CLIMATE CHANGE, HYDROLOGY, AND WATER RESOURCES

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Abstract. Growing atmospheric concentrations of carbon dioxide and other trace gases are leading to climatic changes with important implications for the hydrologic balance and water resources. These "greenhouse gases" are expected to alter the radiative balance of the atmosphere, causing increases in temperature and changes in many other climatic variables. Recent hydrological research strongly suggests that this so-called "greenhouse effect" will alter the timing and magnitude of runoff and soil moisture, change lake levels, and affect water quality. Such changes raise the possibility of environmental and socioeconomic dislocations, and they have important implications for future water resources planning and management. This paper reviews state-of-the-art research into the implications of climatic changes for the hydrologic cycle and for water resources and discusses the implications of such changes for future water planning and management.

INTRODUCTION

Concern over global climatic changes caused by growing atmospheric concentrations of carbon dioxide and other trace gases has increased in recent years as our understanding of atmospheric dynamics and global climate systems has improved. These gases, principally carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4), and chlorofluorocarbons (CFCs), alter the heat balance of the Earth by retaining long-wave 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 greenhouse gases [*Hansen*, 1988].

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 subsequent effects on the quantity and quality of regional water resources. Yet these consequences are poorly understood.

Recent hydrological research strongly suggests that plausible climatic changes caused by increases in atmospheric trace gas concentrations will alter the timing and magnitude of runoff and soil moisture, change lake levels and groundwater availability, and affect water quality. Such a scenario raises the possibility of dramatic environmental and socioeconomic dislocations and has widespread implications for future water resources planning and management.

A BRIEF HISTORY OF THE DEVELOPMENT OF THE CLIMATE AND WATER LITERATURE

Much of the earliest literature on climatic change focused on the ability of society to alter local climatic conditions, rather than on the impacts of climatic changes on society [see *Study of Critical Environmental Problems (SCEP)*, 1970; *Study of Man's Impact on Climate (SMIC)*, 1971]. How, for example, might large reservoirs affect downwind temperatures or precipitation patterns? How might large-scale land use modifications alter local climatic conditions? Even when attention finally turned to anthropogenic climatic changes, such as greenhouse warming, very little of the early work considered possible impacts on water resources; instead, most research focused on the implications of higher temperatures and altered precipitation patterns for agricultural production and the level of the oceans. This lack of attention to water resources was due to three factors: an early focus on large-scale computer simulations of the climate, uncertainty about how future precipitation patterns would be affected by climatic changes, and doubts about appropriate hydrological methods for evaluating future (and uncertain) climatic changes.

One of the few early attempts to evaluate the interactions among hydrology, water supply, and climatic conditions was the *National Research Council Panel on Water and Climate* [1977, p. 3] study *Climate, Climatic Change, and Water Supply.* At that time, the authors concluded,

> Future water shortages may be exacerbated by climatic change, but unfortunately the climatologist's current forecast

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> ability is insufficient to aid the water-resource planner or hydrologic designer. To be useful to water-resource planning, climatic-change forecasts would need to be specific by area and be accurate over the 50 to 100 year design-life of the water-resource system. . . . There is no evidence that such a forecast ability either exists or will appear within the immediate future.

Despite problems in accurately forecasting regional effects, the *National Research Council Panel on Water and Climate* [1977, p. 19] also concluded, "there are many useful measures that could be implemented now that would help to mitigate the undesirable effects of future water shortages."

Not until 1985, when the Scientific Committee on Problems of the Environment (SCOPE) published its report "Climate Impact Assessment"[*Kates et al.*, 1985], were water resources considered in detail by the climate impacts community. Even then, major reviews continued to ignore water resources (see, for example, *Bolin et al.*, [1986]). By this time, however, the hydrologic community had begun to raise important questions about assessment techniques and critical water resource issues. How might ecosystems and resource management be affected by greenhouse warming? What types of hydrologic models are available for climate impact assessment, and which are appropriate for regional studies?

Researchers in the 1980s also began to explore the regional hydrologic effects of greenhouse warming through detailed case studies, using a variety of methods. In 1985 the World Meteorological Organization (WMO) published a review of the effects of climatic variations on water resource systems that included specific recommendations for testing and validating different assessment methods [*Klemeš*, 1985]. This was followed in 1987 by a summary of the sensitivity of water resource systems to both future climatic change and existing climatic variability [*WMO*, 1987]. Also in 1987, the International Association of Hydrological Sciences (IAHS) devoted a session of the XIXth General Assembly of the International Union of Geodesy and Geophysics (IUGG) to climate and water resources and published a collection of articles on the subject [*Solomon et al.*, 1987]. In 1988 the Australian division of Atmospheric Research held a meeting on climatic change and published a book with a section evaluating the implications of greenhouse warming for Australian hydrology and water resources [*Pearman*, 1988]. Most recently, the American Association for the Advancement of Sciences (AAAS) convened a panel to write a book on the implications of climatic change and variability for water resources in the United States [*AAAS*, 1989]. Under the auspices of the AAAS an attempt was made to study the entire scope of the problem, from basic physical, climatological, and hydrologic issues to questions of political and economic allocation of water resources under new climatic conditions.

Much remains to be done. 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 to reduce the consequences of climatic change.

METHODS OF ANALYSIS

Novaky et al. [1985] and *Beran* [1986] distinguish between hydrology and water resources, where hydrology is 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 focus on 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 effect of climatic changes on municipal water supply, hydroelectricity production, reservoir design and management, reliable yield, and irrigation requirements.

Ideally, there are three steps to evaluating 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 step 1; and (3) assess the implications of the hydrologic variations identified in step 2 for the performance of such water resource systems as dams, aqueducts, reservoirs, groundwater recharge basins, and so on. These steps are indicated schematically in Figure 1. Hydrologists, water-resource planners, and engineers have important roles to play in each step.

Accurate quantitative estimates of 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.

Armed with such quantitative climatological estimates, hydrologists can use simulation models of watersheds to evaluate the impacts of climatic changes on runoff, soil moisture, snowmelt rates, and other hydrologic variables.

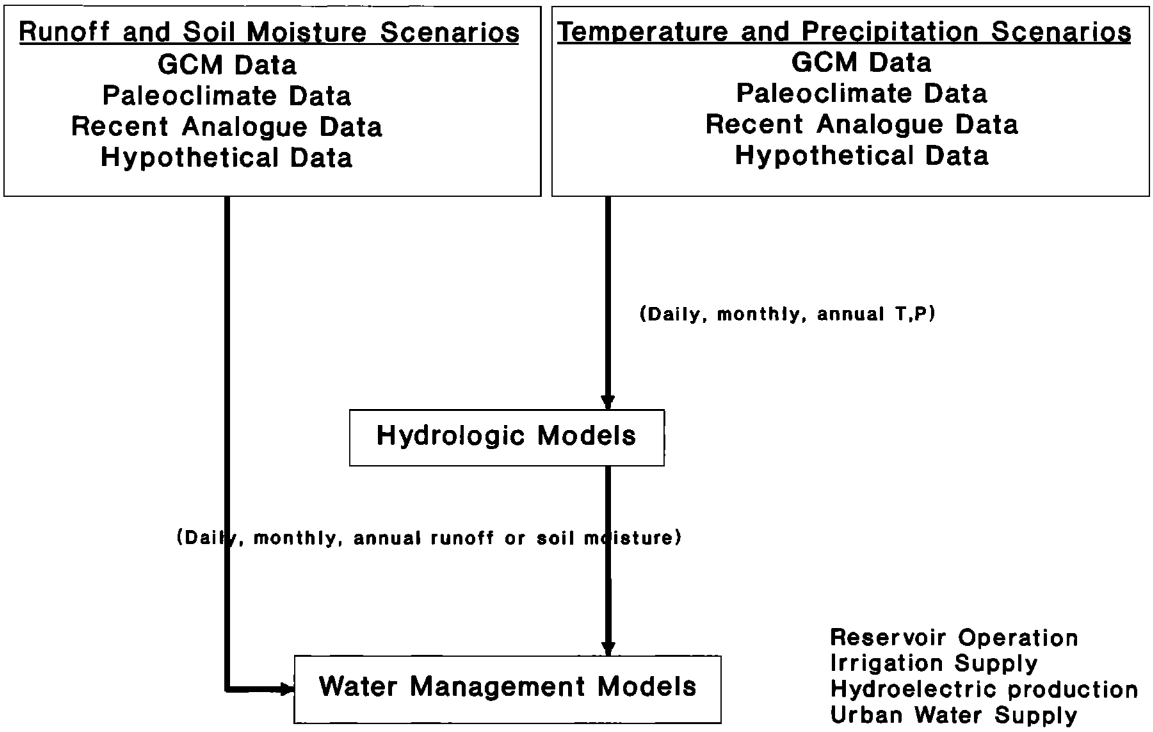


Figure 1. Methods for evaluating the hydrologic and water resource implications of climatic changes. Climate change scenarios can be generated using general circulation models (GCMs), paleoclimatic data, recent climate analogue data, or hypothetical climate data. Two types of scenarios can be generated: hydrologic or climatological. Climatological scenarios use changes in temperature, precipitation, or other climatological variables to drive hydrologic models, and the hydrologic output is used as input to water management models. Alternatively, hydrologic scenarios of runoff and soil moisture can be generated and used directly to drive water management models. Each technique has advantages and limitations as described in the text.

Finally, water managers can use the new hydrologic estimates to evaluate the performance and design of their systems under different climatic conditions. Thus flood control or reservoir operation can be studied, hydroelectric output optimized, emergency floodplain management plans revised, and drought planning reviewed.

To assess the implications of the greenhouse effect for water resources, regional-scale details of future changes are needed for temperature, precipitation, evaporation, wind speed, and other hydroclimatological variables. Our ability to predict these details, however, is limited, and we must therefore resort to the use of climate scenarios. 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 [*WMO*, 1987].

Direct Use of General Circulation Models

There are diverse ways in which global climate may be affected by human actions. But we are unable to see clearly either the direction of changes in climate or the nature of the subsequent societal impacts. Because we cannot "do the experiment" of altering global climate in a laboratory, we must attempt to model climate and climatic changes, an imprecise alternative because of the complexity of the global climate system. 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 [*Manabe*, 1969*a, b*; *Schlesinger and Gates*, 1980; *Manabe and Stouffer*, 1980; *Manabe and Wetherald*, 1980; *Wetherald and Manabe*, 1981; *Ramanathan*, 1981; *Manabe et al.*, 1981; *Hansen et al.*, 1983, 1984, 1988; *Washington and Meehl*, 1983, 1984; *Wilson and Mitchell*, 1987; *Mearns et al.*, 1989; *Schneider et al.*, 1989].

General circulation models currently provide the best information on the response of the atmosphere to increasing concentrations of greenhouse gases. In theory, GCM estimates of changes in hydrologic variables, such as runoff, could be used directly to estimate changes in water resources. The *U.S. Environmental Protection Agency* [1984] took this approach to estimate possible impacts of greenhouse warming on precipitation, runoff, and soil moisture over large areas of the United States. Using the Goddard Institute for Space Studies (GISS) model, they note that although significant hydrologic changes can be expected under a doubled CO_2 climate, the hydrologic output from GCMs was not sufficiently accurate to define future conditions in particular watersheds.

Manabe and Wetherald [1986] used the Geophysical Fluid Dynamics Laboratory (GFDL) general circulation model to look at soil moisture in the midcontinental region of the United States and concluded that significant drying may occur if the concentration of CO_2 in the Earth's atmosphere is doubled. Although the results from the various GCMs are not in complete agreement on the issue of midcontinental summer dryness [e.g., *Schlesinger and Mitchell*, 1985, 1987; *Mitchell and Warrilow*, 1987], more recent studies are beginning to confirm significant soil moisture reductions [*Wilson and Mitchell*, 1987].

One other feature of GCM-computed hydrologic changes merits special attention: the decrease and earlier disappearance of winter snowpack. Although estimates of 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 responsible for much of the summer soil moisture effects discussed earlier. Similar alterations of snowfall and snowmelt conditions have now been identified in regional model studies, discussed in detail below.

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 2 increase in resolution requires approximately a factor of 8 increase in computer time [*Somerville*, 1987]). With a typical model resolution of 4.5° latitude by 7.5° longitude and nine vertical layers in the atmosphere, computing 1 year of weather at 30-min intervals takes 10 hours of computer time on a Cray XMP computer, one of the fastest in the world.) Present resolutions are usually from 4° to 7.5° latitude by 5° to 10° longitude, grid areas 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 [*WMO*, 1987]. 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 [see *Manabe*, 1969*a*]. 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 [*Manabe and Wetherald*, 1985]. Efforts are being made to improve GCM hydrology [*Dickinson*, 1984], such as through improvements in vegetation parameterizations and the behavior of soils, but until such improvements occur, those interested in the implications of climatic changes for water resources must look for other 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. This approach is described below.

Paleoclimate Analogues

Variations of climatic 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 trying to identify periods that may be similar to future greenhouse conditions, we can explore where significant changes in water availability may appear.

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 2 and 3 show two such climate reconstructions.

Nicholson and Flohn [1980] explored water availability in Africa using a variety of paleoclimatic records. They suggest that parts of the Sahel region were drier 18,000 years before present (B.P.), became more moist in the period 10,000–4500 years B.P., and then became drier up to the present. These changes can then be related to possible driving forces in the global atmospheric circulation.

The use of pollen in cores from lakes and marshy sites also can provide very long climate records, as shown by *Adam and West* [1983], who analyzed pollen in cores from Clear Lake in northern California to estimate both temperature and precipitation during the past 130,000 years. *Velichko* [1984] also used "paleofloristics" to reconstruct past climatic conditions across the area of the Soviet Union during the late Pleistocene interglaciation. These data are now being used by Soviet climatologists seeking climate analogues for assessing the implications of greenhouse warming on soil moisture and runoff.

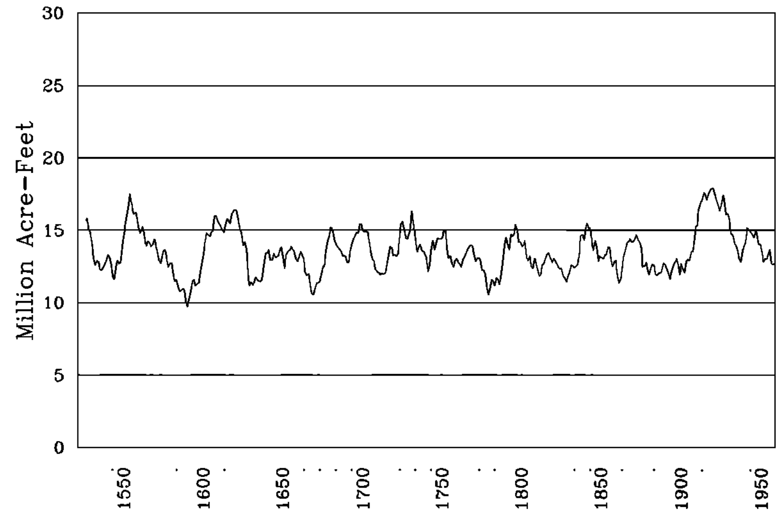


Figure 2. The 400-year runoff record in the Colorado River Basin reconstructed from tree rings (plotted as a 10-year moving average) [from *Stockton and Jacoby*, 1976]. Note the anomalously high runoff during the early twentieth century. This short period was used to determine allocations for the 1922 Colorado River compact.

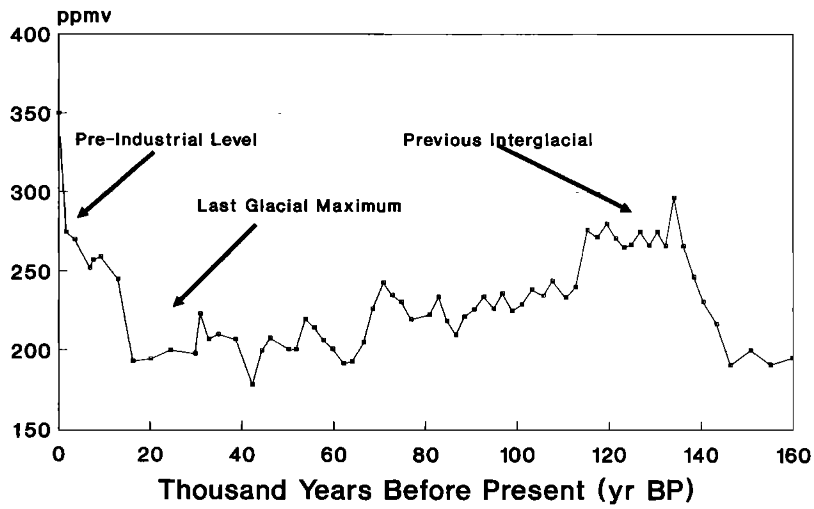


Figure 3. Atmospheric carbon dioxide concentration in parts per million by volume (ppmv) for the past 160,000 years, reconstructed from the Vostok ice core, Antarctica [from *Barnola et al.*, 1987]. Note the high CO_2 concentration during the most recent interglacial, the low CO_2 concentration during the most recent glacial maximum, the rise in CO_2 at the start of the current interglacial (18,000 years B.P.), and the recent dramatic increase in CO_2 concentration due to industrial activities.

Morgan [1985] compiled a continuous record of temperature from the third century A.D. calculated from oxygen isotope ice core data from the Antarctic. *Aristarain et al.* [1986] measured the deuterium content of snow layers in Antarctica to generate a temperature record from 1850 to the present, and they note that several thousand years of record may be accessible in parts of the Antarctic. Indeed, the more recent Vostok core [*Barnola et al.*, 1987] extends the record of atmospheric CO_2 concentration back 160,000 years (Figure 3).

In an early climate reconstruction, *Snyder and Langbein* [1962] evaluated the role of changes in temperature and precipitation in altering the level of a Pleistocene lake in Spring Valley, Nevada. Similarly, *Goodfriend et al.* [1986] explored the paleoclimatic evidence for climatic changes in the area of the Jordan River Basin and the Dead Sea, another terminal lake sensitive to changes in inflow and evaporation. They identified large fluctuations in the level of the Dead Sea in the late Pleistocene period up through 4300 years B.P.

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 [*Budyko and Izrael*, 1987]. In this work the Holocene optimum (about 6000 to 5000 years B.P.) is considered an analogue for a 1°C warming; the last interglacial (about 125,000 years B.P.) is considered an analogue for a 2° to 2.5°C warming; and the Pliocene climatic optimum (about 3 to 4 million years B.P.) 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.

Techniques are also available for extending the current instrumental record back several centuries [*Stockton*, 1977]. Such reconstructions can provide valuable information on both past climatic conditions and the vulnerability of our water resource system to future changes. In a striking example, *Stockton and Jacoby* [1976] used tree rings to extend the runoff record in the Colorado River basin back more than 400 years (Figure 2).

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: about 30 years from the late 1890s to the early 1920s. In 1976, when the historical record was reconstructed back to the middle 1500s, the period from 1890 to the 1920s stood out as a time of abnormally high runoff (Figure 2). 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.

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 may differ considerably from the anthropogenic changes now anticipated. And third, because these past changes typically predate human activity, we have no evidence of how they might affect society. Because of this last limitation, attention has lately turned to the use of more recent climatic extremes within the instrumental record.

Recent Climate Analogues

Modern instrumental data can be used to develop climate scenarios. Examples from the literature include a review and adjustment of instrumental temperature records from central Canada from 1768 up to 1910 [*Ball and Kingsley*, 1984]; a reconstruction of temperature for North America from 1602 to 1961 using high-quality tree ring records [*Fritts and Lough*, 1985]; a reconstruction of the long-term precipitation record at Padova, Italy, from 1725 to 1981 [*Camuffo*, 1984]; and the development of an annual rainfall index for southern California from 1769 to 1834 using agricultural records from the Spanish period [*Rowntree*, 1985]. These types of analyses can greatly extend the useful historical record in a region.

Long-term records can then be analyzed for examples of climatic variability that offer insights into the vulnerability of water systems. *Wigley et al.* [1984] looked at precipitation records in England and Wales for the period 1766–1980 to evaluate whether there had been a change in the frequency of wet and dry rainfall extremes. *Jones* [1984] then used these data to reconstruct river flow to study the effects of climate on water availability. Similarly, *Palutikof* [1987] used scenarios constructed from the instrumental record to explore possible impacts on United Kingdom water resources in the early years of a climatic change.

On a far larger scale, *Bradley et al.* [1987] compiled precipitation data from the mid 19th century, northern hemisphere land areas in an effort to look for trends. In the last 30 to 40 years, significant increases in mid-latitude precipitation (35° to 50°N) and decreases in low-latitude precipitation (5° to 35°N) have been observed. 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 the present society to future climatic changes. *Glantz and Ausubel* [1984], *Changnon* [1987*a*], *Gleick* [1988], *Morrisette* [1988], *Cohen* [1988], and *Karl and Reibsame* [1989] all discuss regional water resource impacts that are a function of past climatic variability. 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 may have a 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 in relation to future climatic conditions. Such scenarios (e.g., +2°, +3°, +4°C; increases or decreases of 10% or 20% 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 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

TABLE 1. Regional Studies Using Hypothetical Climate Scenarios

Study	*Scenario*		
	Temperature	*Evapo-transpiration*	*Precipitation*
Stockton and Boggess [1979]	± 2°C		± 10%
Němec and Schaake [1982]	+1°C, +3°C		±10%, 25%
Revelle and Waggoner [1983]	+2°C, +4°C		-10%
Flashcka et al. [1987]	±2°C		±10%, 25%
Gleick [1986*b*, 1987*a*, *b*]	+2°C, +4°C		±0%, 10%, 20%
Fitzgerald and Walsh [1987]		±5%, 10%, 15%	±5%, 10%, 15%, 20%
Schaake [1989]		±10%	±10%, 20%

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 used to estimate impacts on water resources. If accurate estimates of future water availability are to be calculated, regional 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 using hydrologic models for assessing regional impacts of climatic changes has several attractive characteristics. First, diverse modeling techniques exist. This 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 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 climate 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. Many 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 models [*Viessman et al.*, 1977; *Linsley et al.*, 1982]. For the purpose of climate impact assessment an important distinction can be made between (1) 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, such as the models of *Schwarz* [1977], *Revelle and Waggoner* [1983], and *Stockton and Boggess* [1979], and (2) those techniques that are physically based mathematical descriptions of hydrologic phenomena, the so-called deterministic or conceptual models [*Němec and Schaake*, 1982; *Gleick*, 1986*a*, *b*, 1987*a*, *b*; *Mather and Feddema*, 1986; *Cohen*, 1986; *Flaschka et al.*, 1987; *Bultot et al.*, 1988].

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 different types of hydrologic phenomena. The models vary in their ability to represent or reproduce 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 model design, data requirements, and the objectives of the analyst.

Because of these varied strengths and limitations a set of criteria for using regional models to evaluate the hydrologic impacts of climatic changes must be considered. *Gleick* [1986*b*], expanding on the work of *Schaake and Kaczmarek* [1979], developed a set of six important technical factors to be considered when selecting and using a regional hydrologic model to study the impacts of changes in climate on regional water resources: (1) the inherent accuracy of the model; (2) the degree to which model parameters depend upon 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; and (6) compatibility with existing general circulation models.

The Inherent Accuracy of the Model

Models vary in their ability to reproduce existing hydrologic conditions in a watershed. The *World Meteorological Organization* [1975] studied a series of simulation models in order to evaluate their strengths and weaknesses. They concluded that many models perform well for humid basins but that explicit accounting models such as water balance models were distinctly superior in semiarid and arid basins. Perhaps even more significant was the observation that simpler models showed better results than complex models when the quality of input data is poor.

Initial Model Calibration and Changing Conditions

When first calibrating a model, assumptions are made about initial values of input parameters. If necessary, input parameters are varied until the fit between predicted and observed data is considered satisfactory. The dependence of a model on its initial calibration has particular significance for those circumstances where a climatic change significantly affects the underlying predefined parameters of a model. Under these conditions, such as a change in the extent of vegetative cover, the initial calibration of the model is no guarantee that the model can be used accurately for evaluating conditions following a climatic change.

The Availability of Input Data, Including Comparative Historical Data

Historical data must be available both to calibrate any given model and to evaluate the accuracy and applicability of a model to any given watershed. Unless a model can be validated using actual historical records, its value for estimating the effects of changes in climate must be questioned.

The Accuracy of Input Data

The quality of the input data is also important for model validation and for the initial choice of model parameters. Hydrologic measurements are frequently inaccurate, leading to complications in achieving a good fit during model calibration. Adjusting input parameters to meet bad data will result in biases in subsequent model runs.

Model Flexibility, Ease of Use, and Adaptability

Modeling techniques designed for one hydrologic regime may not be directly applicable to different watersheds, because of variations in the timing, nature, and magnitude of flows. For assessment techniques to be applicable to many diverse watersheds the modeling techniques must be flexible in their approach. As noted earlier, additional complexity is no guarantee of model accuracy; it also reduces model adaptability and ease of use.

Compatibility With Large-Scale Climate Models

The desire for compatibility with general circulation models arises from our desire to understand how climatic changes will affect water resources. Since general circulation models now provide the most detailed information on future changes in climate, the ability to link regional hydrologic models with output from GCMs will improve our ability to understand the regional impacts of global climatic changes. Although GCMs do not provide sufficient detail on regional impacts to be used for purposes of prediction, they do provide an internally consistent description of plausible patterns of climatic change. By linking GCMs and regional hydrologic models, we can develop methods that enhance the abilities of both. In this way, estimates of climatic changes can be incorporated into models of watersheds to evaluate possible alterations in water availability and vulnerable points of existing water supplies. And this technique will become even more important as GCMs improve their resolution and their hydrologic parameterizations.

Models designed to evaluate the impacts of climatic changes on runoff must be able to (1) reproduce reasonably well the historical streamflow record and (2) 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 [*Chow*, 1964; *Viessman et al.*, 1977; *WMO*, 1975; *Klemeš*, 1985]. Almost all of these, however, deal with validating models under stationary climatic conditions. When the goal is to investigate effects of climatic changes, additional effort must be made to extend the validation to conditions of nonstationary 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. A variation on this test is to calibrate the model on average conditions and verify that the relative errors during dry periods and wet periods are of similar distribution and magnitude.

What is the basis for credibility of a regional hydrologic model? *Klemeš* [1985, p. 9] summarizes,

> A hydrological simulation model must demonstrate, before it is used operationally, how well it can perform the kind of task for which it is intended. Since no simulation model is intended merely to show how well it fits the data used for its development, performance characteristics derived from the calibration data set are insufficient evidence for its satisfactory performance. The data used for model validation (verification) must represent a situation similar to that in which the model will be used, as it is recognized that data from the actual situation to be simulated are not available.

Different methods have been used in the past few years to evaluate climate-induced changes in water availability (see *Dooge* [1986], *Beran* [1986], *Gleick* [1986*b*], and *Changnon* [1986*b*] for summaries of methods and approaches), including both conceptual and stochastic models. In one of the earliest comprehensive studies, *Stockton and Boggess* [1979] used the empirical relationships derived by *Langbein et al.* [1949] to predict changes in runoff for the 18 water resource regions of the coterminous United States. Using only hypothetical annual average changes, they concluded that warmer and drier shifts in climate would be the most problematic for water availability. *Revelle and Waggoner* [1983] also used the empirical relationships of Langbein et al. to evaluate hypothetical climate change scenarios for the Colorado River Basin. They concluded that annual runoff in this region is especially sensitive to changes in temperature. In one of the first regional studies, *Němec and Schaake* [1982] used a more detailed deterministic approach to look at the impact of hypothetical temperature and precipitation scenarios in an arid and a humid watershed.

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 [*Cohen*, 1986; *Gleick*, 1986*b*, 1987*a*, *b*; *Flaschka et al.*, 1987; *Bultot et al.*, 1988; *U.S. Environmental Protection Agency*, 1988]. Table 2 lists some of those studies that used general circulation model scenarios of climate change as input to regional hydrologic models.

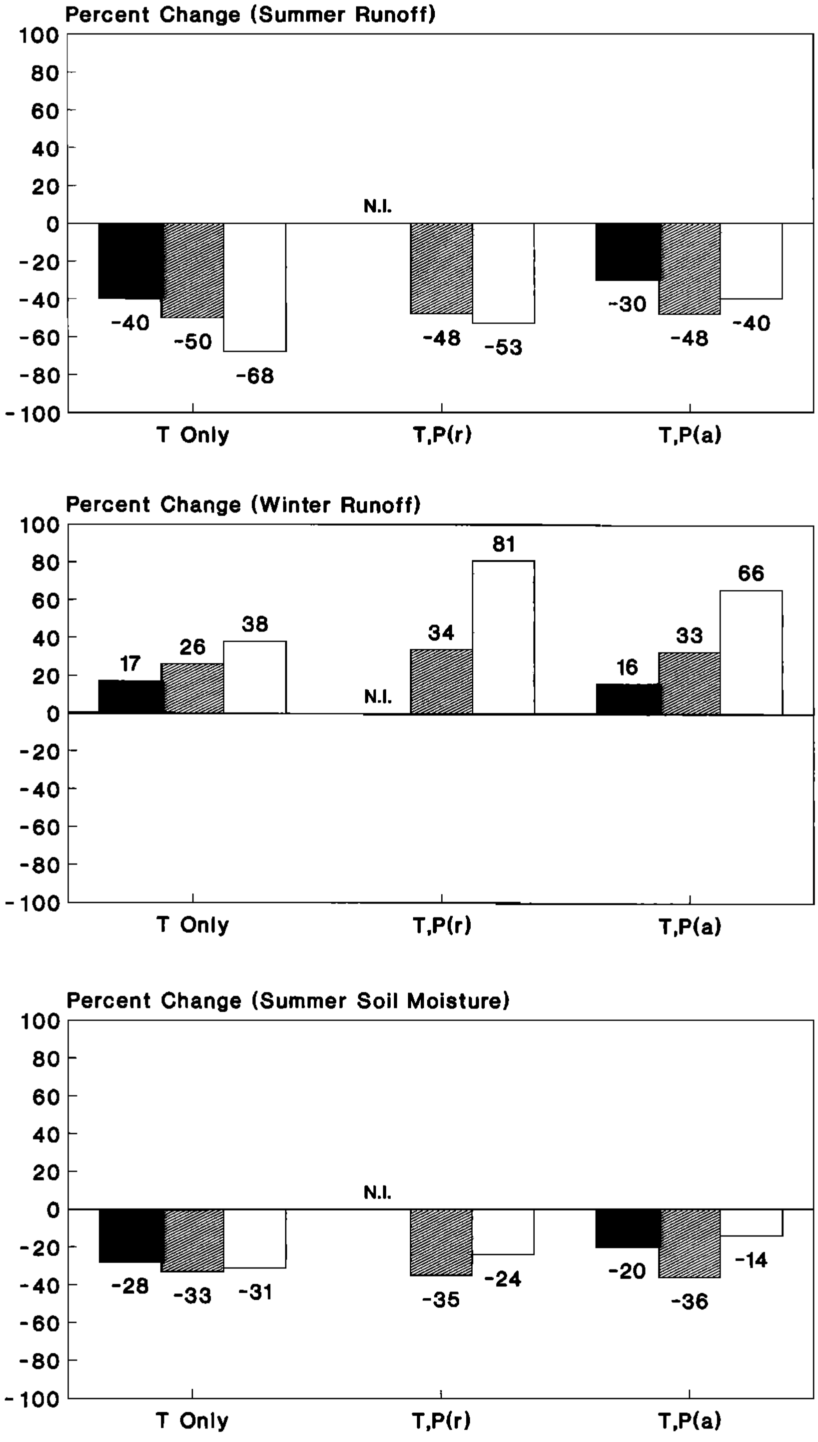
Cohen [1986] evaluated the implications of general circulation model temperature and precipitation scenarios for water levels in the Great Lakes. The net basin water supply of the Great Lakes was predicted to decline in response to greenhouse warming over a wide range of climate scenarios, including 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 by between 15% and 30%.

In a study of the Sacramento Basin in California, *Gleick* [1986*a*, *b*, 1987*a*, *b*] identified hydrologic impacts that were robust and consistent over a wide range of both hypothetical and GCM-generated climate change scenarios. These 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%, winter runoff increased by 16% to 81%, and summer soil moisture decreased by 14% to 36% (Figures 4*a*–4*c*). The principal mechanism driving these hydrologic effects is a dramatic change in snowfall and snowmelt conditions. Because of higher temperatures a greater fraction of annual and seasonal precipitation falls as rain, rather than as snow. This 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

TABLE 2. Hydrologic Studies Using GCM Output

Study	*GISS*	*GFDL*	*NCAR*	*OSU*
Gleick [1987*b*]	X	X	X	
Cohen [1986]	X	X		
Mather and Feddema [1986]	X	X		
Sanderson and Wong [1987]	X			
Bultot et al. [1988]	X			
U.S. Environmental Protection Agency [1989]	X	X		X

Different GCM runs were used by different researchers. Thus the results of each study must be reviewed individually. Please refer to individual studies for details of methodologies and basin-specific assumptions. Abbreviations are defined as follows: GISS: Goddard Institute for Space Studies, New York; GFDL: Geophysical Fluid Dynamics Laboratory, Princeton, New Jersey; NCAR: National Center for Atmospheric Research, Boulder, Colorado; and OSU: Oregon State University, Corvallis.



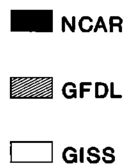


Figure 4. Changes in seasonality of runoff and soil moisture in the Sacramento Basin, California, due to climatic change [from *Gleick*, 1987*b*]. (*a*) The percent change in average summer (June, July, and August) runoff between the model historical run ("base case") and eight GCM-derived doubled carbon dioxide scenarios is shown. Note that all scenarios show a decrease in summer runoff. (*b*) The same plot is shown for average winter runoff (December, January, and February). Note that all scenarios show large increases in winter runoff. (*c*) The percent change in average summer (June, July, and August) soil moisture between the base case and eight GCM-derived scenarios is also illustrated. All scenarios show 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, and by increased summer evapotranspiration [*Gleick*, 1987*a*, *b*]. Abbreviations are defined as follows: NCAR: National Center for Atmospheric Research; GFDL: Geophysical Fluid Dynamics Laboratory; GISS: Goddard Institute for Space Studies; T only: temperature changes only; T, P(r): temperature and relative (percent) change in precipitation; T, P(a): temperature and absolute change in precipitation; and N.I.: NCAR relative precipitation run not included.

summer soil moisture. This effect has now been noted in other regions [*Shiklamanov*, 1987; *Bultot et al.*, 1988; *U.S. Environmental Protection Agency*, 1988; *Martinec and Rango*, 1989] and has been identified in GCM results [*Manabe and Wetherald*, 1986; *Wilson and Mitchell*, 1987].

Two other results are particularly noteworthy. First, annual runoff appears to be more sensitive to changes in precipitation than to changes in temperature [*Gleick*, 1987*b*; *Flaschka et al.*, 1987; *Karl and Reibsame*, 1989], an effect described theoretically by *Wigley and Jones* [1985]. 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 [*Gleick*, 1987*b*; *Bultot et al.*, 1988; *U.S. Environmental Protection Agency*, 1988]. 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, as described above.

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 the 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.

IMPACT ON WATER RESOURCES AND WATER MANAGEMENT

Ultimately, unless climatological 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 new 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, and a wide range of environmental services, such as fisheries, waterfowl habitat, and wetlands preservation. Table 3 [from *Novaky et al.*, 1985] presents the sensitivity of water management problems to climatic variability and change.

TABLE 3. The Sensitivity of Water Resources to Climatic Variability

Water Resource Management Methods & Techniques	*Sensitivity to Climatic Events* *Within-Year*	*Annual*	*Multi-Year*	*Century*
Protection against floods	X	X		
River training	X	X	X	
Drainage		X	X	X
Water quality	X	X	X	X
Wastewater renovation		X	X	
Water supply		X	X	X
River canalization (dams)		X	X	
Storage reservoirs		X	X	X
Groundwater utilization		X	X	X
Water transfers		X	X	X
Soil moisture management	X			
Erosion control	X			

From *Novaky et al.* [1985]

While little research has been done in these areas, some recent findings are described below. 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.

Reservoir Reliability

An early paper on reservoir reliability by *Schwarz* [1977] identified a range of likely changes and offered a framework for identifying where the failure of existing operating methods might occur. *Němec and Schaake* [1982] looked at a set of hypothetical climate scenarios and evaluated reservoir reliability under conditions of altered runoff for a humid and an arid watershed. They concluded that increased storage may be needed to offset the effects of climatic changes, if traditional definitions of reliable yields are to be maintained. More recently, *Dracup and Kendall* [1989] evaluated how changes in runoff due to greenhouse warming may alter reservoir reliability or the need for reservoir capacity. In their analysis, reservoirs designed and operated under current climatic conditions will be severely stressed by climatic changes. Of particular concern is that the volume of storage needed to maintain existing water yields may change significantly as greenhouse warming progresses.

Water Quality

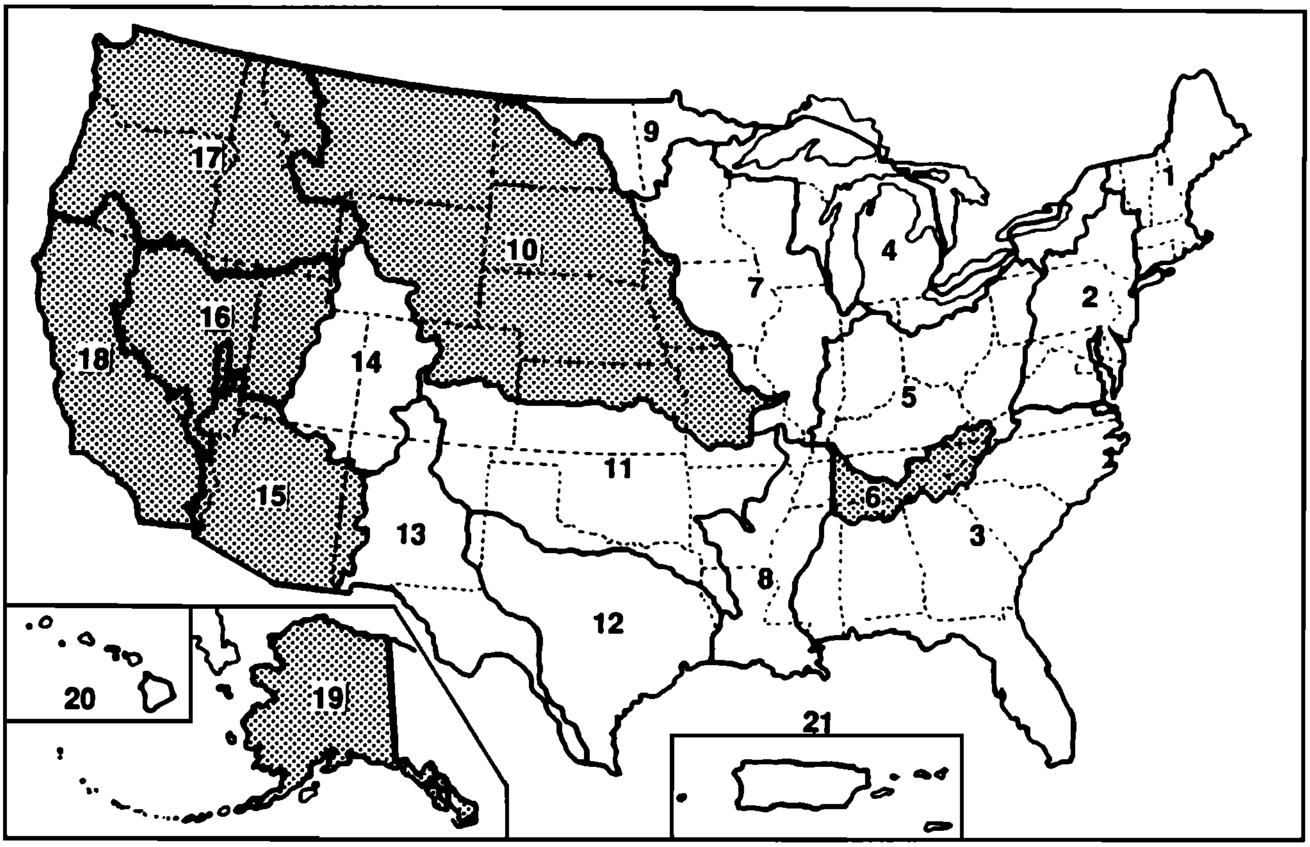
Coutant [1981] identified rising temperature and reductions in streamflow due to climatic changes to be of primary important for water quality. Existing computer simulations of waste degradation and oxygen dynamics can be used to quantify the implications for water quality of greenhouse warming. *Henderson-Sellers* [1987] developed a simple box diffusion model to investigate the effects of increasing atmospheric CO_2 upon reservoir water quality and suggested that increased evaporative losses from reservoirs could lead to enhanced nutrient loading and accelerated eutrophication.

Jacoby [1989] and the *U.S. Environmental Protection Agency* [1988] addressed the issue of using existing models for identifying how to maintain satisfactory water quality under conditions of changing climate. In particular, if climatic changes reduce the freshwater available for diluting wastewater, recharging aquifers, or repelling salinity in estuaries, expensive water quality protection measures may be required. *Williams* [1988] looked at the effects of climatic changes on salt water penetration into the San Francisco Bay and the Sacramento/San Joaquin Delta. He warned that a greenhouse warming may require greater releases of freshwater from the upstream reservoirs (so-called "carriage water") during spring and summer low-flow periods to flush salt water back toward the San Francisco Bay to protect water supply intakes and natural ecosystems in the delta. The increased need for carriage water could threaten the amount of freshwater that can be made available for southern California.

Energy Production

Hydroelectricity production is vulnerable to existing climatic variability. Reductions in annual runoff, increased interannual variability of drought episodes, and more pronounced seasonality of flows would all affect hydroelectric production. In regions where significant fractions of electricity are generated with water (see Figure 5), a climatic change that reduces water availability or changes the seasonality of runoff may lead to the need for

Figure 5. Regions of the United States dependent on hydroelectricity for between 20% and 100% of electricity supply [from *Gleick*, 1989]. These regions are particularly sensitive to climatic changes that reduce the amount of water available for hydroelectricity generation.



KEY TO REGIONS

1 NEW ENGLAND	7 UPPER MISSISSIPPI	12 TEXAS-GULF	17 PACIFIC NORTHWEST
2 MID-ATLANTIC	8 LOWER MISSISSIPPI	13 RIO GRANDE	18 CALIFORNIA
3 SOUTH ATLANTIC GULF	9 SOURIS-RED-RAINY	14 UPPER COLORADO	19 ALASKA
4 GREAT LAKES	10 MISSOURI	15 LOWER COLORADO	20 HAWAII
5 OHIO	11 ARKANSAS-WHITE-RED	16 GREAT BASIN	21 CARIBBEAN
6 TENNESSEE			

expensive replacement power [*Gleick*, 1988, 1989; *Miller*, 1989]. In California, during the 1976–1977 drought, $500 million worth of fossil fuels were consumed to replace lost hydroelectricity supplies [*Gleick*, 1988].

Miller [1989] examined in more detail the potential impact of altered water supplies on the electric power industry in the United States. She identified seasonal reductions in water availability as an important threat to reliable hydroelectricity supply. Another major problem facing the energy industry is the availability of cooling water for thermal power plants. Fortunately, the consumptive use of water for thermoelectric cooling is only around 2% of the total consumptive use, and a wide variety of alternative cooling technologies can be adopted should future water shortages emerge.

Irrigation Demands

Hargreaves [1981] discussed the implications of higher temperature for agricultural water demand. He pointed to both rising evapotranspiration due to rising temperatures and decreasing precipitation as critical factors for identifying climatic zones for agriculture. He also noted that irrigation may become increasingly important to ensure the adequacy of water supplies for crop production.

Peterson and Keller [1989] extended this work and evaluated the implications of changes in temperature and precipitation for the net irrigation requirement, the depth of irrigation needed to maximize production at a particular location, and the future irrigated percent of cultivated land. They concluded that a warmer climate will have its greatest impact in dry regions (such as the western United States), where irrigators will be hard-pressed to maintain current levels of irrigation. For their scenario of a 3°C temperature increase and a 10% decrease in precipitation, cultivated areas in the western United States could decrease by nearly 30%, unless efforts are made to improve the efficiency of water use or to develop new supplies.

Environmental Services

Coutant [1981] raised the question of adverse biological responses in estuaries due to altered freshwater flows and increased salinity and recommended the use of mathematical and biophysical models to study estuaries, such as the Chesapeake Bay, the Hudson River, or the Delaware Bay. *Josselyn and Callaway* [1988] look at the implications of decreased freshwater flows and changes in salinity for the rich ecosystem of the San Francisco Bay–San Joaquin Delta region and identified some adverse consequences of greenhouse warming for phytoplankton productivity and fish breeding and survival.

Cooper [1989] noted that impacts on recreation, wildlife, and esthetics are often the early warning signs that something is wrong with our environment. He identified a wide range of climatic changes that would adversely affect environmental services offered by freshwater resources and proposed active measures to anticipate and alleviate any detrimental consequences.

CONCLUSIONS

Global climatic changes caused by an increased concentration of atmospheric trace gases will have important and diverse implications for freshwater resources. While we cannot see clearly the direction or magnitude of many important changes, research in the past few years has highlighted important regional vulnerabilities and has improved our understanding of appropriate methods for addressing hydrologic and water resource questions.

In the long run, large-scale general circulation models of the climate may be able to give us 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 our understanding of climatic vulnerabilities, including reviewing the paleoclimate and more recent instrumental 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.

Some of the regional results described here support recent suggestions that mid-latitude summer soil moisture reductions may occur in many regions of the world. The principal physical mechanisms involved (the decrease in snow as a fraction of total winter precipitation, an earlier and faster disappearance of winter snowpack because of higher average temperatures, and a more severe evapotranspiration demand during the warmer summer months) are both physically plausible and consistent with the hydrologic mechanisms that lead to regional summer soil moisture drying in the GCMs. While other, countervailing hydrometeorologic features may well exist, such as cloud cover/evapotranspiration feedbacks, the consistency of the soil moisture and runoff results observed here must be considered a first warning of possible important changes in regional water availability. As more information on these other factors develops, it can be incorporated into hydrologic models to provide more detailed regional assessments.

Ultimately, if realistic estimates of changes in regional water availability are to be calculated, a number of advances are needed. In order to be valuable to water resource planners, regional hydrologic assessments must include (1) a focus on short time scales such as days or weeks, rather than annual or even monthly averages; (2) the ability to incorporate into regional studies the increasingly detailed assessments of changes produced by GCMs; (3) the ability to produce information on hydrologically important variables, such as changes in runoff and available soil moisture; and (4) 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 mean 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 our water systems can be convinced that the problem of climatic change is sufficiently real and pressing to require their attention. Much work remains to be done.

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