracken, M.C., & Luther, F.M., eds., *Projecting the Climatic Effects of Increasing Carbon Dioxide*, U.S. Department of Energy DOE-0237, Washington, D.C., 1985, pp. 81-148.

23. Schlesinger, M.E., & Mitchell, J.F.B., "Climate Model Simulations of the Equilibrium Climatic Response to Increased Carbon Dioxide," *Review of Geophysics*, 25, 1987, pp. 760-798.

24. Mitchell, J.F.B., & Warrilow, D.A., "Summer Dryness in Northern Mid-Latitudes Due to Increased CO_2," *Nature*, 330, 1987, pp. 238-240.

25. Somerville, R.C.J., "The Predictability of Weather and Climate," *Climatic Change*, 11, 1987, pp. 239-246.

26. Manabe, S., & Wetherald, R.T., "CO_2 and Hydrology," *Advances in Geophysics*, 1985, pp. 131-157.

27. Dickinson, R.E., "Modeling Evapotranspiration for Three-Dimensional Global Climate Models," in Hansen, J.E., & Takahashi, T., eds., *Climate Processes and Climate Sensitivity*, American Geophysical Union Monograph 29, Maurice Ewing Vol. 5, 1984, pp. 58-72.

28. Stockton, C.W., & Jacoby, Jr., G.C., "Long-Term Surface-Water Supply and Streamflow Trends in the Upper Colorado River Basin Based on Tree-Ring Analyses," *Lake Powell Research Project Bulletin*, No. 18, University of Arizona, Tucson, 1976.

29. Barnola, J.M., Raynaud, D., Korotkeich, Y.S., & Lorius, C., "Vostok Ice Core Provides 160,000-Year Record of Atmospheric CO_2," *Nature*, 329, 1987, pp. 408-418.

30. Budyko, M.I., & Izrael, Y.A., eds., *Antropogeniye Izmenenia Klimata*, Gidrometeoizdat, Leningrad, in Russian, 1987.

31. Wigley, T.M.L., Lough, J.M., & Jones, P.D., "Spatial Patterns of Precipitation in England and Wales and a Revised Homogeneous England and Wales Precipitation Series," *Journal of Climatology*, 4, 1981, pp. 1-25.

32. Jones, P.D., "Riverflow Reconstruction from Precipitation Data," *Journal of Climatology*, 1984, pp. 171-186.

33. Palutikof, J.P., "Some Possible Impacts of Greenhouse Gas Induced Climate Change on Water Resources in England and Wales," in Solomon, S.I., Beran, M., & Hogg, W., eds., *The Influence of Climate Change and Climatic Variability on the Hydrologic Regime and Water Resources*, IAHS Publication No. 168, Proceedings of the Vancouver Symposium, August 1987, pp. 585-596.

34. Bradley, R.S., Diaz, H.F, Eischeid, J.K., Jones, P.D., Kelly, P.M., & Goodess, C.M., "Precipitation Fluctuations Over Northern Hemisphere Land Areas Since the Mid-19th Century," *Science*, 237, 1987, pp. 171-175.

35. Glantz, M.H., & Ausubel, J.H., "The Ogallala Aquifer and Carbon Dioxide: Comparison and Convergence," *Environmental Conservation*, 11, 1984, pp. 123-131.

36. Changnon, Jr., S.A., "Climate Fluctuations and Record-High Levels of Lake Michigan," *Bulletin American Meteorological Society*, Vol. 68, No. 11, 1987, pp. 1394-1402,

37. Gleick, P.H., "Climate Change and California: Past, Present, and Future Vulnerabilities," in Glantz, M.H., ed., *Societal Responses to Regional Climatic Change: Forecasting by Analogy*, Westview Press, Boulder, Colorado, 1988, pp. 307-327.

38. Morrisette, P.M, "The Rising Level of the Great Salt Lake: An Analogue of Societal Adjustment to Climate Change," in Glantz, M.H., ed., *Societal Responses to Regional Climatic Change: Forecasting by Analogy*, Westview Press, Boulder, Colorado, 1988, pp. 169-196.

39. Cohen, S.J., "Great Lakes Levels and Climate Change: Impacts, Responses, and Futures," in Glantz, M.H., ed., *Societal Responses to Regional Climatic Change: Forecasting by Analogy*, Westview Press, Boulder, Colorado, 1988, pp. 143-168.

40. Karl, T., & Reibsame, W., "The Impact of Decadal Fluctuations in Mean Precipitation and Temperature on Runoff: A Sensitivity Study Over the United States," *Climatic Change,* Vol. 15, No. 3, 1989, pp. 423-447.

41. Stockton, C.W., & Boggess, W.R., "Geohydrological Implications of Climate Change on Water Resource Development," U.S. Army Coastal Engineering Research Center, Fort Belvoir, Virginia, 1979.

42. Nemec, J., & Schaake, J., "Sensitivity of Water Resource Systems to Climate Variation," *Hydrological Sciences,* Vol. 27, No. 3, 1982, pp. 327-343.

43. Revelle, R.R., & Waggoner, P.E., "Effects of a Carbon Dioxide-Induced Climatic Change on Water Supplies in the Western United States," in National Academy of Sciences, *Changing Climate,* National Academy Press, Washington D.C., 1983.

44. Flaschka, I.M., Stockton, C.W., & Boggess, W.R., "Climatic Variation and Surface Water Resources in the Great Basin Region," *Water Resources Bulletin,* Vol. 23, No. 1, 1987, pp. 47-57.

45. Gleick, P.H., "Methods for Evaluating the Regional Hydrologic Impacts of Global Climatic Changes," *Journal of Hydrology,* 88, 1986, pp. 99-116.

46. Gleick, P.H., "The Development and Testing of a Water Balance Model for Climate Impacts Assessment: Modeling the Sacramento Basin," *Water Resources Research,* Vol. 23, No. 6, 1987, pp. 1019-1061.

47. Gleick, P.H., "Regional Hydrologic Consequences of Increases in Atmospheric CO_2 and Other Trace Gases," *Climatic Change,* 10, 1987, pp. 137-161.

48. Fitzgerald, B.M., & Walsh, M.A., "Significance of Greenhouse Changes to Irrigation Water Supplies in New South Wales — A Case Study of the Severn Valley," Report of the Department of Water Resources, North Sydney, New South Wales, Australia, 1987.

49. Schaake, J.C., "From Climate to Flow," in the American Association for the Advancement of Sciences, Waggoner, P.E., ed., *Climate Change and U.S. Water Resources,* John Wiley and Sons, Inc., New York, 1990, pp. 87-138.

50. Viessman, Jr., W., Knapp, J.W., Lewis, G.L., & Harbaugh, T.E., *Introduction to Hydrology,* 2nd ed., Harper & Row, Publishers, New York, 1977.

51. Linsley, Jr., R.K., Kohler, M.A., & Pauhlus, J.L.H., *Hydrology for Engineers,* McGraw-Hill, Inc., New York, 1982.

52. Schwarz, H.E., "Climatic Change and Water Supply: How Sensitive Is the Northeast?," in *Climate, Climatic Change, and Water Supply,* National Academy of Sciences, Washington, D.C. 1977.

53. Gleick, P.H., "Regional Water Availability and Global Climatic Change: The Hydrologic Consequences of Increases in Atmospheric CO_2 and Other Trace Gases," Energy and Resources Group, doctoral dissertation, ERG-DS-86-1, University of California, Berkeley, 1986.

54. Mather, J.R., & Feddema, J., "Hydrologic Consequences of Increases in Trace Gases and CO_2 in the Atmosphere," in *Effects of Changes in Stratospheric Ozone and Global Climate, Volume 3,* U.S. Environmental Protection Agency, Washington, D.C., 1986, pp. 251-271.

55. Cohen, S.J., "Impacts of CO_2-Induced Climatic Change on Water Resources in the Great Lakes Basin," *Climatic Change,* 8, 1986, pp. 135-153.

56. Bultot, F., Coppens, A., Dupriez, G.L., Gellens, D., & Meulenberghs, F., "Repercussions of a CO_2 Doubling on the Water Cycle and on the Water Balance: A Case Study for Belgium," *Journal of Hydrology,* 99, 1988, pp. 319-347.

57. Chow, V.T., ed., *Handbook of Applied Hydrology,* McGraw-Hill Book Company, New York, 1964.

58. World Meteorological Organization (WMO), "Intercomparison of Conceptual Models Used in Operational Hydrological Forecasting," *Operational Hydrology Report No. 7,* World Meteorological Organization, Geneva, Switzerland, 1975.

59. Klemes, V., "Sensitivity of Water- Resource Systems to Climate Variations," World Climate Applications Programme, WCP-98, World Meteorological Organization, 1985.

60. Dooge, J.C.I., "Effects of CO_2 Increases on Hydrology and Water Resources," paper presented at European Economic Community Symposium on CO_2 and Other Greenhouse Gases: Climatic and Associated Impacts, Brussels, November 4, 1986.

61. Changnon, Jr., S.A., "An Assessment of Climate Change, Water Resources, and Policy Research," *Water International,* 12, 1987, pp. 67-76.

62. Langbein and others, *Annual Runoff in the United States,* U.S. Geological Survey Circular 5, U.S. Department of the Interior, Washington, D.C., 1949.

63. U.S. Environmental Protection Agency, "The Potential Effects of Global Climate Change on the United States," draft report to Congress, U.S. Environmental Protection Agency, Office of Policy,

Planning, and Evaluation, October draft, 1988.

64. Sanderson, M., & Wong, L., "Climatic Change and Great Lakes Water Levels," in Solomon, S.I., Beran, M., & Hogg, W., eds., *The Influence of Climate Change and Climatic Variability on the Hydrologic Regime and Water Resources*, IAHS Publication No. 168, Proceedings of the Vancouver Symposium, August 1987, pp. 477-487.

65. Shiklamanov, I., "Effects of Climate Changes on Soviet Rivers," paper presented at the International Symposium of the XIXth General Assembly of the International Union of Geodesy and Geophysics (IUGG), Vancouver, British Columbia, Canada, August 9-22, 1987.

66. Martinec, J., & Rango, A., "Effects of Climate Change on Snowmelt Runoff Patterns," in *Remote Sensing and Large-Scale Global Processes*, Proceedings of the IAHS Third International Assembly, Baltimore, Maryland, IAHS Publ. No. 186, 1989.

67. Wigley, T.M.L, & Jones, P.D., "Influences of Precipitation Changes and Direct CO_2 Effects on Streamflow," *Nature*, 314, 1985, pp. 149-152.