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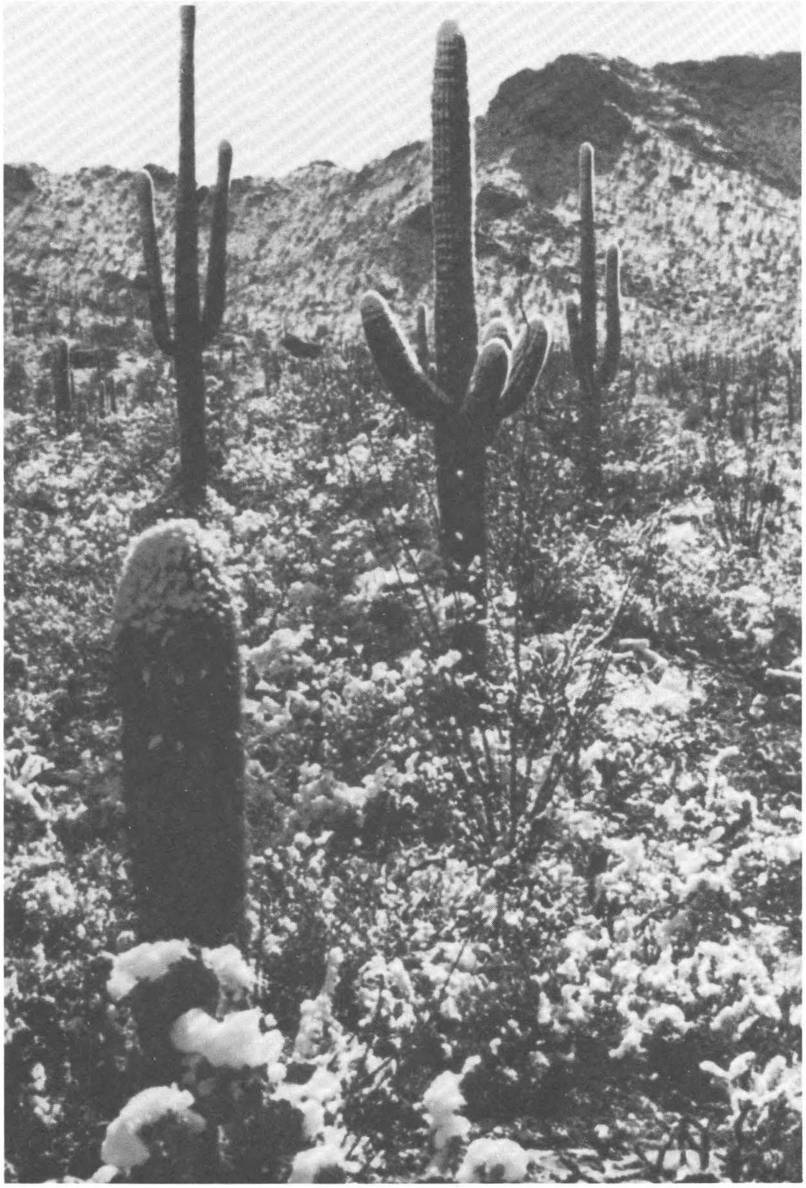

WATER RESOURCES IN THE TWENTY-FIRST CENTURY—

A STUDY OF THE IMPLICATIONS OF CLIMATE UNCERTAINTY

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By Marshall E. Moss and Harry F. Lins

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FOREWORD

The uncertainty associated with global-climate change and attendant implications for water and land resources represents one of the major scientific challenges of the 20th century. The geophysical and geochemical complexities inherent to the study of climate change are enormous. Disciplines from within the atmospheric, hydrospheric, terrestrial, and biological sciences are compelled now, as never before, to cooperate in studying the climate system, especially the intricate interactions of the processes comprising it.

For more than a decade, the U.S. Geological Survey has been an active participant in Federal programs designed to enhance scientific understanding of climate variability and change as well as the social, economic, and political implications of such change. Recent revisions to the U.S. National Climate Program Plan call for a significant increase in the role and responsibilities of the Geological Survey. To meet the challenge of enhanced participation in the study of climate, the Survey is currently engaged in the development of new programs that build upon and expand our previous efforts.

One of the most fundamental aspects of this expansion involves the development of new insights into the potential water-resources implications of climate change. A better understanding of the global-hydrologic cycle is frequently cited as a critical climate research need. ''Water Resources in the Twenty-First Century—A Study of the Implications of Climate Uncertainty'' presents the elements of the Geological Survey's program for studying climate and hydrology. It incorporates the Survey's strong and traditional approach that couples research, data collection, and interpretive studies. We believe that it demonstrates the strength of the U.S. Geological Survey's commitment to the national and international attempts to understand the nature and effects of climate change.

Dallas L. Peck
Director

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By Marshall E. Moss *and* Harry F. Lins

Abstract

The interactions of the water resources on and within the surface of the Earth with the atmosphere that surrounds it are exceedingly complex. Increased uncertainty can be attached to the availability of water of usable quality in the 21st century, therefore, because of potential anthropogenic changes in the global climate system. For the U.S. Geological Survey to continue to fulfill its mission with respect to assessing the Nation's water resources, an expanded program to study the hydrologic implications of climate uncertainty will be required. The goal for this program is to develop knowledge and information concerning the potential water-resources implications for the United States of uncertainties in climate that may result from both anthropogenic and natural changes of the Earth's atmosphere. Like most past and current water-resources programs of the Geological Survey, the climate-uncertainty program should be composed of three elements: (1) research, (2) data collection, and (3) interpretive studies. However, unlike most other programs, the climate-uncertainty program necessarily will be dominated by its research component during its early years.

Critical new concerns to be addressed by the research component are (1) areal estimates of evapotranspiration, (2) hydrologic resolution within atmospheric (climatic) models at the global scale and at mesoscales, (3) linkages between hydrology and climatology, and (4) methodology for the design of data networks that will help to track the impacts of climate change on water resources. Other ongoing activities in U.S. Geological Survey research programs will be enhanced to make them more compatible with climate-uncertainty research needs.

The existing hydrologic data base of the Geological Survey serves as a key element in assessing hydrologic and climatologic change. However, this data base has evolved in response to other needs for hydrologic information and probably is not as sensitive to climate change as is desirable. Therefore, as measurement and network-design methodologies are improved to account for climate-change potential, new data-collection activities will be added to the existing programs. One particular area of data-collection concern pertains to the phenomenon of evapotranspiration.

Interpretive studies of the hydrologic implications of climate uncertainty will be initiated by establishing several studies at the river-basin scale in diverse hydroclimatic and demographic settings. These studies will serve as tests of the existing methodologies for studying the impacts of climate change and also will help to define subsequent research priorities. A prototype for these studies was initiated in early 1988 in the Delaware River basin.

INTRODUCTION

Recently, climate has attained the status that Charles Dudley Warner long ago claimed for the weather; that is, "everybody" talks about it. But counter to the old saw about weather, "somebody" is doing something about the climate of the Earth—"somebody" is changing it. However, it is uncertain whether the changes at any point or at any time will be beneficial or detrimental. At this time, the only certainty pertaining to climate change is that its potential impacts on humankind will be pervasive. Describing the trend within the scientific community toward more integrated interdisciplinary studies of the Earth to cope with the uncertainties of change, Bretherton (1987) states:

> This movement gains a sense of urgency from signs that human activities are altering our global environment in unprecedented ways, with consequences for our children and grandchildren that we are barely able to comprehend. Although some of the changes may well be beneficial, others may not. Without an adequate understanding of what is happening, all are likely to be stressful.

Among the resources most likely to be impacted significantly is water.

Water is one of the physical elements that must be studied intensively in order to develop a better understanding of the potential for climatic change. Thus, the hydrologist is a necessary component in developing the science of global environmental change in addition to serving as a linkage to the water-resources decisionmakers, who need the anticipated new knowledge to decrease the stress that Bretherton so aptly describes. Traditionally, the U.S. Geological Survey (USGS) has played a significant role in the development of the world's hydrologic knowledge and information. However, the water-resources mission of the Geological Survey, discussed in more detail subsequently, cannot be effectively fulfilled in the 21st century without active participation in the national and international programs investigating global climate change. This document provides a basis for planning the evolution of the Geological Survey water-resources activities in light of the potential for climate change in a decadal timeframe.

This document is the synthesis of ideas derived from discussions with many of the authors' colleagues both from within and from outside the U.S. Geological Survey. The authors particularly would like to acknowledge the contributions of Mark Ayers, Julio Betancourt, Fred Nichols, Dave Peterson, and Tom Winter.

PERSPECTIVES ON CLIMATE, HYDROLOGY, AND THE U.S. GEOLOGICAL SURVEY

The concept of climate is an evolving one, and today there are usages within the scientific community for this term that are at variance with each other. Therefore, a working definition for the purposes of this document is provided here:

> Climate—the unconditioned, statistical (probabilistic) description of the sequence of measures of a suite of properties that describe the atmospheric components of the environment of a locality or region.

In other words, climate comprises the likelihoods, independent of weather-forecasting skill, of such properties as sunshine or percentage of cloud cover, amount and intensity of precipitation, or the magnitude and direction of wind. Weather is a realization or happening at any particular instant from within the realm of possibilities described by the appropriate climate descriptions for that instant.

Both climate and weather impact the study of the Earth's water resources, which is known as hydrology. Hydrology, through its linkage with climate, entails the statistical description of water-related environmental conditions; but it also, through its relation with weather, involves an accounting of the individual realizations in time of such conditions. Thus, conceptually, the term "hydrology" refers to a broader field of study than either climatology or meteorology. In this regard, hydrology is more analogous to the term "atmospheric sciences," which encompasses both climatology and meteorology. With these distinctions drawn, it is possible to define a role for the Geological Survey in the study of the hydrologic implications of climate uncertainty.

Climate Variability, Change, and Uncertainty

The classical definition of climate was a quasi-static one; climate was described by the normal or most common weather conditions. It was recognized that climate could change on a time scale of centuries to millennia, but the averages of limited historical data were the best key to what might happen weatherwise in the future. Such an approach suffered from several shortcomings. First, the averages or norms of weather properties do not comprise a sufficient set of statistics to describe the atmospheric environment. The variability and particularly the extremes of weather are often more useful for climate applications than are norms. Second, examination of longer historical records demonstrated that periods of deviation of weather from its norms could last significantly longer than could be explained on a statistical basis. The Little Ice Age is such an example (Eddy, 1976). Third, for many areas of the world, the periods of data collection are too short and the numbers of meteorological stations are too few to accurately describe the local climate, even on a quasi-static basis. Thus, study of any climate-related phenomenon such as water resources must contend with significant uncertainty even before the consideration of potential anthropogenic change of the Earth's atmosphere.

Climate varies periodically on at least three temporal scales: (1) daily, (2) annually, and (3) over geological ages. Over the daily cycle, changes in insolation and temperature are as distinct as night and day; over the annual cycle, clouds, precipitation, and winds may vary seasonally as well; and at the geologic time scale, ice sheets wax and wane causing drastic swings in all climate parameters. The changes associated with each of these periods can be attributed primarily to the distribution of incident solar radiation across the Earth's surface. However, another factor that causes variation in the Earth's climate is the makeup of its atmosphere, which controls the amount of energy that passes from the Earth back into space. Radiative gases in the atmosphere, like carbon dioxide, methane, ozone, and water itself, are called greenhouse gases. Analogous to the glass panes in the gardener's greenhouse, these gases permit the passage of the Sun's short-wave energy in to the Earth but deter the longer wave energy reradiated by the Earth from dissipating into space. Thus, the greenhouse gases temper the Earth's climate by retaining energy within the atmosphere.

Since the Industrial Revolution, the use of energy has increased immensely. For the last century much of that energy has come from the consumption of fossil fuels like coal, petroleum, and natural gas. A byproduct of the consumption of fossil fuels is carbon dioxide, which is released to the atmosphere. The concentration of carbon dioxide in the atmosphere has been measured at the top of Mauna Loa in Hawaii since 1958; figure 1*A* illustrates the significant increase in this gas, which frequently has been cited as a likely cause of climatic change. Increasing the carbon dioxide in the atmosphere is analogous to increasing the thickness of the glass panes in a greenhouse—each results in a more efficient deterent to the loss of long-wave energy. Retention of more energy within the atmosphere eventually will result in a global increase in temperature. Perhaps even more disturbing than the increase in atmospheric carbon dioxide is the sporadic but increasing rate at which it is increasing, as is shown in figure 1*B*.

The climatic impacts of increasing concentrations of carbon dioxide will be compounded by increases in other

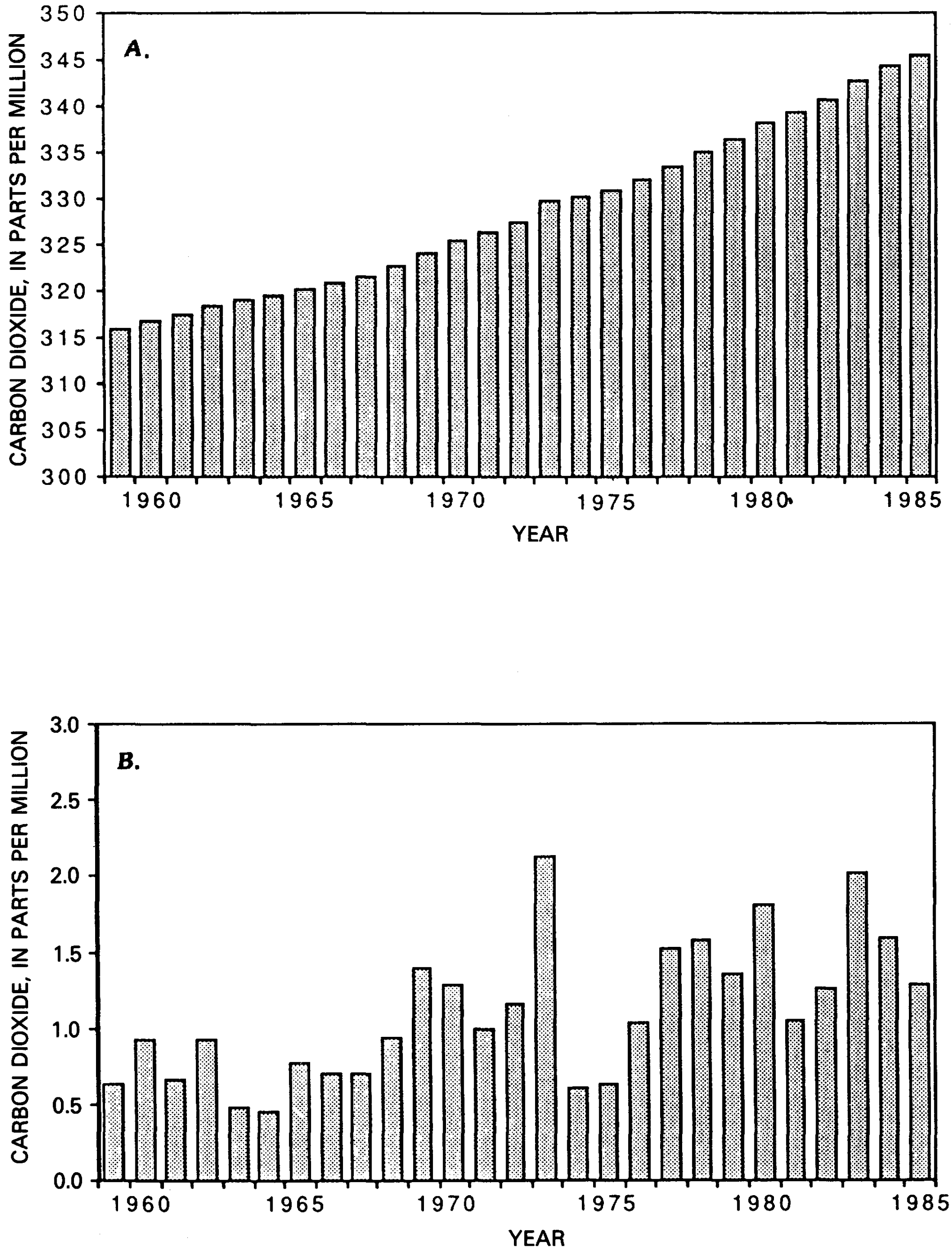

Figure 1. Annual mean concentrations of atmospheric carbon dioxide measured at the Mauna Loa Observatory (*A*) and annual changes in mean concentrations (*B*).

greenhouse gases in the atmosphere (Clark, 1982). In 1985, a group of eminent scientists convened in Villach, Austria, to discuss this problem. They reached a consensus that the global-mean temperature would increase by 1.5 to 4.5° Celsius during the first half of the 21st century (World Climate Programme, 1986). However, because of the dynamic nature of the Earth's oceans and atmosphere, such a change will not occur uniformly over the surface of the Earth. Some areas will warm in excess of the global mean, others less, and probably some will cool.

An important aspect of the greenhouse effect is the potential for positive or negative feedbacks among the phenomena that cause either exacerbation or modulation of the initial effect. For example, increased energy within the atmosphere will cause added evaporation of water from the Earth's surface. If cloud cover is not increased significantly by the added atmospheric water, the greenhouse effect will compound because of the radiative properties of the additional water vapor. On the other hand, if cloud cover increases significantly as a result of the increased evaporation, the clouds will reflect part of the incoming solar radiation and thus will modulate the greenhouse effect.

Concomitant with changes in temperature, other climatic factors also can be expected to vary as a result of the modified atmosphere. Thus, after several decades in which climatic uncertainty seemed to be decreasing as knowledge and information increased, it seems that climatic uncertainty suddenly has increased dramatically.

The Climate-Hydrology Continuum

Unlike climate, the boundaries and definition of hydrology have been rather broadly accepted for several decades. A typical definition is:

> Hydrology—the science that deals with the waters of the Earth, their occurrence, circulation, and distribution, their chemical and physical properties, and their reactions with their environment, including their relation to living things (Federal Council for Science and Technology, 1962).

This level of acceptance was not always so. Meinzer (1942) traces the evolution of the meanings of hydrology from the beginning of the 20th century, when the U.S. Geological Survey used "hydrology" to denote only the study of waters beneath the surface of the Earth. At that time, the study of surface water was referred to as "hydrography" and "hydrometry."

Although many hydrologic studies are conducted from a perspective that is more akin to weather than climate, there is a field of endeavor within hydrology that relates directly to climate, and that is the study of the normal behavior of aspects of the land phase of the hydrologic cycle. Some of the earliest reported hydrologic studies were of this type. Meinzer (1942, p. 14–15) attributes the first studies relating hydrology to climate to Pierre Perrault and Edme Marriotte, who were French contemporaries of the 17th century. Each labored independently to demonstrate that rainfall on the drainage basin of the Seine River was sufficient to be the ultimate source of runoff in the river. Their studies were attempts to add evidence to the theory of the hydrologic cycle that had been espoused a century and a half earlier by Leonardo da Vinci.

A more recent, but also classic, study is that of Langbein and others (1949), which graphically relates the normal runoff in rivers of the United States to the climate measures of precipitation and temperature (fig. 2). Some of the more enduring aspects of the Langbein study were its illustration of (1) how runoff, for a given annual precipitation, decreases as temperature increases; (2) how runoff, for a given temperature, increases with precipitation; and (3) how the numerical difference between precipitation and runoff, for a given temperature, increases with precipitation and

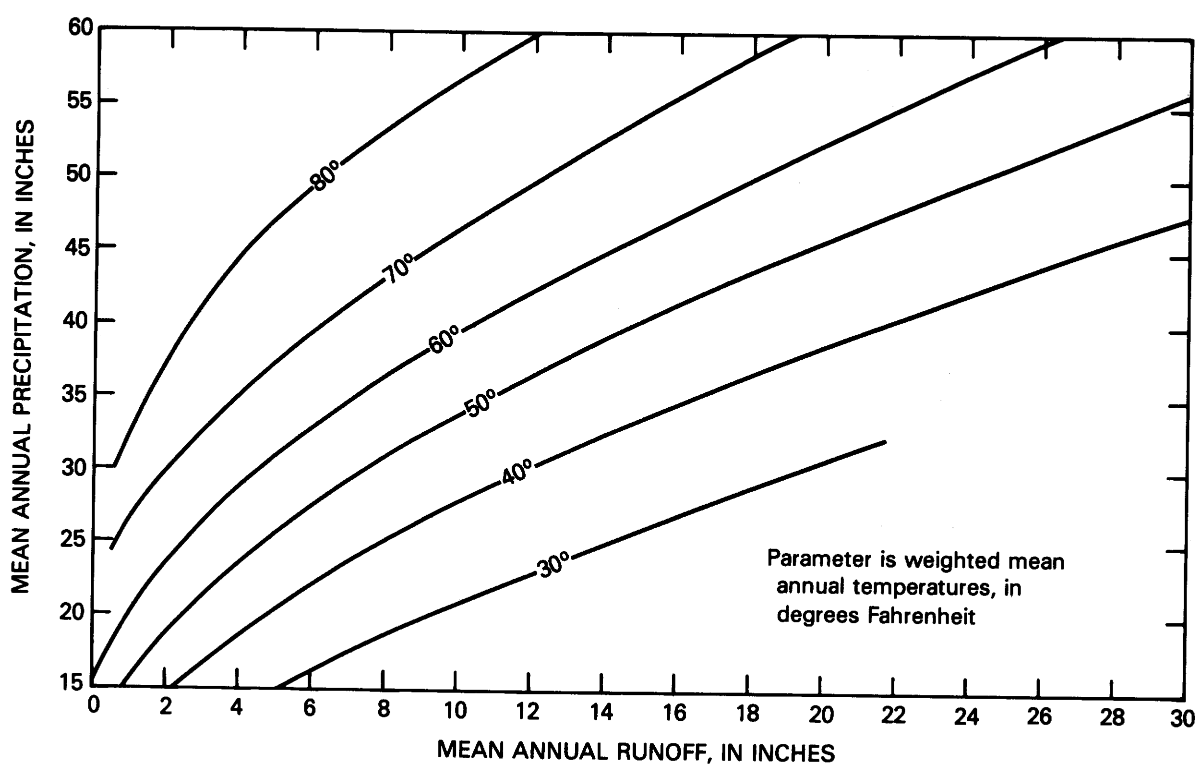

Figure 2. Relation of annual runoff to precipitation and temperature. Source: Langbein and others, 1949.

ultimately reaches a constant representing the limiting rate of evapotranspiration. Although in more recent years there has been an increasing emphasis placed on studying such conditions using numerical models, Langbein's fundamental points have endured. The study continues to this day as a mainstay in the definition of impacts of climate change on streamflow (Revelle and Waggoner, 1983).

A rapidly emerging field of study within hydrology focuses on flooding and related sedimentary processes that occurred during the period from the mid- to late Holocene up to the advent of systematic stream gaging. Such paleoflood studies are having significant impacts on flood-probability estimation. For example, Webb (1985) determined that the frequency of large floods on the Escalante River in south-central Utah was at a maximum 1,100 to 900 years ago and that the largest flood, occurring approximately 950 years ago, was seven times larger than the maximum recorded at any of the river's gaging stations. These flood-frequency changes, in turn, have produced changes in the Escalante's upstream alluvial channel. Valley-margin stratigraphy representing 1,600 years of deposition indicates that since 1,100 years ago, when large floods were at a maximum, a marshy flood plain gave way to a dry, fire-swept meadow wherein a 24-m-wide and 2.5-m-deep arroyo formed.

Although this arroyo filled with sediments between 500 and 400 years ago, floods between 1909 and 1940 recut the arroyo to up to 100 m wide and 17 m deep. Although land use practices have clearly been associated with significant changes in watershed and flood-plain conditions, there also has been a subtle climate shift that has increased the amount of summer precipitation and intensity of storms.

Another example, relevant to both floods and droughts, is their relation to large-scale atmospheric and oceanic phenomena. The occurrence and magnitude of the aperiodic El Niño-Southern Oscillation (ENSO) phenomenon, which spans the South Pacific Basin, have been shown to relate to climatic and hydrologic anomalies from Asia (Shukla and Paolino, 1983) to South America (Hastenrath, 1978; Ropelewski and Halpert, 1987) and to the western and southeastern parts of the United States (Ropelewski and Halpert, 1986) (fig. 3). Such associations, although statistically significant, are often weak, and their physical basis is poorly understood. Considerably more research is necessary before such associations can be used in warning of extreme hydrologic events.

The above examples demonstrate the dependence of several hydrologic variables on climate factors, but the interrelation is not always so unidirectional; studies of the oasis effects of irrigated lands have demonstrated the feedback from living plants, the water surface, and moist soil to modify local microclimates (Oke, 1978). However, the potential magnitudes of the feedbacks for large-scale hydrologic phenomena are just now beginning to be

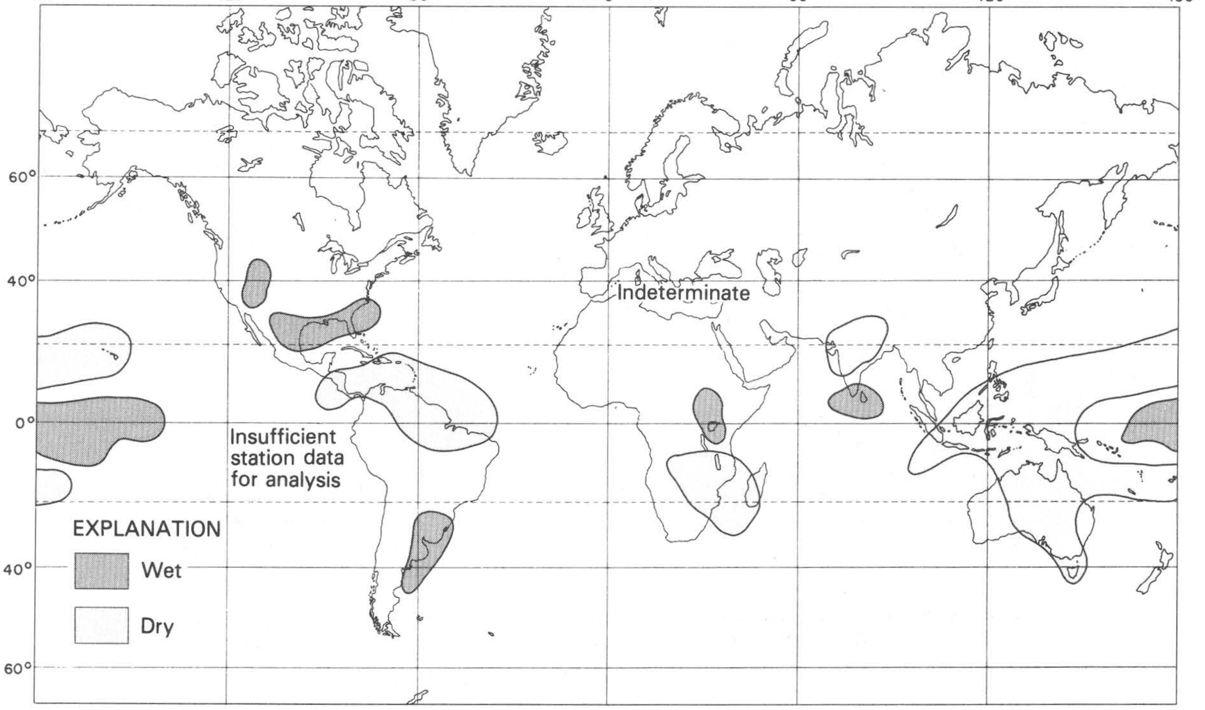

Figure 3. Regions exhibiting a consistent precipitation response signal to El Niño-Southern Oscillation episodes. Source: Ropelewski and Halpert, 1987.

addressed. For example, Barnett and others (1988) have demonstrated the effect that added snow cover and subsequent increased soil moisture in Eurasia have on deterring the subsequent monsoon in South Eastern Asia. This same study shows strong correlations between Eurasian snow cover and the atmospheric conditions over all of North America.

A common characteristic of each of the above examples is that significant levels of uncertainty exist with respect to the exact forms of the interdependence of climate and hydrology and also with respect to the parameters that quantify the interdependence at any given time and location. Therefore, current uncertainties pertaining to the availability and quality of water resources in the 21st century must be viewed as a manifestation of the climatic uncertainty described in the previous section.

Because new hydrologic uncertainties exist and the current level of scientific understanding does not permit their quantification, scenario analysis (Lave and Epple, 1985) has become an accepted tool for exploring potential impacts. Scenario development in the climate-change arena has been based on three separate, but potentially complementary, approaches: (1) reconstruction of prehistoric climates from geologic evidence (paleoclimatology), (2) analysis of aberrant-climate periods in recorded history, and (3) computation of future conditions using physically based three-dimensional General Circulation Models (GCM's). Lamb (1987) has described some of the shortcomings of each of these three. However, any one of today's scenarios points to potential disruptions in certain parts of the water-based economies of the world, while providing added opportunities for other parts. Within the United States, this mix of potential disruptions and opportunities is no more evident than it is on the global scale; the potential for disruption may be greater in the United States than in many other countries, however, because the relatively mature development of our water resources makes them more vulnerable to perturbations.

Because of the potential for major impacts on social, economic, and environmental conditions in the United States, and because of the uncertainties concerning those impacts, major scientific studies are being planned and some already have begun. These studies are being carried out both at the national and global scales.

The Water-Related Mission of the U.S. Geological Survey

The water-related activities of the U.S. Geological Survey are executed by its Water Resources Division. The stated mission of Water Resources Division is to provide the hydrologic information needed for managing the Nation's water resources (Chase and others, 1983). This information is developed by conducting hydrologic research, by collecting basic hydrologic and water-use data, and by performing interpretive studies of the Nation's water resources at various scales from local to national. These three program components are interfaced with the Nation's information users through the release of publications and hydrologic data and through data-coordination, cataloging, and retrieval services.

For almost 100 years, the Geological Survey has been providing hydrologic information to the Nation that is essential for coping with water-supply uncertainty and for protecting the citizenry from the devastations of floods and droughts. For a shorter period of time, the Nation also has depended on the Geological Survey's information to set and implement policies for dealing with the degradation of the quality of its water resources. Thus, the Geological Survey is well positioned by tradition, as well as by the scientific momentum of its current activities, to play a key role in providing information to address the recently recognized increment of hydrologic uncertainty associated with the potential for global climate change. In fact, it will be impossible for the Geological Survey to continue to meet its mission responsibilities in the 21st century if the potential impacts of climate change are not taken properly into account.

Although the Geological Survey has not been one of the major Federal participants in the climate-change activities of the last decade, it has not been isolated from them either. In 1976, the Geological Survey convened a workshop to stimulate discussion of the effects of climate variation on the land and water resources of the Nation (Smith, 1978a,b). As a result of the workshop, a Geological Survey climate plan was developed (Howard and Smith, 1978) that to date has been implemented only to a modest degree. The plan is consistent with the responsibilities of the Geological Survey as specified in the first U.S. National Climate Program Plan, a document called for in the National Climate Program Act (Public Law 95-367) and prepared by the National Climate Program Office of the National Oceanic and Atmospheric Administration in conjunction with other Federal agencies. However, as more knowledge and information have accumulated and as Federal agency activities have shifted, the National Climate Program Plan has been revised (National Climate Program Office, 1988), and the responsibilities of the Geological Survey have increased to that of a lead agency for the study of the interactions between climate and hydrology.

For the Geological Survey to become a focal point for hydrology in the climate-change arena, the significant, but diffuse, climate-related activities that currently are being conducted within the Water Resources Division need to be brought into perspective; their roles relevant to a common goal need to be evaluated, and weaknesses and critical gaps need to be identified. By carrying out these steps and rectifying weaknesses and gaps as resources can be made available, the Geological Survey indeed will have a program on the hydrologic implications of climate uncertainty. The goal for this program is:

> To develop knowledge and information concerning the potential water-resources implications for the United States of uncertainties in climate that may result from both anthropogenic and natural changes of the Earth's atmosphere.

Knowledge and information, as referred to in this goal, encompass fundamental research into the linkages of climate and hydrology, collection of basic data, and the development of technology that facilitates interpretation of the data in light of the research findings. Although the goal is water-resources driven, this program cannot be isolated from current and future advances in climatology, biology, geochemistry, geology, or any of a multitude of interdependent sciences. Nor can the national focus of the goal be interpreted as a limitation to consider only U.S. science and U.S. data bases. The Water Resources Division must be more involved in international scientific endeavors, like the International Geosphere Biosphere Programme and the World Climate Programme, that portend significant progress toward its goal.

ELEMENTS OF A PROGRAM ON THE HYDROLOGIC IMPLICATIONS OF CLIMATE UNCERTAINTY

Elements from each of three major categories of the traditional activities of the Water Resources Division of the Geological Survey—research, data collection, and interpretive studies—are essential in a comprehensive program designed to address the hydrologic implications of climate uncertainty. Maintenance of the proper balance of activities among the three categories at each stage of its evolution will be a key to the program's effectiveness. The final chapter of this document discusses the program balance; the present chapter describes its composition within each of the above categories.

Research

Like climate, the word research has a diversity of meanings even within the scientific community. Therefore, for clarity of presentation, the following definition is used in this document:

> Research—the development of understanding through the conceptualization and testing of new ideas.

More specifically, hydrologic research is the development of understanding about (1) the paths along which water moves on and in the land masses of the Earth, (2) the rates of movement along various paths, (3) the chemical, biological, and physical character of the constituents transported by the water, (4) the controls on the rates of movement of and interactions among water and its transported constituents imposed by the atmosphere, the geosphere, the biosphere, and the oceans, and, conversely, (5) the impacts on the atmosphere, geosphere, and biosphere caused by the presence or absence of water in or on the land.

The research component of the program is partitioned into two types: (1) fundamental or process oriented and (2) model oriented. Because one type of research often builds on the results of research of the other type, most research projects carry out activities in both categories at any given time. Thus, the line delimiting these categories of research often is difficult to distinguish even within any particular project. However, the categories have utility in describing the elements of the proposed program.

Process-Oriented Research

Process-oriented research, as used herein, refers to the development of increased understanding about how the processes that control the land phase of the hydrologic cycle interact and how they interact with other processes that they impact. Because of the intrinsic interconnectivity among elements of the Earth's environmental system, the hydrologic impacts of climate change ultimately will depend on adjustments in the lithosphere and biosphere, as well as in the atmosphere. Therefore, the study of any single component or pair of components of the Earth's complex system in isolation from others has inherent limitations. Many of the interconnections are poorly understood, and thus fundamental research is needed. Such research will provide insights into likely changes in advance of their appearance in the environment and subsequently will facilitate development of timely guidance for coping with the changes. A list of the primary elements to be addressed by process-oriented research is provided in table 1.

Table 1. Themes and issues in process-oriented research

Theme	Specific issues
Problems of scale	Infiltration. Evapotranspiration. Aquifer recharge. Surface runoff.
Extreme conditions	Floods. Droughts.
Complex environments	Unsaturated zone. Lakes. Snow and ice. Estuaries.
Special topics	Biogeochemical cycles. Paleohydrology. Hydroclimatology. Water quality.

Much is currently known about many of the hydrologic processes, particularly as they function in the laboratory or on small plots of land. The knowledge developed in the laboratory and on small plots inherently is limited to the lower end of both the spatial and temporal scales of interest in hydrology and frequently is isolated from many of the factors that may be relevant in the natural environments in which the processes function.

Many of the questions concerning the hydrologic implications of climate uncertainty cannot be addressed adequately by improving process understanding at modest scales. Therefore, the majority of the elements contained in the fundamental research component of the program will be oriented toward development of understanding the aggregate of processes at work over reasonably large and diverse areas of land—the scale problem (Dooge, 1982).

An example of a process that is reasonably well understood at the small scale is the concept of infiltration, which describes the passage of precipitated, ponded, or flowing water from the surface of the Earth into its interior. Much is known about infiltration from the laboratory or at small field-plot scales (Dooge, 1982). Rates of infiltration depend on the nature and water content of the soil or rock that receives the infiltrated water, the chemical, physical, and biological character of the source water, and in the case of precipitation, the rate at which water is supplied to the surface. At many larger scales of interest—that is, agricultural fields or larger areas—most of the factors that control infiltration will vary significantly. Because of the complexity of the relations among the controlling factors, the knowledge of infiltration derived at small scales is difficult to apply at large scales. This quandary is compounded by the current inability to collect and interpret sufficient quantities of precise and accurate data to describe adequately the spatial variability of the controlling factors. Thus, gaining more insight on infiltration over medium to large areas is an essential.element of the program.

Another hydrologic process whose understanding is impacted by scale is the reverse of infiltration, that is evapotranspiration, which takes water out of the Earth and the biosphere and returns it to the atmosphere. In most water-balance studies, evapotranspiration is computed as the residual after all other relevant flows and reservoirs have been taken into account. There are two primary reasons that it is treated so: (1) evapotranspiration is a highly nonlinear function of the energy available to transform liquid water to water vapor at the surface of the Earth or on a plant surface, and (2) the energy balance on the land surface or on a plant is highly variable both in space and in time. As climate changes, the statistical characteristics of the energy balance will change, as will the availability of water at land surface. In response to significant shifts in water availability, the local plant community also can be expected to change (Eagleson and Segaria, 1985). Therefore, evapotranspiration probably will be very sensitive to climate change. Of the major water balance components, evapotranspiration is the least documented. Unlike precipitation and runoff, evapotranspiration has not been measured systematically across the Nation. Its character at various spatial and temporal scales must be determined.

In many regions of the United States, ground water is an abundant resource that has accumulated over long periods of time. It is a resource that can be drawn upon at rates that vary as functions of the volume of ground water in storage and the rates at which it is replenished. The rate at which ground water is replenished is known as aquifer recharge and, to a first approximation, it is equal to the difference between infiltration and evapotranspiration. Because these processes are controlled by many interrelated factors sensitive to scale, it follows that aquifer recharge must be as well. For ground-water development to proceed in a wise and measured fashion under climate uncertainty, the process of aquifer recharge must be better understood.

As a first approximation, the difference between precipitation and infiltration is surface runoff. Runoff is the primary source of water for most floods producing serious property damage and loss of life in the United States. As a result of its direct linkage to infiltration, the processes controlling the generation of surface runoff are poorly understood at spatial scales larger than field plots. Thus, even if climate change were not a significant issue, research on the process of runoff from catchments and basins is an area that warrants renewed support. The added uncertainty attendant to climate change only serves to augment an existing need for research on this phenomenon.

Another category of the hydrologic continuum requiring process-oriented research is extreme hydrologic conditions. The extremes of the hydrologic continuum, floods and droughts, have been studied largely in statistical contexts. Much of water-resource planning is based on the normal or average conditions over some standard period of instrumented observations. Such an approach ignores the question of how representative the available data may be of the true expected conditions. This question is particularly relevant for decisions that entail planning horizons that extend 20 to 100 years into the future.

Historically, water-resource systems have been designed on the assumption that future climate conditions, hence floods and droughts, would be similar to those observed in the systematic record. This assumption, known as stationarity, has long been controversial in hydrology. If significant climate change occurs in the coming decades, it will invalidate the stationarity assumption and force a change in the procedures for estimating the occurrence of hydrologic extremes; the 100-year flood of today will not be the same as that of the mid-21st century. Importantly, the change will not be attributable simply to a longer record of floods, as is frequently the case today but, rather, to a shift in the character of the causal factors of flooding. In a situation of climate change, shifts in the likelihood of flooding or droughts would be continual, lasting to the time at which the climate change has ceased. Consequently, data-based descriptions of floods and droughts will be of limited utility unless a better understanding of the causal processes and their rates of change relative to ongoing climate change is attained.

A third class of problems requiring process-oriented research involves complex hydrologic environments such as the unsaturated zone, lakes, regions of snow and ice, and estuaries. Each of these environments plays an important role in the hydrologic cycle, and the dynamics associated with each often are poorly understood.

For example, the characterization of the transport of water, as vapor or liquid, and other climatically significant gases through the unsaturated zone is crucial to understanding how the zone functions as a source or sink of such substances. To amplify this point, preliminary studies in Nevada have recently indicated that the unsaturated zone is a methane sink, yet in the past it has been characterized as a methane source. On a molecule-per-molecule basis, methane is a much more efficient greenhouse gas than carbon dioxide, and methane also is increasing in the atmosphere (National Research Council, 1986). Thus, the question of whether the unsaturated zone is a modulator or an intensifier of climate change vis-a-vis methane cycling is an important one that is yet to be answered.

Lakes integrate the hydrologic system of their watershed because they are in direct contact with each of the three major water components: atmospheric water, streamwater, and ground water. Therefore, lakes reflect changes in the supply of water, chemicals, and other materials that enter them from their airshed and watershed. In addition, depending on the residence time of water and chemicals in lakes, internal chemical and biological processes further modify the character of lakes. Because of the wide variety of lake sizes, geologic settings, and watershed-area to lake-area ratios, lakes can be used to assess climate variability and the impact of that variability on their watersheds over time scales ranging from days to years (Goldman, 1988).

Perhaps the greatest role lakes have in the linkage of climate and hydrologic processes is their ability to capture the historical record of hydrologic processes in their sediments. Lake sediments are comonly used to study past hydrologic, climatic, and land use changes, primarily for the last 13,000 years (Dean and others, 1984), and in some cases for many tens of thousands of years.

Snow-covered areas on land, and ice on both land and sea, are extremely sensitive barometers of climate variability and change. Perhaps more importantly, these areas exert a major influence on the Earth's radiation budget as well as on atmospheric and oceanic circulations. Seasonal variations in the areal extent of snow are the most significant contributors to global albedo changes. Albedo refers to the ratio of radiant energy reflected by a surface to that incident upon it. The presence or absence of snow, which has the highest albedo of any natural feature on the Earth's surface (80–90 percent), dramatically affects the absorption of solar radiation and, therefore, surface air temperature. Snow also provides the water-supply base for parts of the Western United States. Answers to questions regarding how climate change will affect the spatial distribution and timing of snowfall and consequent water-supply conditions and resource-allocation strategies must be sought. Similarly, numerous questions associated with snow and ice dynamics must be answered to measure and to model more accurately snow and ice volumes and interactions with other hydrologically significant variables. Moreover, more detailed information on the characteristics and dynamics of glaciers, continental ice sheets, and sea ice is essential for deriving better estimates of climatic and hydrologic conditions, including changes in sea level, from climate models.

River-estuarine systems, the meeting place of freshwater and saltwater, are among the world's most complex hydrodynamic, chemical, and biological environments. They are also, as a result, exceedingly sensitive to climatic and anthropogenic influences. These systems, which typically support large population centers, provide much of the water needed for domestic consumption, industry, and agriculture (irrigation) (fig. 4). Developing an understanding of how the river-estuarine environment varies in association with variations in climate and human activity is essential for effective resource management.

One of the more obvious estuarine responses to climate variability and change, having major societal and economic importance, relates to instream movement of the freshwater-saltwater interface. Saltwater intrusion can seriously degrade coastal land and water resources. The projected acceleration in the rise of sea level in the 21st century (Revelle, 1983) will promote upstream shifts in the position of the interface and increase the landward intrusion of saltwater, thus endangering municipal freshwater supplies from rivers and ground-water reserves. In some regions, reduced streamflows also could increase the demand for coastal ground-water withdrawals and generate a need to deepen and widen shipping channels.

In addition to the relatively direct impact of climate change on coastal water resources, there are a number of more complex and subtle interactions among the estuarine hydrodynamic, chemical and biological realms. Such processes include changes in river-borne sediment transport and deposition and changes in estuarine biogeochemistry. Preliminary research indicates that realistic modeling of these interactions is highly dependent on the development of nonsteady-state formulations of estuarine physics and associated biogeochemistry with flow.

The final categories of the hydrologic continuum for which expanded process-oriented research is needed include

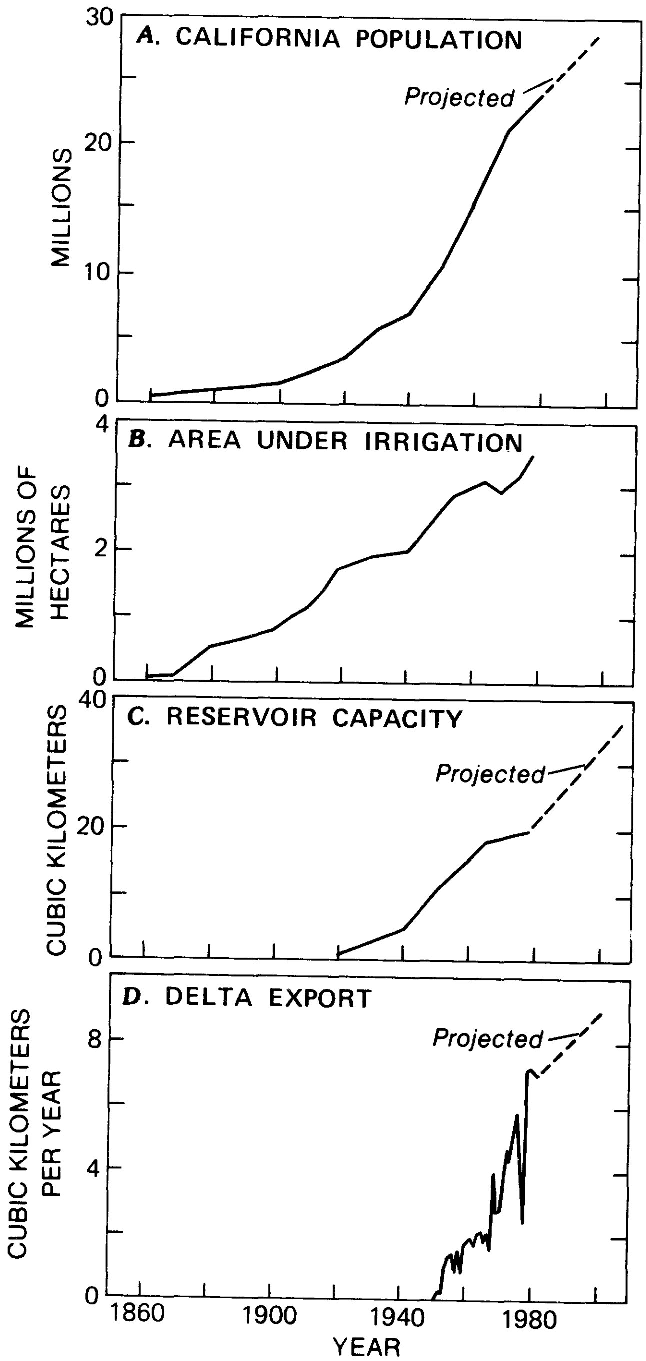

Figure 4. Population growth in California (*A*); land under irrigation (*B*); water storage capacity of reservoirs in the Sacramento and San Joaquin river basin (*C*); and historic and projected export of water from the delta by the Federal Central Valley and State water projects (*D*). Source: Nichols and others, 1986.

biogeochemical cycles, paleohydrology, hydroclimatology, and water quality. A growing body of evidence indicates that the rate of cycling of greenhouse gases through the hydrosphere, atmosphere, biosphere, and lithosphere has the potential to perturb the global climate and that climate change, conversely, can produce feedbacks to change significantly rates of cycling. Carbon dioxide and methane are just two of the greenhouse gases that play a significant role in the study of climate change. Nitrous oxide, ozone, and industrial halocarbons also are related intimately to climate and the hydrologic cycle. Because these gases impact on and are impacted by the water resources of a region and, more broadly, of the globe, the study of biogeochemical cycles must be an integral part of the study of the hydrologic implications of climate uncertainty.

Paleohydrology, the study of geologic and biologic evidence of past hydrologic events, is another special research topic of increasing fundamental importance with respect to climate change. The aim of paleohydrology is to describe hydrologic variations that span intervals beyond the range of instrumental records, from glacial-interglacial cycles to seasonal anomalies, and to identify their causes. The need to study past evidence of climatic and hydrologic change is derived from the brevity of most instrumental records, which are commonly shorter than the planning horizons for applied hydrology and water-resources management. Moreover, it is important to place the relatively brief systematic record in its proper perspective over the longer historic and geologic past. The different response times and sensitivities of the atmosphere and oceans (from weeks to centuries) suggest that high-frequency phenomena (interannual variability) are transient responses to a continuously varying climate system. Because the full impact of an anthropogenically induced warming may take centuries to develop, an understanding of long-term climate dynamics may be necessary to model the evolution of equilibrium environmental conditions.

High-resolution proxy data, that is, geologic and other surrogate records, are indispensible for improving estimates of the annual mean, annual variance, and long-term persistence of hydrologic phenomena. However, proxy records suitable for hydrologic analysis are limited both in geographic coverage and interpretive methodological development. Presently, interannual proxy records are restricted to tree rings, sediment varves (both marine and lacustrine), coral bands, ice layers, and written records. The continued development and expansion of meaningful and usable high-resolution and spatially diverse proxy time series are essential elements of the research program to supplement inadequacies that exist in the recorded data base.

Hydroclimatology, the study of hydrologic events and conditions within their climatologic context, is another special topic of process-oriented research. It encompasses large-scale interactions between the atmosphere and hydrosphere. Hydroclimatology, by focusing on atmospheric forcing, provides a mechanism for integrating the physical sources of variability in a hydrologic time series with the statistical properties of the varying driving force itself. This integration has the benefit of enhancing our understanding of hydrologic processes and also the quantitative assessment of their variability (Hirschboeck, in press; Lins, 1985a, b).

Recent research indicates that specific regions of the globe respond in a consistent manner to large-scale atmospheric and oceanic circulations. These consistent responses, or teleconnections, provide a basis for predicting areas of water deficits and surpluses attendant to climate change. The concept of teleconnections, introduced by Walker (1923) and refined by Namias (1981), actually refers to the statistical cross-correlation between atmospheric anomaly patterns separated by synoptic (1,000–2,500 km) to hemispheric distances. Some of the best documented teleconnections, the Pacific/North American, the Central North Pacific, and the Southern Oscillation patterns, for example, have been clearly associated with distinct patterns of streamflow variability in western North America, as shown in figure 5. Refinement

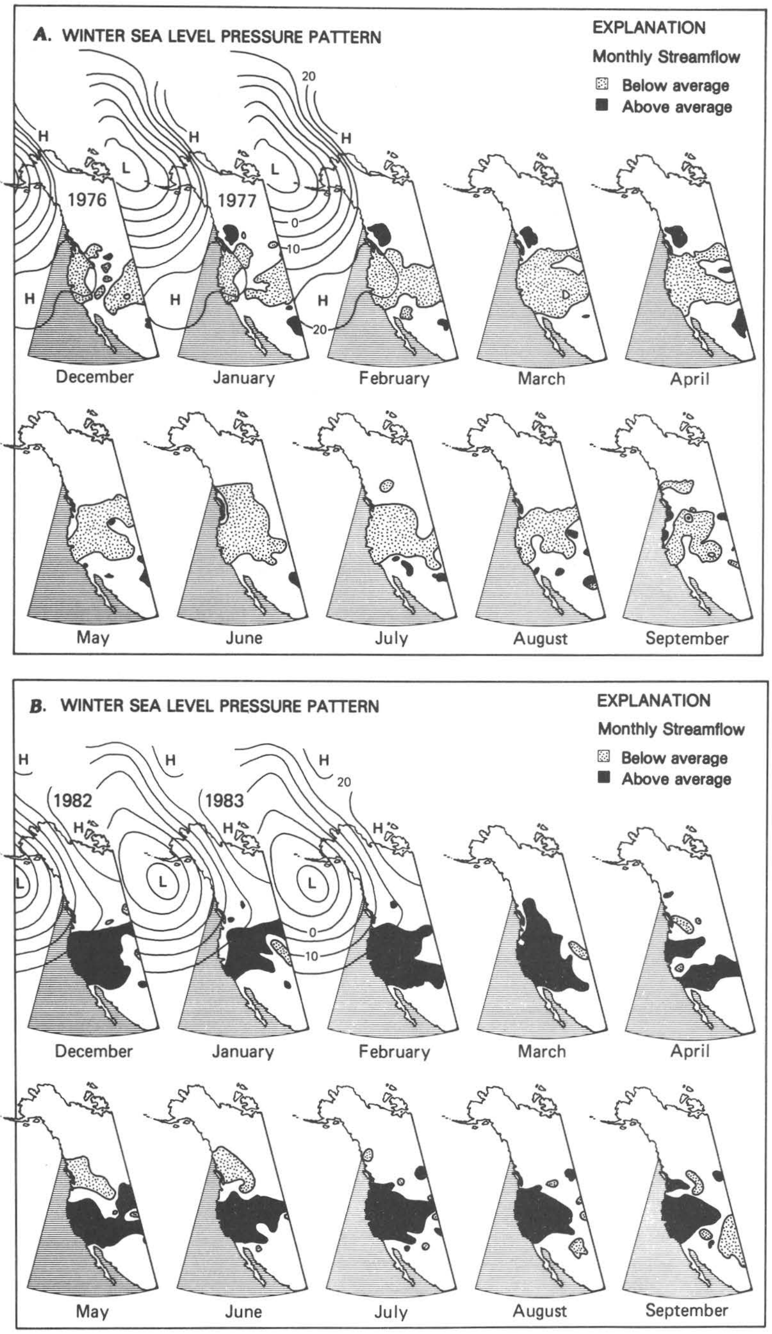

Figure 5. Mean sea-level pressure (in millibars minus 1,000) and monthly streamflow patterns: (*A*) winter 1976–77 and (*B*) winter 1982–83. "Below average" refers to the lower quartile flow and "above average" to the upper quartile of flow. Source: Peterson and others, 1987.

of these associations and expanded hydroclimatic analysis of regional patterns nationwide, and at monthly time scales, offer potential for water-resource planning and assessment.

Water-quality aspects of the hydrologic continuum form the final special topic of process-oriented research. In recent years, water quality has received an increasing emphasis within the hydrologic-research community. However, little of that emphasis has been directed toward the impacts on water quality of climate change. As improved understanding of the potential for modified rates of streamflow, ground-water recharge, and evapotranspiration is developed, this new knowledge will shed light on concomitant changes in the concentrations and residence times of various chemical and biological species that comprise water quality.

Model-Oriented Research

Mathematical models are numerical representations of real-world phenomena and the interactions among phenomena. In hydrology such models are used to represent the essence of existing, fundamental hydrologic knowledge and to integrate that knowledge with the hydrologic and related data that are available within an area of interest. Hydrologic models are used as research tools, as descriptive devices in interpretive water-resources studies, and as planning and design instruments in water-resources decision-making. Each usage is relevant in coping with climate uncertainty. The proper utilization of hydrologic models for any purpose requires that the characteristics and limitations of the models be known and understood.

Hydrologic models are necessarily imperfect representations of the phenomena that they are constructed to mimic. Inherent errors in the data derived from such models result from (1) spatial and temporal scale limitations within the models' structures, (2) the imperfect state of the hydrologic knowledge upon which they are based, (3) the simplifications required in reducing complicated phenomena to relatively simple mathematical expressions, and (4) errors present in the input data that drive the models.

As a point of clarification, model-oriented research is distinct from model development. Modeling research addresses the quantification of errors present in the model output and the search to reduce those errors. In contrast, model development deals with the initial construction of the model and its incorporation into a modeling framework. Components of the model-oriented research element of the program appear in table 2.

Table 2. Components of model-oriented research

Model form	Scale/type
Process	General circulation. Mesoscale. Basin scale.
Stochastic	Disaggregation. Risk. Data-network analysis and design.

Process Models

To address the full suite of hydrologic implications of climate uncertainty, models that simulate hydrologic processes over a wide range of spatial scales are required. At one end of the spectrum of spatial scale is a class of models known as general circulation models, which are commonly referred to as GCM's and occasionally improperly are called global climate models. GCM's depict the circulation of mass and energy in the atmosphere in three spatial dimensions, on a global scale, and at varying levels of detail that include components of oceanic and land-surface processes (Washington and Parkinson, 1986). In general, attempts are made in the model to represent all physical processes believed to be important. The variables used to drive GCM's include components of the wind field or vorticity, temperature, and water-vapor content. Typically, the data are aggregated into cells of several degrees latitude and longitude around the globe, and at 6 to 10 levels vertically through the lower atmosphere. The stored quantities are then stepped forward in time by applying the equations of motion and the first law of thermodynamics, so that mass, energy, and momentum are conserved. The equations also include terms describing surface friction, radiative and latent heating, and other physical processes.

One of the most crucial aspects of GCM's involves the mathematical description of the interactions between the Earth's surface and its atmosphere. Typically, the surface fluxes of heat, momentum, and moisture are described using bulk aerodynamic formulas. Land-surface temperature and soil moisture are commonly calculated by equations incorporating daily and seasonal heat and moisture storage and their vertical fluxes. Significantly, although current GCM's are structurally complex and computationally demanding even for the latest generation of supercomputers, in many respects their representations of the physical processes and conditions at and immediately below the land surface are exceedingly simple and inaccurate. Sensitivity studies indicate that climatic simulations are very sensitive to changing land-surface processes and properties, particularly those of the hydrologic cycle.

A critical aspect of general circulation modeling involves parameterizing the interactions between the surface and the atmosphere. Parameterization refers to the expression of the statistical effects of various small-scale (subgrid scale) transport processes in terms of the large-scale (grid-scale) variables explicitly resolved by the model (Global Atmospheric Research Program, 1975). Because of the wide range of scales of interacting atmospheric processes in relation to the limited spatial resolution of computational grids and observation systems, it is technically and economically impractical to observe or explicitly calculate the effects of small-scale processes in detail. However, these subgrid processes are significant, and it is important to relate their statistical effects to measurable or computable conditions at larger scales. Because the arbitrary specification of small-scale effects does not accommodate full interaction with the larger scale resolvable state of the atmosphere, parameterization is required.

To illustrate the problem associated with specifying subgrid processes at the grid scale, consider how a typical GCM treats soil moisture (fig. 6). At the Earth's surface, the moisture content of the top 15 cm of soil is a highly variable quantity, responding to differing vegetation, soils, and geomorphological characteristics. Over an area the size of a 5° latitude by 5° longitude grid square, a map of soil-moisture content would appear as a complex mosaic. Yet, the input to the GCM is a single value for the entire grid square. Clearly, for most of the globe's land surface, this is a poor representation of soil-moisture conditions.

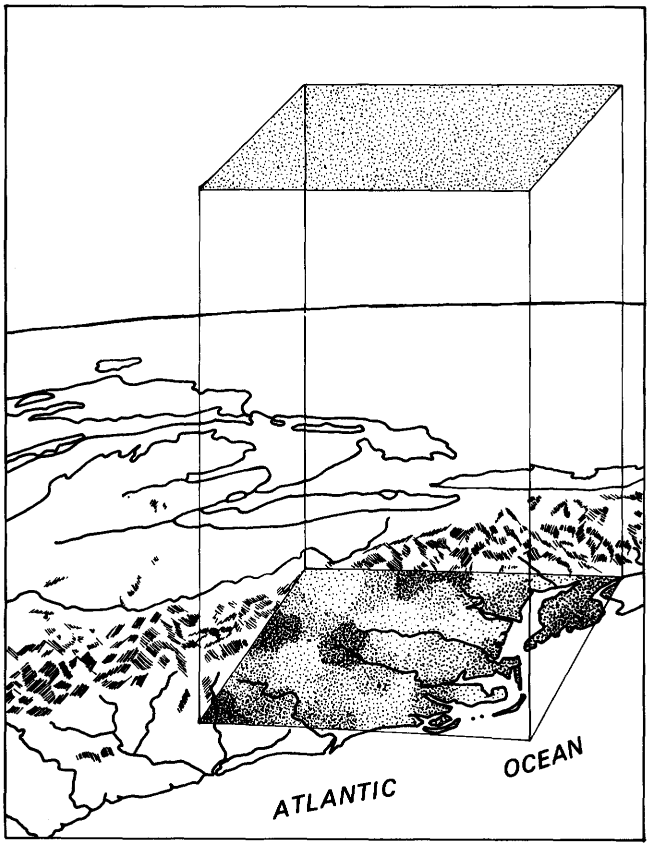

Figure 6. Characterization of how the spatial variability of a surface condition such as soil moisture, which varies over a scale of meters, is generalized to a single value through parameterization.

Linking hydrology and climate through GCM's is very difficult. Accounting for the myriad of interacting processes, including precipitation, interception, infiltration, runoff, and evapotranspiration, with any degree of precision or realism is very complicated, and procedures for handling these intricacies are largely underdeveloped or totally lacking.

Significantly, hydrologists, especially those involved in surficial-process and ground-water modeling, have been addressing many of these same problems and can make major contributions toward their solution. Whereas atmospheric modelers have focused their attention primarily on processes over characteristic scales ranging from 10,000 to 100,000 km², hydrologic modelers have dealt with smaller scale processes, those occurring over field (<1 km²) or catchment (100–1,000 km²) areas. Importantly, hydrologists have had to confront many of the same basic issues to parameterize field-scale processes in catchment-scale models. Although adequate solutions have not been found always, those processes significantly affecting catchment response have been identified. Thus, the hydrologic community has acquired important insights necessary in guiding parameterizations from catchment scales up to GCM-grid scales.

An intermediate step of great significance has been undertaken by atmospheric modelers to enhance the realism of subgrid-scale processes by application of a finer mesh grid. This work, generally referred to as mesoscale modeling, is a spatially and temporally limited form of general circulation modeling. Their basic physical and mathematical foundations are the same, although more detail is incorporated at the mesoscale. Pielke (1984) defines mesoscale as having a characteristic horizontal spatial scale of 10 km² to 50,000 km² with a time scale of about 1 to 12 hours. Clearly, this scale of analysis is much more consistent with that used in hydrology and affords a sound basis for substantial interaction between the atmospheric and hydrologic modeling communities. The mesoscale class of models, with the inherent ability to nest within the broader GCM's, provides a likely pathway for incorporating more realistic hydrologic conditions into climate simulations at the global scale. Perhaps more important for hydrologists, however, is the potential for improving the output of catchment models by using the output of mesoscale models as input.

At the smaller end of the spatial scale are the basin or catchment models commonly used by hydrologists. The actual information content of such model outputs has seldom been investigated, however, and their sensitivities to varying climate conditions are generally unknown. One exception is the small-catchment rainfall-runoff model developed by the U.S. Geological Survey (Dawdy and others, 1972). Lichty and Liscum (1978) have devised a procedure for estimating the information about flood-recurrence intervals that the model can extract from weather records. A factor, illustrated in figure 7, also has been mapped that defines the impact of existing climate conditions on flood frequencies in small catchments of the United States east of the Rocky Mountains. Studies of this sort will be carried out for other models and for characteristics other than floods, and the procedures will be extended to estimate the impacts of climate change on the models' abilities to generate hydrologic information.

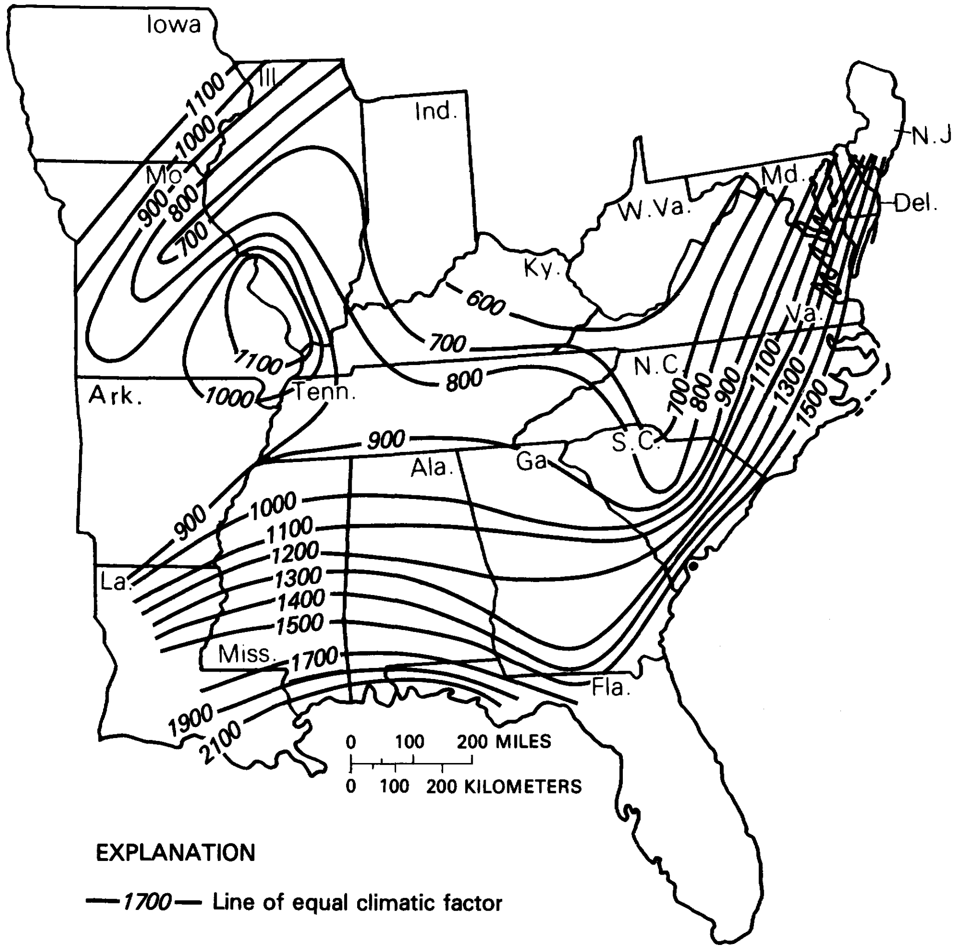

Figure 7. Geographic variation of the climate factor for the 100-year-recurrence-interval flood. The factor is the ratio of peak-flood discharge that has a probability of exceedance of 1 percent in any given year to a mathematical description of the physical characteristics of the drainage basin that could yield the flood; the mathematical description was derived by regression techniques used on an exhaustive set of drainage characteristics and model output. Source: Lichty and Liscum, 1978.

Stochastic Models

Because of the inherent imprecision in physically based hydrologic models, a special class of models, known as stochastic models, has been developed. Stochastic models are based on principles of probability and statistics and can be used to describe either hydrologic phenomena or the errors that derive from physically based hydrologic models. The uses of stochastic models are:

(1) To provide language in which assumptions may be stated about observed time series (Parzen, 1962);

(2) To provide insight into the most realistic and/or mathematically tractable assumptions to be made concerning the stochastic processes that are adopted as models for time series (Parzen, 1962); and

(3) To provide a tool for obtaining approximate solutions to the complex problems that arise in making water-resources decisions. (Moss and Tasker, 1987).

However, for stochastic modeling to remain a useful aspect of hydrology in the 21st century, its language and mathematical constructs must be expanded to describe hydrologic processes that are changing in response to climate change.

A priority area for stochastic-modeling research deals with disaggregation models, which develop statistically representative data at scales of time and space that are finer than those of the data that are available to drive the models. The priority results from the mismatch between the relatively large grid sizes of the current general circulation models and the much smaller scales at which most hydrologic analyses must be performed to meet the needs of water-resources decisionmakers. For example, suppose that one wants to know the impact of computed values of precipitation on the likelihood of flooding in a small catchment contained within the 5° grid of a GCM. Because the catchment is much smaller than the GCM grid and because the response time of the catchment is significantly smaller than the time step of the GCM, the time series of precipitation values from the GCM must be disaggregated in both time and space to extract the desired information. Although disaggregation modeling in the time dimension is relatively advanced at the current time (Bras and Rodriguez-Iturbe, 1985, p. 147–154), little progress has been made in the spatial dimension, and none has occurred in the bidimensional domain of space and time.

Another crucial type of stochastic modeling research involves data-network analysis and design. Most, if not all, methodologies for the design of hydrologic-data networks are based on statistical or stochastic descriptions of the hydrologic phenomena to be monitored. Underlying most of these methodologies is an assumption of stationarity of the stochastic processes. It has been demonstrated in many widespread, but isolated, settings that nonstationarities exist in hydrologic records (Riggs, 1985). Nevertheless, most hydrologic services continue to rely on stationarity assumptions in the allocation of their data-collection resources. The potential for anthropogenic climate change has heightened awareness of the disparity between underlying assumptions and potential realities in the 21st century.

Moss (1986) presents an approach, dealing with data collection in a regional or national framework, that pertains to nonstationarity. However, this approach is in an early stage of development.

As mentioned earlier, the large, but unknown, uncertainty contained in all currently available climate-change projections necessitates reliance on scenario analysis, which is perhaps the most elemental, but still rational, strategy for dealing with uncertainty. To progress beyond the use of scenario analysis to a more effective strategy, the uncertainties in climate projections must be quantified, and a decisionmaking structure for coping with the resulting risks must be elucidated. The theory for decisionmaking under uncertainty exists (Raiffa, 1970), but the complex stochastic nature of the inherent errors contained within the hydroclimate models needs to be determined before the theory can be brought to bear.

Data Collection

The collection of data is a universal requirement of scientific endeavor. Until rather recently, hydrology has been to a large degree an empirical science; data collection has been the basis for most of its successes. In hydrology, as with most other sciences, data are used in two general ways: (1) the computation of statistics and (2) the calibration and testing of models. These two categories of data use are not distinct from each other, however. Often models are calibrated by means of the statistics of relevant data, while the computation of many statistics presumes an underlying stochastic model for the data. Although not distinct, the differentiation between statistical and modeling uses of data is useful in describing the role of data collection in studying the hydrologic implications of climate uncertainty.

Hydrologic-data collection for the computation of statistics entails the quantification of spatial and temporal hydrologic phenomena both on and beneath the Earth's surface. Monitoring of both the quantity and quality of the Nation's water resources for compliance with laws, compacts, and treaties is a major aspect of this type of data usage. Because the resources for data collection are not unlimited, most traditional strategies for statistical data collection have depended on one of two major approaches: synoptic or temporal. Seldom are aspects of both significant in a single strategy. Synoptic approaches rely on occasional or periodic bursts of data at given times to define the spatial distribution of the hydrologic phenomena of interest; a well known synoptic data base from outside hydrologic science is the decadal U.S. census. Temporal approaches, on the other hand, rely on less spatial resolution through the establishment of a network of sites at which the phenomena of interest are measured continually, or nearly so, through time. Because many of the needs for hydrologic information are site specific, the hydrologic data-collection activities of the U.S. Geological Survey generally have used temporal strategies instead of synoptic ones.

Land-Based Data

An example of a temporal network that is relevant in addressing questions of climate uncertainties is the U.S. Geological Survey Benchmark Network, consisting of 57 sites at which streamflow and water quality have been measured for almost 25 years (Cobb and Biesecker, 1971; Lawrence, 1987). The locations of the benchmark sites are shown in figure 8. As its name implies, this network was established to provide the Nation with records of hydrologic conditions at sites that would be affected minimally by human activities on their drainage basins. Although the benchmark concept did not explicitly anticipate the current concerns about climate change, this network of sites is a critical component of the data base that will be used to detect and track climate influences on the Nation's water resources.

For this purpose, the principal shortcomings of the benchmark network are (1) the short length of records currently available, (2) the limited number of sites at which data are being collected, and (3) the limited suite of variables that are being measured at each site. Obviously, the first shortcoming is irreconcilable; one cannot go back in time to redress it except rarely through paleohydrologic studies.

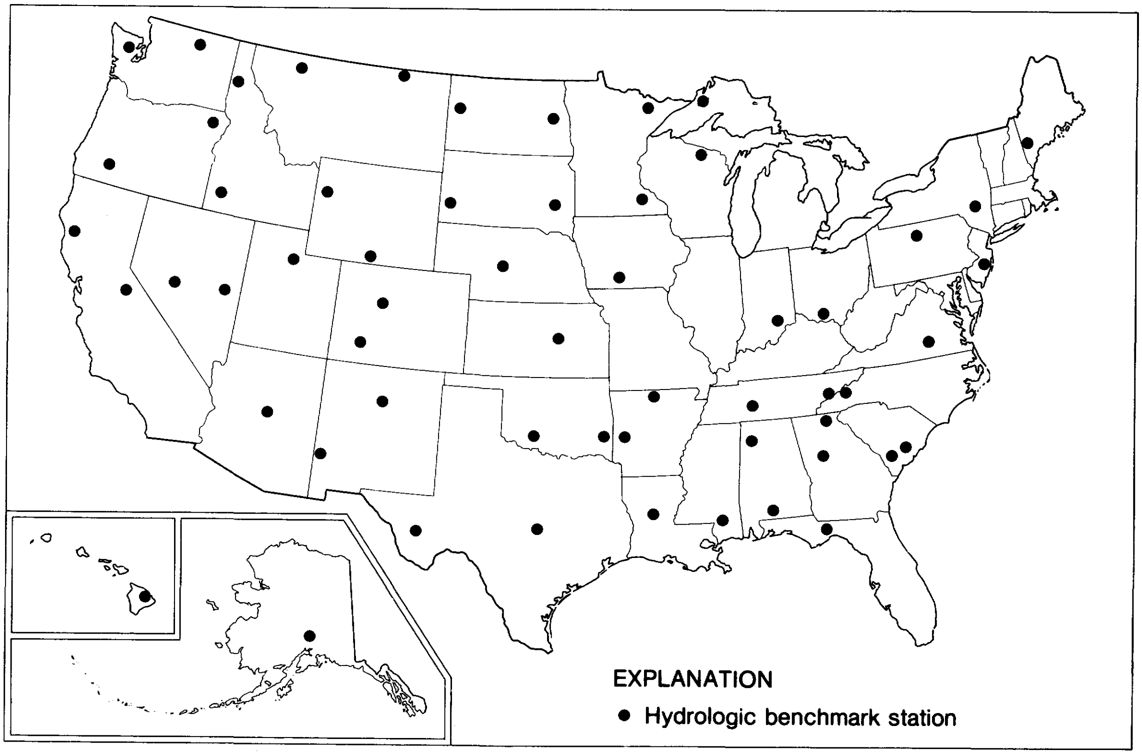

Figure 8. Locations of U.S. Geological Survey benchmark stations.

However, items 2 and 3 will be ameliorated as part of the data-collection element of the program.

Climate data for the benchmark drainage basins are sporadic in time and in space; this facet of the network limits its utility for studying climate-hydrology interactions. The first priority for increased data collection under this program will be the installation of permanent climate stations on each benchmark drainage basin. Because of the climate variability over areas within the range of the benchmark drainage basins (approx 5–2,500 km^2), several climate stations may be desirable in many of the basins. However, the network-design methodology for specifying the ideal number and locations of climate stations for each basin currently does not exist. Therefore, a single climate station will be installed on each, and deployment of other stations will await the methodology that is to be developed in the research element of the program.

Even though new sites can be added to the benchmark network as funds are made available, any new site will never be as powerful in tracking the impacts of potential climate changes as would the original sites. The information contained in the charter sites never can be recovered fully for the new sites. Nevertheless, if significant climate change is not too immediate, time remains for the establishment of significant data bases at new locations. Criteria for the new sites, both the number of sites and the characteristics of the individual sites, also will be developed within the research element of the program.

A histogram of the percentage of continuous stream gages in the United States by area of their drainage basin, as determined from the files of the National Water Data Exchange (Williams and Knecht, 1981), appears in figure 9. The drainage basins of the benchmark network fall on the smaller end of the spectrum of gaged watersheds. Because of the incongruity between the spatial resolution of general circulation models and that of the Benchmark Network, the benchmark sites will contribute only a minor amount of information for the calibration and testing of general circulation models. Another set of stations at a more appropriate areal scale will be needed for this purpose. Currently, the Geological Survey is making a detailed search of the existing data base to identify stations that either are active now or could be reactivated to provide the requisite data for model testing and for evaluation of the hydrologic information content of the outputs of the GCM's. It is anticipated that both reactivation of some discontinued stations and the establishment of some new ones will be required to develop an adequate data base to achieve these ends.

One area in which hydrologic data generally are not available for either statistical or modeling purposes is that of evapotranspiration. The reason for this is that a cost-effective methodology does not exist to generate the data of the desired temporal and spatial scales. Early in the research element of the program, high priority will be given to the development of the missing methodology. Once the methodology has been demonstrated to be successful,

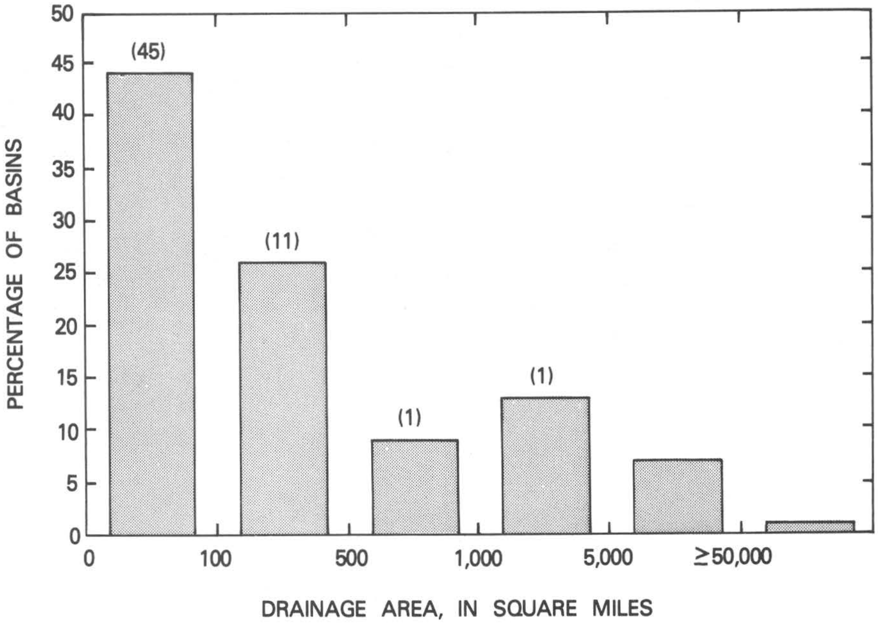

Figure 9. The percentage of continuously operated stream gages in 1987, by drainage area. Number of benchmark stations in each drainage area class appears in parentheses above the respective bar.

it will be deployed as a basic component of the data element.

As has been noted, there is a strong dependency between the data and the research elements of the program. In a mature stage of scientific development, a balance is achieved in the feedback from one element to the other. However, because of the major philosophical changes required to deal with hydrologic implications of significantly increased climate uncertainty, many research components of the program will have to precede the data components. Therefore, definition of major data components (for example, ground-water levels or water-quality variables) will have to evolve as research results are applied in the interpretive studies.

Interface with Remote Sensing

The movement toward large-scale studies of the Earth, with increasingly complex treatments of the interactions among the atmosphere-land-ocean-biota system elements, is generating a growing demand for a variety of high-quality and high-density geophysical measurements. In many areas of research, especially modeling, the data emanating from existing networks are either inappropriate, geographically insufficient, or both. Numerous applications now demand near-continuous spatial data of high resolution (<1 km). To meet these demands, investigators are making more extensive use of remotely sensed data. Indeed, the various programs of the National Aeronautics and Space Administration (NASA), the National Science Foundation, and the National Academy of Sciences encompassed under the rubric of Global Change, all explicitly incorporate a requirement for a permanent network of remote-sensing systems in orbit to complement both existing and new ground-based data networks.

There is a clear role and need for remotely sensed data to support studies relating to climate and hydrology. Many of the most significant problems in hydrology relate to understanding the hydrologic cycle and its interactions with the atmosphere, as well as with the biosphere and lithosphere. Achieving such an understanding, for areas other than homogeneous small-scale basins, requires a combination of in-situ and remotely sensed (airborne and spaceborne) measurements (National Research Council, 1985). The remote measurements are essential for providing an integration, over broad spatial and temporal scales, of the in-situ observations. Moreover, water, because of how and where it occurs and the transformations it undergoes, is amenable to detection in many parts of the electromagnetic spectrum. This fact makes it a particularly appropriate quantity for sensing by remote means.

Although U.S. Geological Survey scientists make extensive use of remotely sensed data in numerous and varied research activities, the agency is not responsible for operating and maintaining a data-collection system based on remote sensing. It supports such systems, however, by providing in-situ observations necessary for both sensor calibration and verifying the interpretation of remotely sensed data. An example of such support involves ongoing participation by the USGS in NASA's First International Satellite Land Surface Climatology Project Field Experiment at the Konza Prairie Long Term Ecological Research Site in northeastern Kansas, which began in 1987 (Sellers and Hall, 1987, written commun.). As part of the experiment, the Geological Survey is operating three surface stations designed to measure the flux of water vapor and sensible heat to the atmosphere. These measurements are important to continuing efforts oriented toward regional-scale estimation of microscale processes, such as evapotranspiration, from remote-sensing platforms (fig. 10).

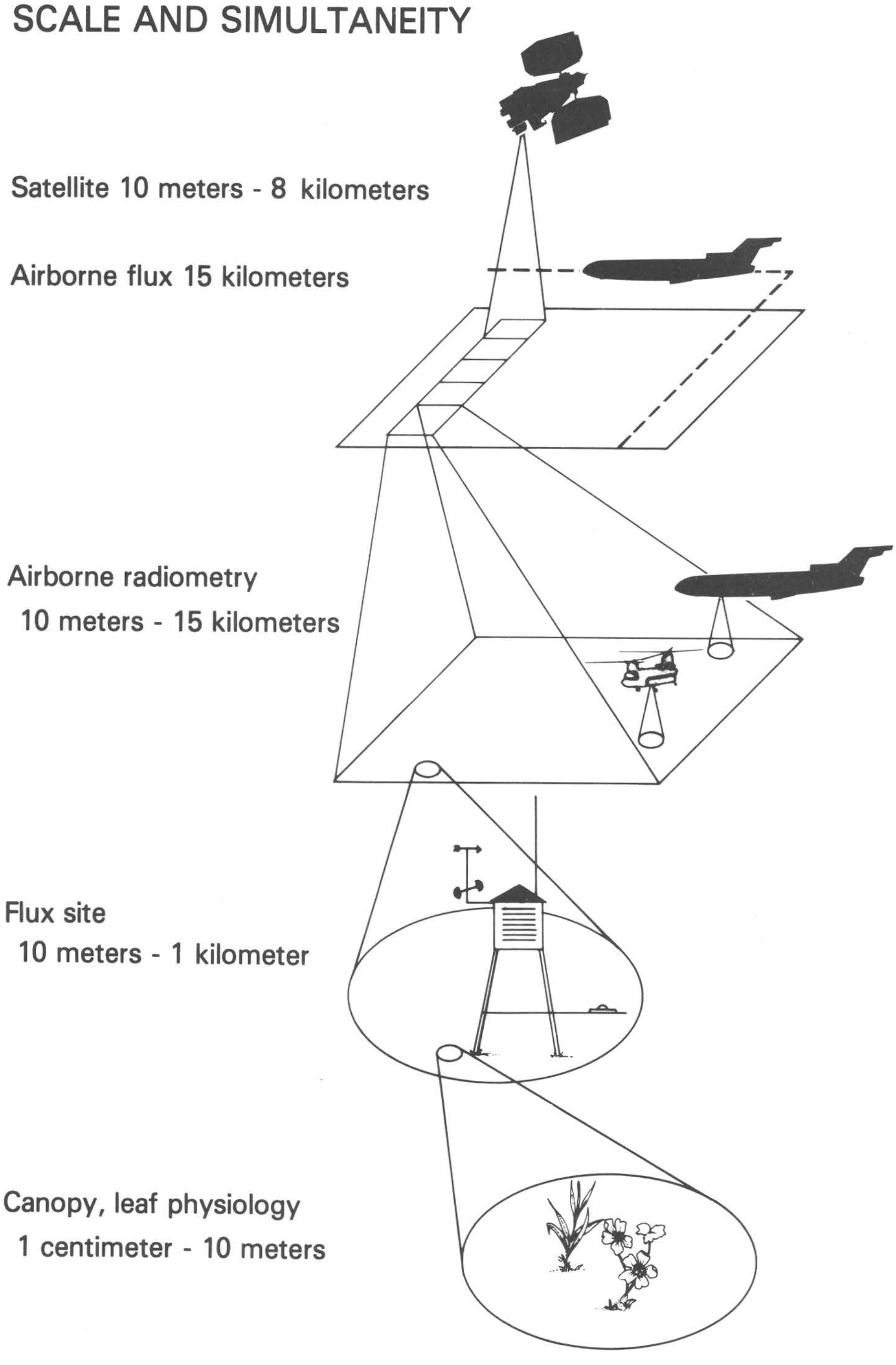

Figure 10. Range of scales addressed by the First International Satellite Land Surface Climatology Project Field Experiment. Source: Brutsaert and other, 1988.

Another example is the development of an in-situ instrument package for measuring the dielectric properties of snow and ice. The Snow and Ice Dielectrics System, developed collaboratively by the Environmental Research Institute of Michigan and the U.S. Geological Survey, is specifically designed to facilitate the spatial extrapolation of snow water-equivalent estimates derived from airborne passive microwave measurements of snow. Activities such as these undoubtedly will expand as large-scale integrated studies of the Earth focus to a greater degree on increasing the detail and versatility of remotely sensed data.

Water-Resources Interpretive Studies

The success of any program designed to study the hydrologic implications of climate uncertainty must be measured in terms of information utility. It is essential that the information generated by a program be carefully matched to the level and scale at which actual policies and decisions affecting the Nation's ability to cope with the uncertainty are made. In terms of water resources, an appropriate areal scale for information synthesis is the major river basin or regional aquifer. Accordingly, the U.S. Geological Survey has initiated a pilot study of the Delaware River basin (Ayers and Leavesley, 1988) (1) to test its capabilities to develop information on the implications of climate uncertainty regarding a number of interrelated aspects of the basin's hydrology; (2) to determine the utility of such information for basinwide water-resources planning in the 21st century; (3) to assess methodological performance and needs for enhancing the utility of such studies; and (4) to evaluate future data requirements for tracking potential impacts of climate change.

Because the Delaware River basin does not encompass the full range of hydrologic phenomena susceptible to climate change, this study is envisioned as the first of several geographically distinct pilot assessments that logically should precede a comprehensive attack on the problem of evaluating the Nation's water resources in the 21st century. The following summary of the Delaware River Basin study provides an example of the scientific complexity associated with such comprehensive, but meaningful, interpretive analyses.

The Delaware River basin encompasses 12,765 mi^2 and crosses four distinct physiographic provinces (fig. 11). Its runoff processes are quite diverse, and man's influence on the movement and storage of water adds considerable complexity to the basin system. The Delaware River serves as a major source of water for an estimated 20 million people both in and outside the basin (Delaware River Basin Commission, 1986).

The availability of water to users is based on many complex systems of reservoirs for storage and pipes, tunnels, and canals for diversion and delivery. The two largest diversions out of the basin are through the New York City aquaduct system to New York City and the Delaware and Raritan Canal to northeastern New Jersey. The freshwater portion of the tidal river below Trenton, the Delaware estuary, serves as a source of ground-water recharge for aquifer systems supplying water to southern New Jersey as well as a water-supply source for the city of Philadelphia and many industries by direct diversion. It is critical for these supplies that the Delaware Estuary along these reaches remain potable, even during periods of prolonged low flow (droughts).

Salinity problems in the estuary have historically been associated with New York City diversion rights. The U.S. Supreme Court (1931; 1954) required the city system to maintain certain instream flows at Montague, N. J., to provide both an adequate water supply and salinity controls in the estuary, an issue of considerable concern to downstream interests. Further, ''Good Faith'' agreements have included instream flow requirements at Trenton, N. J. During the drought of record in 1961–65, and twice since 1980, emergency water-use restrictions have been placed on basin water users to meet basic water-supply demands and instream-flow requirements.

Such experiences illustrate the susceptibility of the basin's water-supply to climate variability and emphasize how longer term climate uncertainty poses potentially serious problems for the Delaware River basin. Moreover, they provide insight on how poorly understood the potential effects are of climate change on the water supplies of the basin, including the ability to maintain instream-flow requirements.

The Delaware River basin study is designed to investigate the hydrologic response of the basin (fig. 12), under the existing management infrastructure, to possible climatic conditions in the mid to late 21st century. Specific objectives include defining the spatial and temporal variability of current and projected climate conditions on four important aspects of water availability within the basin. These are (1) the streamflows and storage associated with the New York City and other basin reservoir systems, (2) the ability to maintain instream flow requirements, (3) the upstream movement of saline water in the Delaware estuary associated with changes in sea level and freshwater inflows, and (4) the resulting potential intrusion of saline water into aquifers adjacent to the estuary.

Although the Delaware River basin is a unique hydrologic system within the United States, the interpretive assessment of this basin is intended to serve as a prototype for similar studies across the Nation. Clearly, other regions will have a different mix of physical system, water-supply, legal, and economic problems attendant with a climate change, but the general approach to evaluating those problems should be applicable. That approach, involving the coupling of advances in process research and data collection with existing hydrologic capabilities, is a robust yet flexible design. It should provide a sound framework for analysis regardless of the hydrologic region or type of climate change.

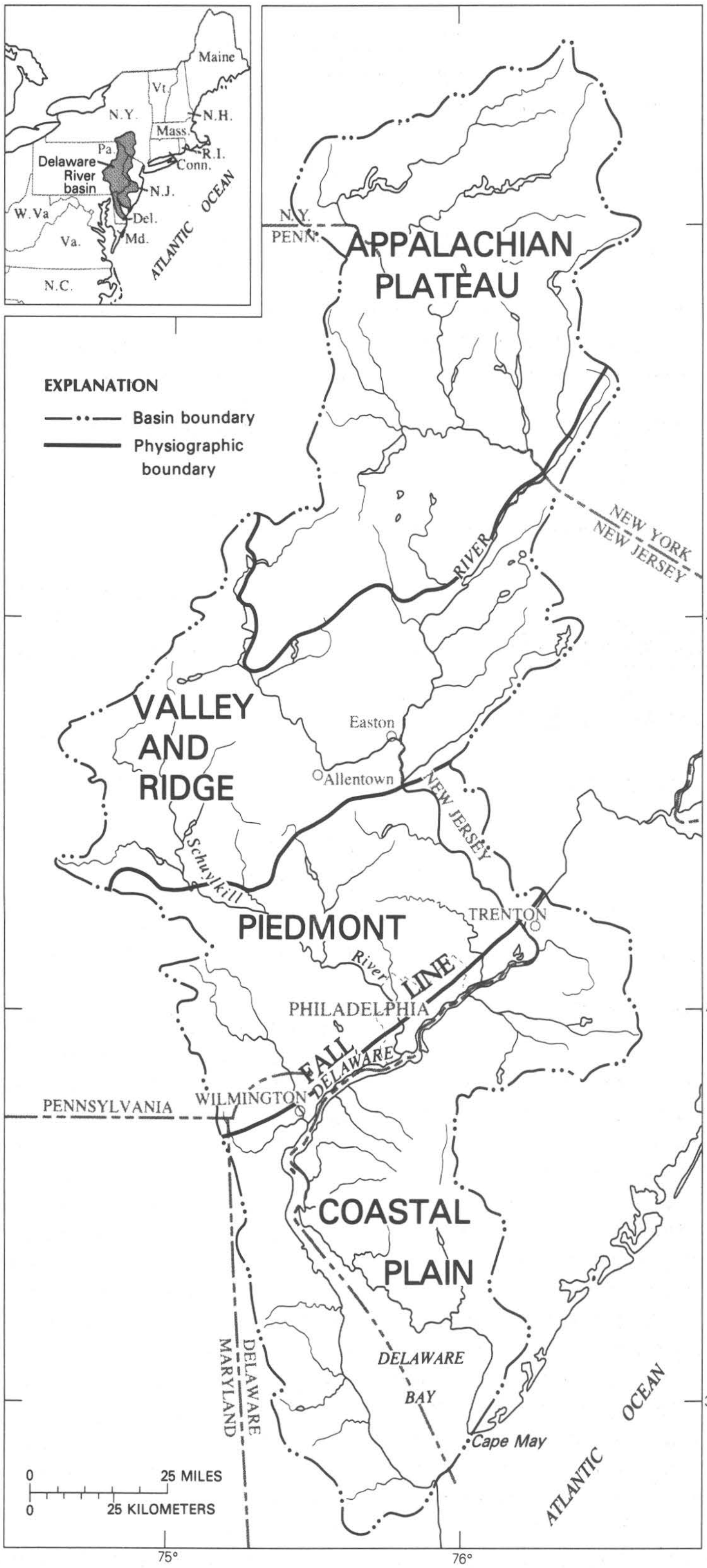

Figure 11. Physiography of the Delaware River basin.

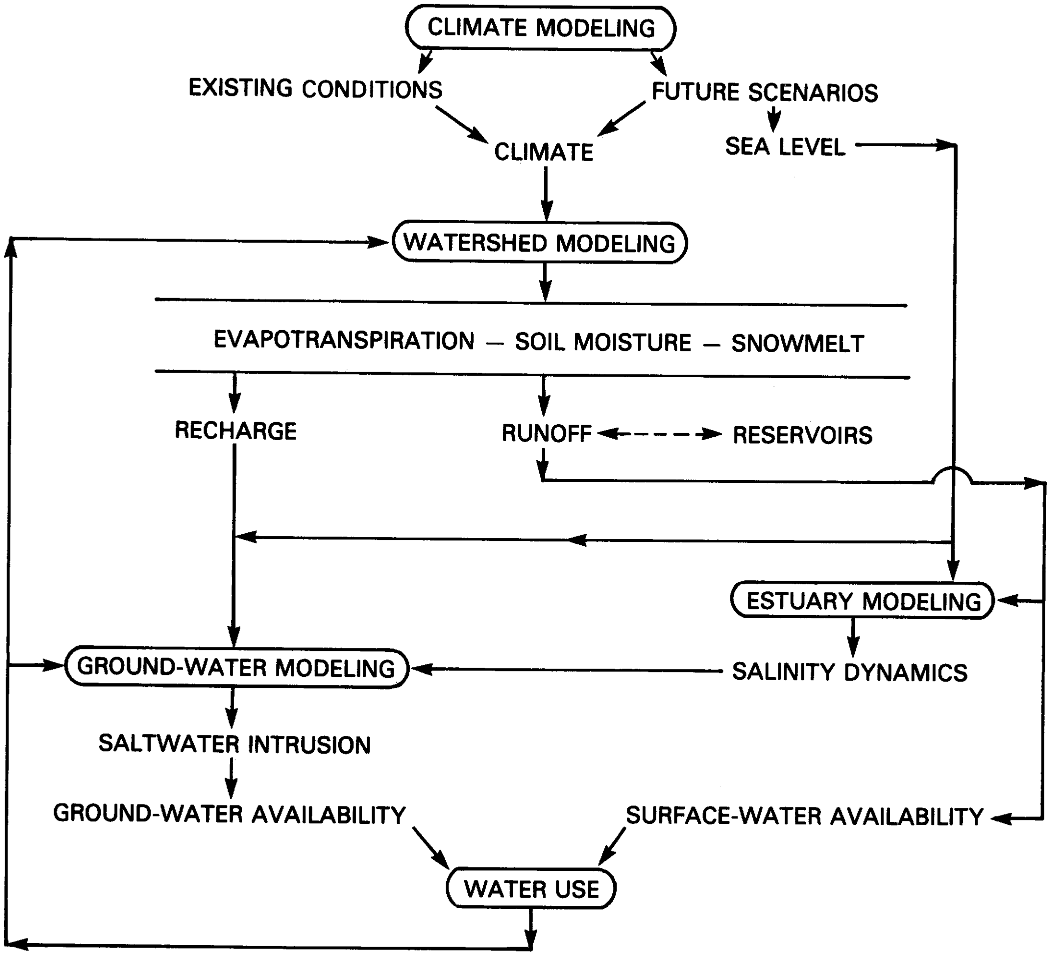

Figure 12. Primary components of the Delaware River basin study.

STRATEGY FOR ACHIEVING THE PROGRAM GOAL

The primary facet of a strategy for dealing with the hydrologic implications of climate uncertainty is the evolution of the resource balance among the three components of the program: (1) data collection, (2) research, and (3) interpretive studies. The strategy must be an evolutionary one because of the high degree of near-term uncertainty in the climate variables that, along with gravity, drive the hydrologic cycle. Information that reduces this uncertainty must be monitored continually by the program administrators, and, as the new information dictates, the program balance should be modified to address more effectively the program goal. In the early phases of the program, the necessity of feedback of information to develop the short-term plan dominates the planning process to the extent that long-term plans can be viewed only in a statistical or probabilistic context.

The planning process is based on the hypothesis that a mature program will consist of a modest balance between research and data collection that will continue to generate new knowledge and information but that will have as its major focus the synthesis and interpretation of the existing knowledge and information across broad ranges of both hydroclimatic settings and water-resources problems and opportunities. This hypothesis dictates that a mature program tends to evolve toward the lower-right quarter of the diagram given in figure 13*A*. As is shown in figure 13*B*, the water-resources activities of the U.S. Geological Survey historically have gravitated from a data-collection focus to a balance in the 1980's that has in excess of 50 percent of its funds expended for interpretive studies. This traditional evolution can be attributed to the prevailing assumption that natural hydrologic processes are in statistical equilibrium at the time scales of a century or so—stationarity. Under such an assumption, it is efficient to expend relatively large sums collecting and analyzing data that will serve as the basis for projections of future water resources. As the data bases expand, the marginal utility of the next increment of data decreases (Moss, 1970), while the hydrologists' abilities to

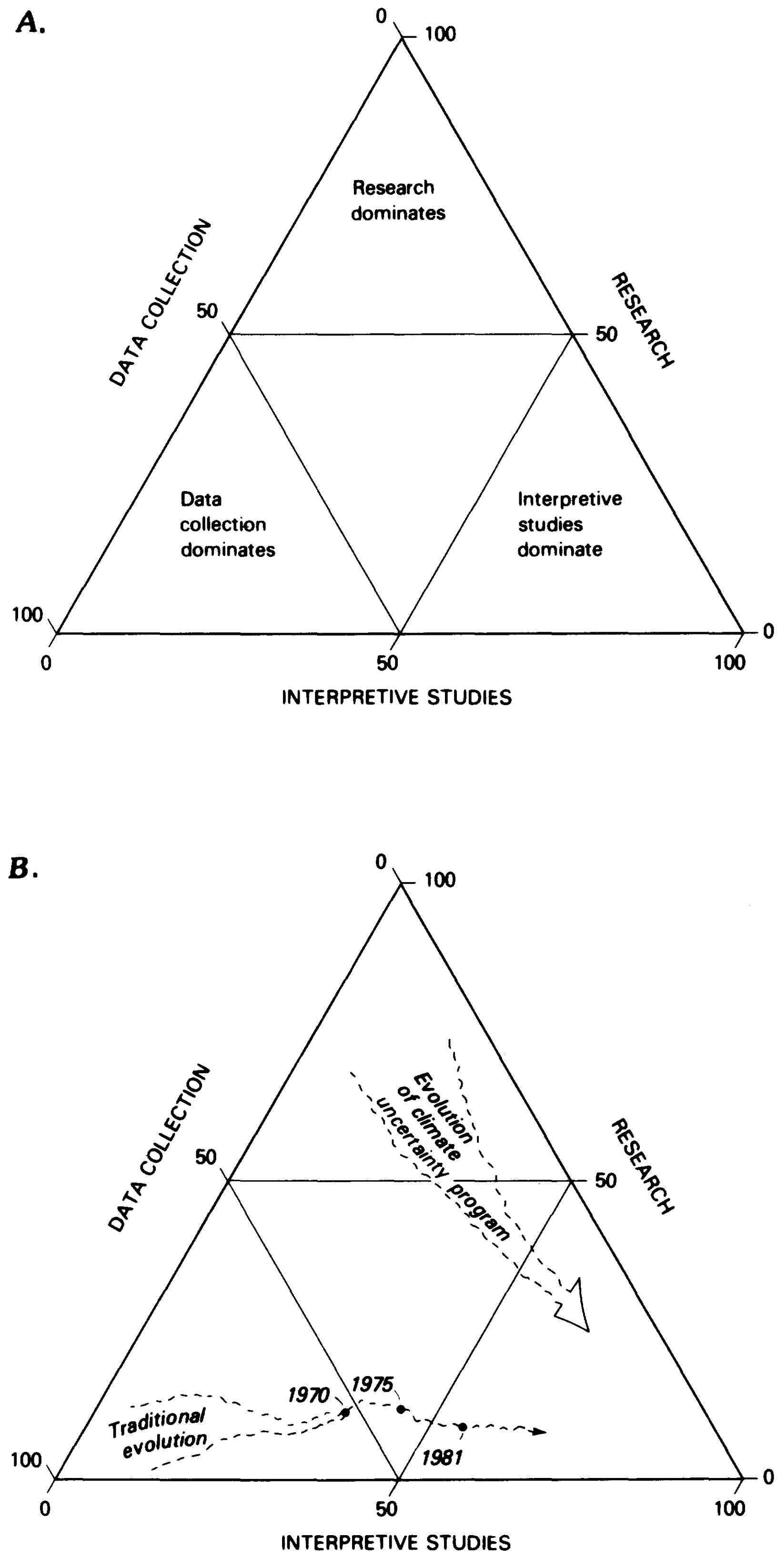

Figure 13. Resource balance among the three components of the climate-uncertainty program: (*A*) areas of single-component dominance and (*B*) program evolutions.

perform interpretive studies using the historical data bases increase. Thus, under the assumption of stationarity, there is a natural tendency to evolve from data collection to interpretation. During this evolution, research has been viewed primarily as a modest investment to address future contingencies.

The potential for climate change provides an impetus to the proposed program to start from a different sector than have the traditional water-resources programs. As was described previously, the lack of sufficient understanding of the major interactions of the hydrosphere with the atmosphere contributes significantly to the level of uncertainty regarding the future characteristics of both. Development of this understanding is requisite for useful projections of future hydrologic conditions as well as for understanding the apparent changes that may be detected as a result of existing data-collection activities. Thus, research will be the dominant component of the climate uncertainty program during its early stages, as shown in figure 13*B*. As research contributes additional understanding, both interpretive studies and data collection will have a strong basis for increased levels of effort.

As shown in table 3, the research needs for this program are partitioned into three categories. The first category, which is called critical, consists of endeavors that currently are underrepresented to a debilitating degree if the program goal is to be addressed in a timely manner. It is noticable that, with one exception, each of these endeavors deals with links between the atmospheric and hydrologic sciences. Because each will be carried out at the disciplinary frontier of hydrology, each increased activity should be planned to take advantage of and interact with complementary activities of other Federal agencies and interdisciplinary, international programs.

The exception to the hydrology-atmosphere interface in this research category is network design. This endeavor is critical because the data-collection component cannot be fully effective until better knowledge and methodologies are available to guide investments in data.

The second category of research endeavors includes facets of existing activities that only may need some redirection and (or) added support to assume their proper role in the program. With the exception of perhaps paleohydrology and biogeochemical cycles, entries in this category are traditional strengths of U.S. Geological Survey hydrologic research.

The final category contains lakes and estuaries, which have been significant components of U.S. Geological Survey research in the past but that will require added emphasis in the decade of the 1990's and beyond. Studies currently are being conducted within the Survey to define more specifically the research needs and opportunities in each of these areas.

Table 3. Research status and priorities

Status	Research
Critical concerns.............	Evapotranspiration.
	Droughts.
	Modeling (general circulation and mesoscale).
	∘ Parameterization.
	∘ Spatial disaggregation.
	Hydroclimatology.
	Network design.
	Snow and ice.
Ongoing concerns............	Infiltration.
	Runoff.
	Unsaturated zone.
	Floods.
	Recharge.
	Paleohydrology.
	Biogeochemical cycles.
	Water quality.
Evolving concerns............	Lakes.
	Estuaries.

As was discussed above, the data-collection component of the program initially will not be of the same magnitude as the research component. However, there are two data-collection activities that merit particular concern. The first of these is augmentation of the benchmark network to provide baseline information for tracking hydrologic change. Modest initial expansion likely would be followed by additional increases as knowledge, methodology, and technology are developed.

The second critical endeavor for data collection is a network for estimating areal evapotranspiration. Although such a network is an immediate need, methodology and technology limit our abilities to deploy the requisite cost-effective measurement systems. Interagency collaboration, such as is currently being carried out in the Konza Prairie of Kansas (Brutsaert and others, 1988), will be required both to redress the technological shortcomings as well as to implement the ultimate solution. The Geological Survey has a key role to play in both aspects.

The program component with the greatest potential for growth is interpretive studies. As information and understanding from the other two components of the program accumulate, the demand for interpretive studies can begin to be met. Indications are that the demand for this type of product already exists as a result of the publicity that climate change has received recently. However, current ability to provide substantive interpretations of the implications of climate change is extremely limited. Thus, a cautious approach to performing interpretive studies is in order. Studies like that in the Delaware River basin, described earlier, will be repeated in other hydroclimatic and demographic settings to test the available methodologies and data bases prior to a major expansion of this component. These early studies will treat the study areas more as large-scale open-air laboratories than as definitive hydrologic assessments. Hydrologic findings pertaining to climate uncertainty will be placed in the context of the existing levels of understanding of the critical issues. As the increments of knowledge and information accumulate, interpretations can be revisited, and the caveats on such studies can be reduced. Eventually, generally accepted procedures can be used, and interpretive studies of the hydrologic implications of climate uncertainty will become a major component of the water-resources activities of the U.S. Geological Survey.

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