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Climate Change and Climate Variability: The Paleo Record

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INTRODUCTION

The written and instrumental record is far too short to give an adequate account of the range of possible behavior of the earth's climate. Instrumental climate records in many regions extend back only a few decades, and direct observations of ecological or geomorphological processes are usually even shorter. These records are all limited to the period since atmospheric carbon dioxide started its upward climb in the early nineteenth century. A window on the preindustrial environment is needed. The techniques of paleoecology and paleoclimatology offer that window and have yielded unique insights to the behavior of the earth's systems.

The geological record reveals that the earth's climate has differed radically from today's during the earth's history. The study of these past conditions provides insights into the possible range of behavior. It has also provided important tests for our understanding of the causes of climate change. It has been possible to use models of climate, such as general circulation models (GCMs), to calculate the expected conditions on our planet at times when its geography was quite different from today's—when, for example, there was only one huge continent, or when the atmosphere had a different composition. Comparison of these expected conditions with those actually revealed by the geological record has helped advance knowledge of the mechanisms driving climate change.

Climate variations on time scales of decades to centuries are particularly important to consider for water resources management. The paleo record has contributed greatly to our understanding of long-term climate variations and enabled quantitative reconstruction of hydrologic variables with annual resolution. In this paper, we first review highlights of climate history as gleaned from the paleo record. We then provide an example of application of tree-ring data to the study of hydrologic variability in the western United States.

WHAT HAS BEEN FOUND SO FAR FROM THE STUDY OF PAST CLIMATE?

The greatest changes have occurred over the longest time scales: millions to hundreds of millions of years. For much of its four-billion-year history, the earth has been relatively warm and free of ice sheets such as those now found in Greenland and Antarctica. Yet, there have been major changes that happened relatively rapidly. For example, there is evidence of major cooling about 37 million years ago, when a long ice-free period ended, and 2.4 million years ago. This second change marked the start of the generally cooler epoch (the Quaternary) that has continued to the present. The best documented processes leading to such major long-term shifts have to do with changes in the distribution of continents and oceans, the rise and decline of major mountain ranges, and variations in sea level. Changes in the relative fluxes between the biological and geological components of the carbon cycle have also played a part by modifying the carbon dioxide concentration of the atmosphere. Such changes in the processes regulating global climate may be thought of as changes in the boundary conditions of the climate system. Large changes in these boundary conditions have taken place on time scales of hundreds of thousands, millions, and tens of millions of years. It is possible that some have occurred more rapidly, but many of the dating techniques used do not possess the resolution necessary to reveal rapid change in the distant past.

In the relatively cool world of the most recent 2.4 million years, the distribution of continents and relief has been much as at present. Since about 875,000 years ago, the climate has undergone repeated major excursions between long ice ages (about 110,000 years each) and much shorter periods of warmer climate (5,000 to 15,000 years). Such a warmer period commenced about 15,000 years ago.

Ocean Sediments

The main evidence for these periodic climate fluctuations

comes from the floor of the deep ocean, which holds sediments made up of the remains of various microscopic animals. The shells of one group, the foraminifera, are made up of calcium carbonate containing oxygen derived from the seawater. Cores have been collected from these sediments at many locations in the oceans, the deepest sediments in each core being the oldest. Hence, we have access to oxygen that was part of the ocean's water at some known time in the distant past. The proportion of the heavy isotope of oxygen (^{18}O) to the more common isotope (^{16}O) in the world's oceans has a strong link to the total volume of water locked up as ice in glaciers and the polar caps. This is because the heavy oxygen is left behind disproportionately when water evaporates from the ocean surface. When this water falls onto the glacier ice as snow, it is correspondingly short of heavy oxygen. As the global volume of ice grows, so the small proportion of heavy oxygen in the ocean water increases. Hence, we can calculate global ice volume from the record of the ratio of the oxygen isotopes ($^{18}O/^{16}O$) in foraminiferan shells from dated ocean sediments.

This record of ice volume changes (Figure 6.1) has been confirmed many times (Emiliani, 1955; Imbrie et al., 1984), not only from analysis of ocean sediments but from studies of the sea level recorded by coral reefs and land-based records such as those from loess. Loess is the deposit formed by fine, wind-blown dust derived from cold desert areas such as the Gobi Desert. Such cold, dry areas are found around the major ice sheets of the ice ages, and so there are regions (e.g., part of Czechoslovakia) where loess is deposited during ice ages but not during the warmer periods between them (Kukla, 1977). The number and timing of such loess deposits was found to coincide with the periods of greatest ice volume calculated from the ocean $^{18}O/^{16}O$ record, providing powerful evidence for the validity of those calculations.

Milankovitch's Four Frequencies

Just as it is possible to separate out the contributions of notes of different pitches or frequencies to a musical sound, so it is possible to break down the global ice volume record into its frequency components (Imbrie et al., 1984). It turns out that there are four major frequencies in the record: one every 100,000 years; one every 41,000 years; one every 23,000 years; and one every 19,000 years. These are the very periodicities predicted for the earth's climate by Milankovitch (1941) as recalculated by Vernekar (1972)

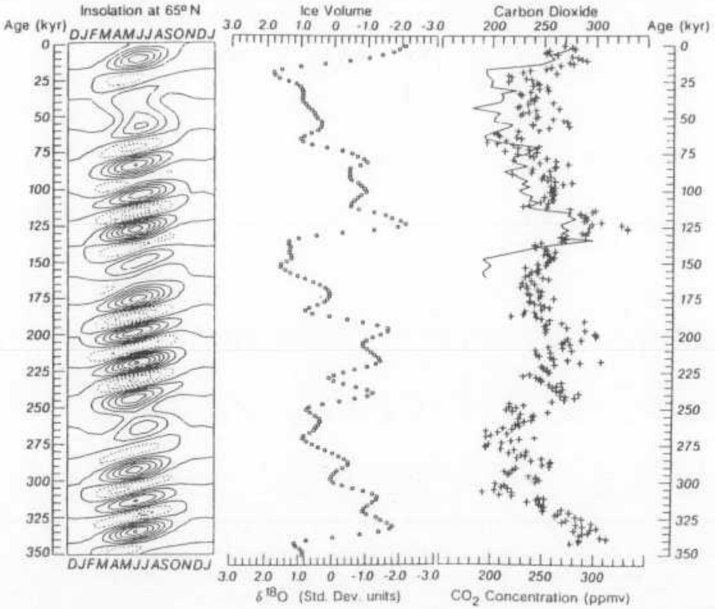

FIGURE 6.1 Central panel: Global ice volume estimated from oxygen-18 deficit in foraminiferan shells over the last 350,000 years. Left panel: Calculated insolation at 65 degrees north (contour interval 10 Wm^{-2}, dashed lines negative). Right panel: Estimated atmospheric carbon dioxide concentration (+, from isotopic ratios in marine sediments; continuous line, as measured in Vostok ice core).
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and Berger (1979). Milankovitch showed that the amount of solar energy reaching the top of earth's atmosphere varied slightly on these time scales as a result of changes in the way the earth revolves around the sun. The 100,000-year periodicity in solar receipts is driven by changes in the eccentricity ("stretch") in the earth's orbit, the 41,000-year periodicity by changes in the obliquity ("tilt") of the earth's axis, and the 19,000- and 23,000-year changes by the precession ("wobble") of the axis.

The fit between the global ice volume record and these variations in solar receipts calculated from celestial mechanics is not perfect. In particular, the earth's climate as recorded by the foraminifera shows a much stronger periodicity at 100,000 years than the astronomical calculations would predict. Further, the

actual changes in the amount of energy received from the sun are small—unlikely that these changes in the earth's orbit alone are big enough to explain the onset and end of the repeated ice ages of the Quaternary; the greater-than-expected observed variation at the 100,000-year periodicity is also a puzzle. On the other hand, the fit between the timing of the orbitally induced changes in solar receipt at high northern latitudes and the major features of the global ice volume record suggests at least a pacemaker role for the orbital variations. It is important to remember that the orbital or "Milankovitch" changes produce marked variations in the seasonal pattern of solar receipts at different latitudes. This will be referred to below in a discussion of the last 20,000 years. The recurrent glaciations of the Quaternary may well have been associated with major extensions equatorward of the mid-latitude arid regions (Dickinson and Virji, 1987; Lézine, 1989). As land surface conditions in arid regions change, so does their contribution to suspended dust in the atmosphere. An extensive effort to analyze ocean cores for dust originating on the continents now underway (Rea and Leinen, 1988) indicates major changes in the atmospheric transport of dust associated with changes between glacial and interglacial periods. Some possible explanations for the importance of the 100,000-year periodicity have to do with the growth, inertia, and effects of the major continental ice sheets associated with the ice ages.

Polar Ice

Remaining polar ice provides the most remarkable record of past climate, particularly for the last glacial cycle, which started more than 110,000 years ago. The snow falling on the central parts of the Greenland or Antarctic ice sheets is trapped for hundreds of thousands of years because the temperature at the base of the ice is too low to allow melting. Hence, by taking core samples from the top of the ice downward, it is possible to sample snow (now ice) that fell in the distant past. A number of techniques are used to calculate the age of ice at a particular depth, including mathematical models of the mechanical processes taking place within the ice. As discussed above, the ratio of the oxygen isotopes ($^{18}O/^{16}O$) in the falling snow and hence in the ice is related to general climate conditions. Both this ratio and that between heavy hydrogen, or deuterium, and ordinary hydrogen ($^{2}H/^{1}H$ or D/H) correlate well with temperatures above the ice at the time the snow fell. The D/H record has been used to construct a record of temperature at the Soviet Vostok station in Antarctica that extends back about 160,000 years, to the end of the ice age before last (Lorius et al., 1990). A range of temperatures of 5 to 6°C over Antarctica is reconstructed. This record corresponds to a remarkable degree to the record of global ice volume derived from foraminiferan $^{18}O/^{16}O$ in ocean cores (Figure 6.2). Not only does the

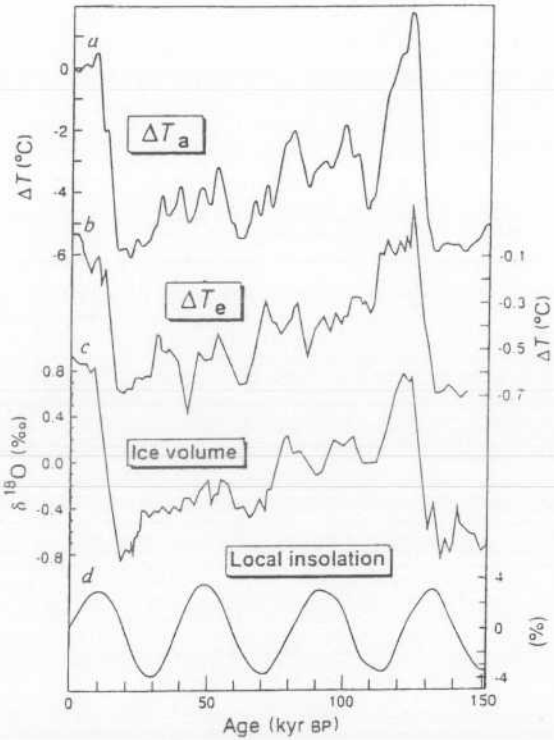

FIGURE 6.2 Temperature deviation, ice volume, and local insolation at Vostok station in Antarctica over the last 150,000 years. Top curve: Temperature (shown as the deviation from modern temperature) calculated from ice D/H ratios. Second curve: Temperature deviation calculated from the greenhouse effect of carbon dioxide and methane. Third curve: Ice volume, derived from the oxygen isotope ration in formaniferan shells of ocean sediments. Lower line: local insolation at 78 degrees south.
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polar ice contain ancient water, but trapped within it is the air that was circulating over the ice sheet at the time the snow fell and became transformed to ice. This air can be extracted from the ice and analyzed for gases such as carbon dioxide and methane. Figure 6.3 indicates that the atmospheric concentrations of these

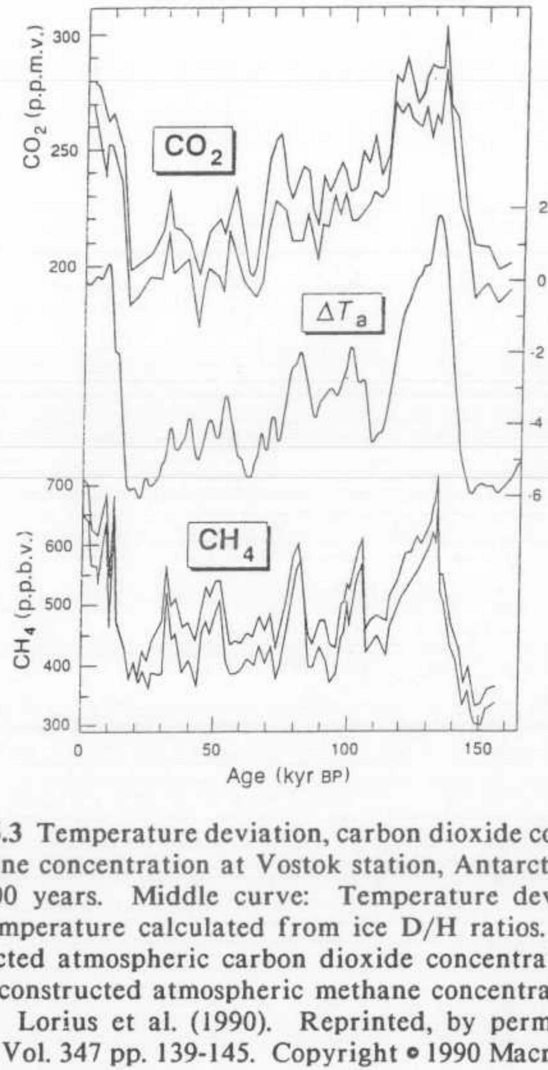

FIGURE 6.3 Temperature deviation, carbon dioxide concentration, and methane concentration at Vostok station, Antarctica, over the last 160,000 years. Middle curve: Temperature deviation from modern temperature calculated from ice D/H ratios. Top curve: Reconstructed atmospheric carbon dioxide concentration. Lower curve: Reconstructed atmospheric methane concentration.
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gases have shown variations remarkably similar to those of temperature over that last 160,000 years. The range of concentrations of atmospheric carbon dioxide—from close to 300 parts per million by volume (ppmv) in the warm periods between ice ages to as low as 180 pp mv in the depths of an ice age—is particularly striking. A calculation of the direct greenhouse effect (with no climate feedbacks) produced by the observed concentrations of carbon dioxide and methane shows that this can account for between 40 and 65 percent of the observed Antarctic temperature change (Lorius et al., 1990) (Figure 6.2).

The most recent ice age ended suddenly, having reached its most severe depths around 18,000 to 20,000 years ago. There were extensive continental ice sheets in both the Northern and Southern hemispheres that started to shrink approximately 14,000 years ago (Broecker and Denton, 1990). The great North American ice sheet centered on the Canadian Shield had disappeared by about 7,500 years ago. Atmospheric carbon dioxide and methane concentrations had increased more than 25 percent to preindustrial levels between 11,000 and 9,000 years ago (Lorius et al., 1990). At the same time, the orbital variations invoked by Milankovitch were producing marked changes in seasonality at high latitudes (more or less equal and opposite in the Northern and Southern hemispheres). At around the time of the glacial maximum (approximately 20,000 years ago), solar receipts at 60 degrees north in summer and winter approximated those of the present day, while around 9,000 years ago the contrast between summer and winter was markedly stronger (Figure 6.4). These and probably other factors produced major changes in regional climates, including that of western North America.

The Western Climate

The middens of pack rats provide invaluable information on past environments in arid and semi-arid regions such as most of the West. These small mammals collect plant materials from a very limited area (about 30 meters in radius). The plant fragments (e.g., twigs, leaves, needles, fruits, and seeds) are often preserved in crystallized urine called "amberat." If identifiable remains of a plant are found in a midden, they constitute firm evidence that the species was present locally. This has made it possible to reconstruct the vegetation of the West over tens of thousands of years, with the help of radiocarbon dating.

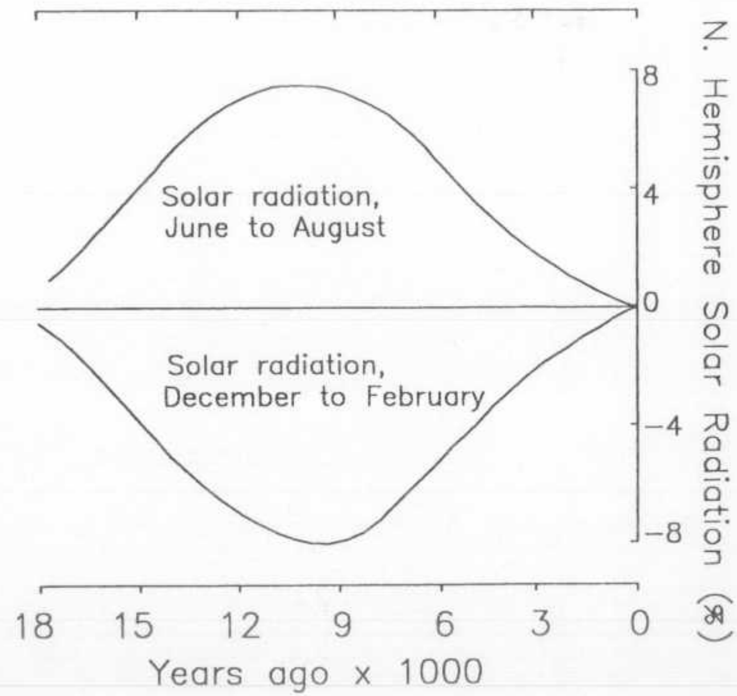

FIGURE 6.4 Insolation at 60 degrees north since the last glacial maximum (after COHMAP, 1988).

Betancourt (1990) has brought these records together in a review of the vegetation history of the Colorado Plateau (Figure 6.5). He demonstrates major changes in plant species distributions between the Late Glacial (15,000 to 11,000 years ago) and Late Holocene (4,000 to 800 years ago) periods. During the Late Glacial period, the upper tree line was several hundred meters lower than at present and boreal forest (spruce and true fir) was found some 900 meters lower. The vegetation patterns were not, however, simply shifted downhill in response to a colder climate. Ponderosa pine (*Pinus ponderosa*) and Colorado pinyon (*Pinus edulis*) are major features of the present vegetation of the Colorado Plateau, but both were absent in the Late Glacial period. Ponderosa was replaced by limber pine (*Pinus flexilis*) in many cases. The absence of ponderosa pine may have been the result of cooler summers and orbitally determined lower insolation in the latter part of the growing

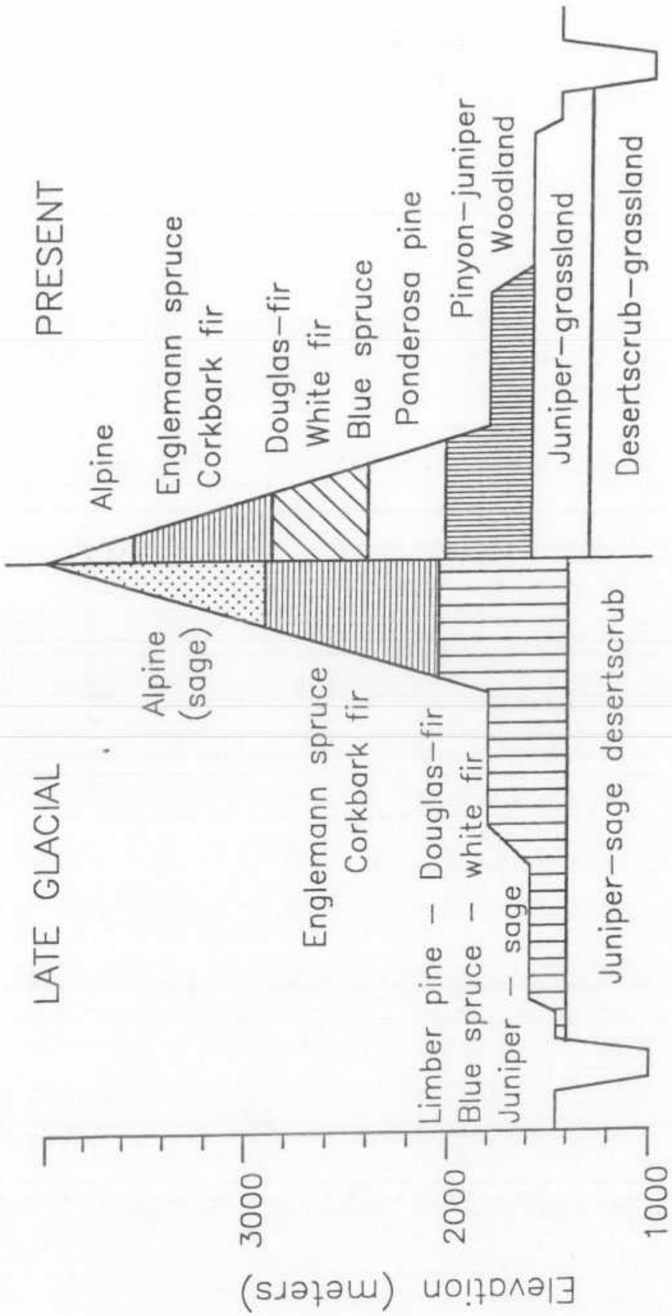

FIGURE 6.5 Generalized late-glacial and present plant zonation on the Colorado Plateau (after Betancourt, 1990).

season. Utah juniper (*Juniperus osteosperma*) was present, probably because of its greater cold tolerance than Colorado pinyon. Betancourt inferred from these and other plant species distributions that the Late Glacial summers on the Colorado Plateau were more than 6°C cooler than at present (Betancourt, 1990)—about the same temperature difference as noted from ice D/H ratios at Vostok in Antarctica. He indicated that the relative proportion of annual precipitation falling in summer (less than 10 percent) was even smaller than in recent times (20 to 30 percent). Note that different climates do not simply have different means, but also different variabilities and seasonalities.

Other evidence of past climate in the West may be extracted from the chemical composition of plant remains found in dated pack rat middens. Just as the D/H ratio in polar ice reflects certain environmental temperatures, so the same ratio in plant cellulose is related to that in the plant's source water and hence, in part, to growing-season temperatures. Long et al., (1990) measured plant cellulose D/H ratios in materials from pack rat middens in the Great Basin and on the Colorado Plateau and from them inferred July temperatures over more than 30,000 years. The general form of the record is very similar to that calculated from a GCM, although the GCM calculated that the difference between present and ice-age temperatures (about negative 2.5°C) is lower than other evidence would suggest.

It has been possible to reconstruct conditions at several times in the last 20,000 years over much of the world by combining information on the composition of marine plankton from ocean cores, pollen from lakes and bogs, plant remains from pack rat middens, and natural records of the water levels in lakes (COHMAP, 1988). Twelve thousand years ago (during the Late Glacial period), with extensive ice sheets still present, such a reconstruction shows that the whole of the American West was wetter than it is now. Between 9,000 and 6,000 years ago, the Pacific Northwest was drier than at present, whereas the Southwest was wetter. Summer temperatures were between 2 and 4°C higher in the West, and winters were probably cooler. The Arizona monsoon started to appear about 9,000 years ago. GCM results using the known boundary conditions (orbital position, carbon dioxide content of air, global ice volume, and sea surface temperatures) at these times produce similar patterns of regional climate. This gives increased confidence in the physical understanding used to build GCMs and hence in their usefulness when considering the effects of changed boundary conditions on the climate system.

Rapid Climate Shifts

Superimposed on the relatively smooth global shift into (gradually) and out of (rapidly) repeated ice ages or glaciations, there have been shorter lurches of widespread, if not global, extent. The most studied of these is an event known as "the Younger Dryas." During the rapid emergence from the last glaciation about 11,000 years ago, northern Europe and northeastern North America plunged back from interglacial conditions broadly similar to today's to the chill of an ice age (a temperature decline of about 6°C). This may have taken only 100 years or less. The period is named for *Dryas octopetala*, a plant of the high Arctic that appeared with other Arctic plants in parts of Europe where forest formerly stood. Perhaps no more than 1,000 years later, this massive "cold snap" ended, maybe even more rapidly than it started. There is tantalizing, but inconclusive, evidence that other major climate changes occurred at the same time elsewhere, for example on the Loess Plateau of China. Even if the Younger Dryas event was strictly a North Atlantic affair, it is of enormous significance because of its scale and speed. Our present state of knowledge would not enable us to anticipate such a change even if it were to start next year. One persuasively argued explanation links the Younger Dryas to massive changes in ocean circulation induced by a change in the point at which most of the meltwater from the retreating North American ice sheet emptied into the sea (Broecker and Denton, 1990). This explanation requires the Atlantic circulation to shift rapidly between alternate modes, resulting in sudden changes in the northward transfer of heat by the ocean that currently gives the North Atlantic periphery climates that would otherwise be found ten degrees further south. It is possible that other such sudden and drastic changes in the last 15,000 years will be found elsewhere as other regions are studied as intensively as Europe and eastern North America.

Other drastic changes, albeit more short lived (lasting 1 to 10 years) than the Younger Dryas, may be associated with very large explosive volcanic eruptions or groups of eruptions. There is very strong evidence for much larger and climatically effective eruptions at various times in the last 10,000 years than have occurred during times of historical record (Hammer et al., 1980; Baillie and Munro, 1988). Even if we understood and could predict the effects of such an eruption on climate, we are unlikely to be able to forecast the eruption itself.

Less drastic changes in climate, lasting one to a few centuries, have been discussed by many authors. The Little Ice Age, a cooler period starting some time between A.D. 1450 and A.D. 1650 and ending perhaps as late as A.D. 1890 (Grove, 1988) has been discussed as if it were a global cooling of about 1.5°C. In fact, the quality of the evidence for this is very mixed and is much more dense in some parts of western Europe and eastern North America than elsewhere. Support comes from traces of glacier advance and retreat in some regions (Denton and Karlen, 1973), oxygen isotope records from annually layered ice caps in Peru and Tibet (Thompson and Mosley-Thompson, 1990), temperature-sensitive tree rings of high elevation trees in California (LaMarche, 1974) and Washington (Graumlich and Brubaker, 1986), and from boreal forest trees in Canada (Jacoby and d'Arrigo, 1989) and the polar Urals (Graybill and Shiyatov, 1989) but not, for example, from tree rings in northern Scandinavia (Briffa et al., 1990). Little evidence is available for lower latitudes or the oceans. Another much-discussed global change is the "Medieval Warm Epoch." There is certainly evidence for warmer conditions in the circum-North Atlantic region at times between A.D. 800 and A.D. 1350 and some indications of the same effect in polar and high-elevation ice cores elsewhere. As in the case of the Little Ice Age, the evidence is far from complete. It is not yet possible to say with confidence whether these much-discussed cold and warm periods were really global or whether the suggestion of a name and a date, usually from European experience, has attracted evidence that really records unconnected events.

In order to resolve these problems it is necessary to use records of environmental conditions that are reliably dated to the calendar year. The most extensive such natural record is provided by the annual rings of trees in the temperate and boreal forests. In dry regions, the width or thickness of the annual ring is often controlled by the availability of moisture, whereas in cool, moist regions ring width or maximum wood density records summer temperatures. An extensive literature documents the techniques used to extract climate information from tree rings (Fritts, 1976; Hughes et al., 1982; Cook and Kairiukstis, 1990). The direct application to hydrologic problems of records of tree growth derived from tree rings is of particular relevance to the topic of this meeting. An example of such a study follows.

TREE RINGS AS HYDROLOGIC INDICATORS

There are better natural records of climate of the last few hundred years in the western United States than anywhere else on earth. These include an extraordinary wealth of climatically sensitive tree-ring records that can be used to place the instrumental period in a wider perspective.

The physical basis for using tree rings as hydrologic indicators in semiarid regions is well understood. The most frequently used tree-ring variable in drought and hydrologic studies has been the ring-width index, a measure of departures from normal of annual diameter growth of the tree. Both the growth increment of a tree and the annual or seasonal flow of a river are closely related to the water balance of the soil integrated over days, weeks, or months. Statistical studies have repeatedly shown that hydrologic variables and annual growth indices from properly selected trees are highly correlated (Schulman, 1956; Stockton, 1975; Smith and Stockton, 1981; Cleaveland and Stahle, 1989).

Spatial Patterns of Drought From Tree-Ring Networks

Where the spatial coverage is sufficiently dense and time coverage sufficiently long, networks of tree-ring data can convey important hydrologic information on the joint space-time variation of moisture anomalies. Without tying the tree-ring patterns to a specific hydrologic variable, we can infer the year-by-year development of drought patterns by mapping tree-ring indices. Spatial and temporal coverage by tree-ring data is especially favorable for such an analysis in the southwestern United States, where some 121 tree-ring sites provide continuous coverage for the years A.D. 1600 to A.D. 1962. The cut-off years for this period are dictated largely by the age distribution of suitable tree-ring sites and the history of field collections in the Southwest. Species of dubious quality for drought reconstruction (e.g., bristlecone pine from high elevations) can be excluded from the analysis.

To summarize drought patterns using tree-ring data, we divided the southwestern United States into a grid of 35 cells, each with a dimension of 3 degrees latitude by 2 degrees longitude (Figure 6.6), grouped tree-ring sites by their enclosing cell, and averaged individual series in each cell together. We then analyzed the resulting 28 "cell-average" tree-ring series (seven cells contained no tree-ring sites) to produce annual maps of relative growth anomalies in two of the more severe multiyear droughts of the A.D. 1600 to 1962 period: A.D 1667 to 1670 and A.D. 1843 to 1848. These droughts are particularly relevant for their widespread coverage of runoff-producing regions. The first drought, A.D. 1667 to 1670, has been reported as particularly extreme in the watersheds of the upper Colorado River and

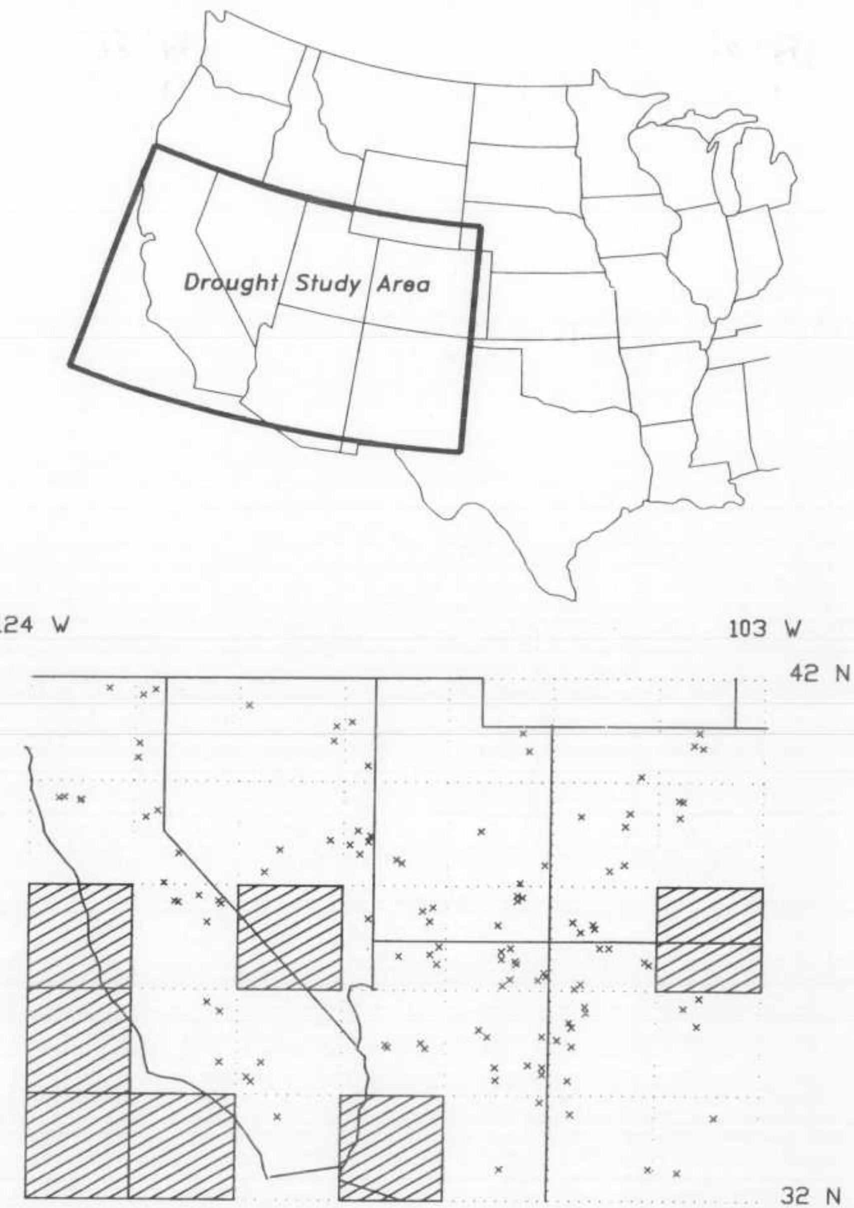

FIGURE 6.6 The grid network we used to group tree-ring sites (designated with an *x*) and tree ring sites. Cells containing no suitable tree ring chronologies are hatched.

the Salt and Verde rivers, which drain the central and eastern highlands in Arizona (Stockton, 1975; Smith and Stockton, 1981). The second drought, A.D. 1843 to 1848, has been noted for its severity in reconstruction of drought and streamflow in the Four Rivers area of the Sierra Nevada of northern California (Earle and Fritts, 1986). This area is a major source of water supply to southern California.

The annual cell-average tree-ring series for the two droughts have been coded on maps by circles of varying size within each cell (Figures 6.7 and 6.8). The radius of a circle is proportional to the exceedance probability, p, of growth index for the year if the index is less than the long-term median, or to 1-p if the index is greater than the long-term median. Circles have been scaled such that the largest or smallest growth value in the 1600 to 1962 period yields a circle with a diameter equal to the width of the cell. In terms of inferred moisture conditions, therefore, a dotted circle filling the cell would indicate the driest (lowest growth) year on record, while a hatched circle would indicate the wettest year on record. No circle (zero radius) implies median moisture conditions.

A practical hydrologic consideration in attempting to quantify drought regionally is the spatial distribution of droughts relative to major runoff-producing areas. The maps in Figures 6.7 and 6.8 clearly show that the spatial scale of drought in individual years of the 1660s and 1840s droughts was generally smaller than the entire Southwest. In most years, therefore, severe deficits in runoff would not be expected over all major runoff-producing areas simultaneously. For example, the Sierra Nevada of northern California appear to have been normal or wetter than normal in 1669 and 1670, when severe drought appears to have occurred in the Colorado Rockies and the central Arizona highlands.

In the 1840s drought, however, the year 1847 stands out as an exception to this generalization and points to the possibility of synchronous severe drought over all major watersheds of the Southwest. The unusually extensive drought of 1847 appears to be imbedded in a generalized 6-year drought that would best be characterized as a "Far West" drought. A temporal pattern to the drought of the 1840s is hinted at: anchoring in the Far West in 1843 and 1844, shifting inland in 1845 so that the extreme northwestern part of the study area was out of the drought pattern, returning to the Far West mode in 1846, expanding dramatically to cover the entire Southwest in 1847, and again shifting to the Far West in 1848. A steep northwest-southeast gradient to wetter than normal conditions is inferred toward the far northern part of the West region. A persistent ridge, probably narrow in longitudinal extent, cells for

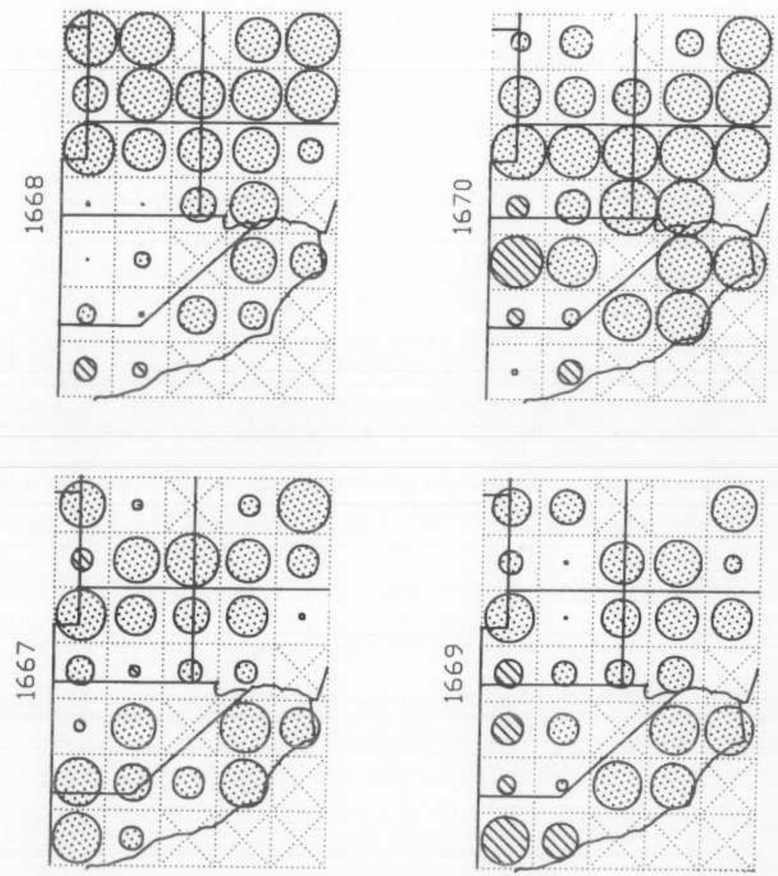

FIGURE 6.7 Maps showing relative departures of growth by grid individual years of the 1660s drought. Low-growth anomalies are dotted; high-growth anomalies are hatched. Scaling of circles is discussed in the text.

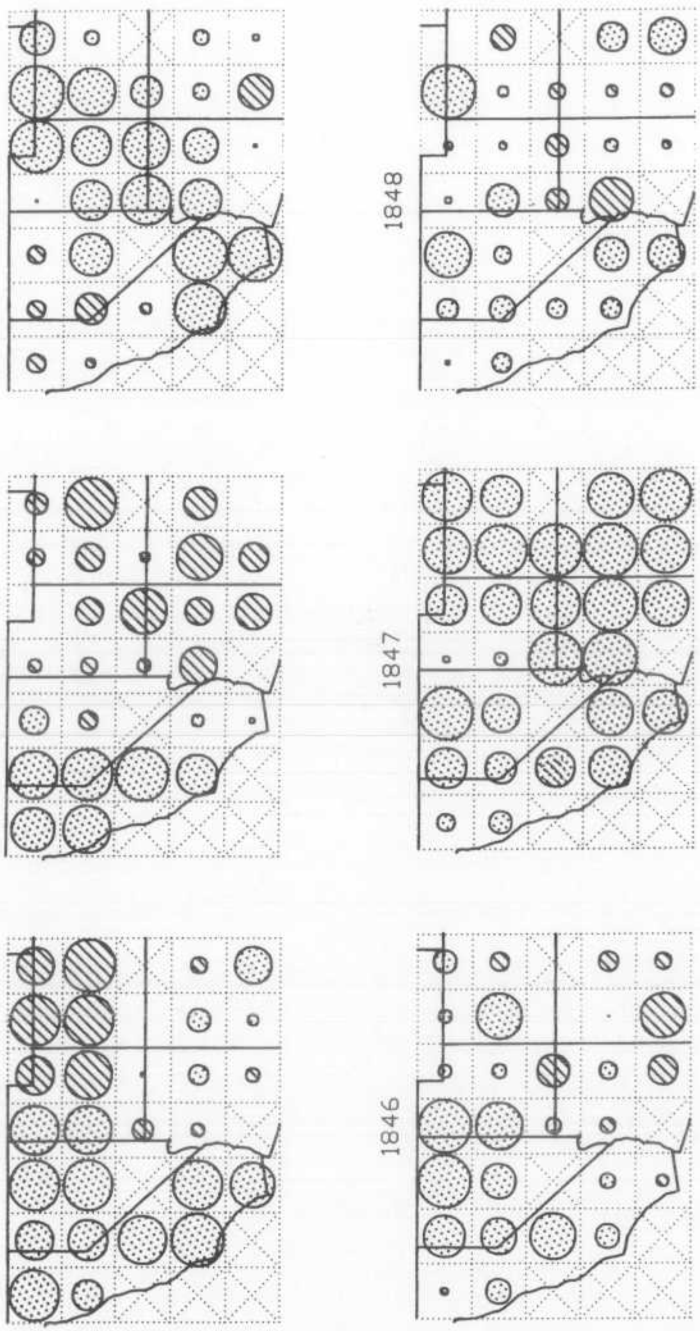

FIGURE 6.8 Map showing relative departures of growth by grid cell for individual years of the 1840s drought. Low-growth anomalies are dotted; high-growth anomalies are hatched. The text explains the scaling of circles.

along the West Coast is a plausible meteorological scenario for most years of this drought. Another possibility is a ridge in the eastern North Pacific whose effects on suppression and diversion of storms did not extend far enough inland, except in 1847, to affect states east of Nevada and California. The very wet conditions in the Colorado Rockies during some years of the Far West drought could possibly have resulted from the movement of storms southeastward from Canada and the Pacific Northwest with intensification over the Rockies. The dry tier of cells along the southern boundary of the Southwest region suggests that movement of storms and moisture from the Southwest under the ridge was probably not the source of wetness in Colorado.

Basin-Specific Streamflow Reconstructions

Where the water resources of a particular watershed or river system are in question, it is often useful to go beyond the mapping of tree-ring variations, as described above, to the quantitative reconstruction of specific hydrologic time series. Tree-ring reconstructions of streamflow have been conducted by the Laboratory of Tree-Ring Research at the University of Arizona for three major river-basin systems in the western United States: the upper Colorado River basin, with parts in Colorado, Wyoming, Utah, and New Mexico; the Salt and Verde rivers in central and eastern Arizona; and the Four Rivers group (Yuba, Sacramento, American, and Feather) of northern California (Figure 6.9).

The four phases in a typical tree-ring reconstruction of streamflow include: (1) planning and collection of hydrologic and climatic data, (2) field sampling and physical preparation of tree-ring samples, (3) selection and calibration of a reconstruction model, and (4) generation of reconstructed streamflow along with cross-validation or verification of the reconstruction (Figure 6.10). Descriptions of available methodology can be found elsewhere (Stockton et al., 1985; Cook and Kairiukstis, 1990). The planning and field sampling steps are especially critical in a hydrologic reconstruction to ensure that the tree-ring data provide an optimum signal for the climatic input governing streamflow. In the West, the strategy includes concentrating sampling as much as possible in the major runoff-producing areas of the watershed.

Stockton's (1975) Colorado River reconstruction serves as a good example of a hydrologic tree-ring study whose results have important implications for water resources. The importance of the

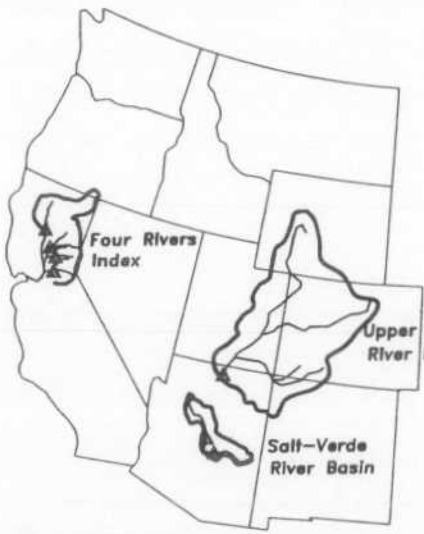

FIGURE 6.9 Map showing locations of three areas for which regional or basin-specific tree-ring reconstructions of streamflow have been conducted by the Laboratory of Tree-Ring Research.

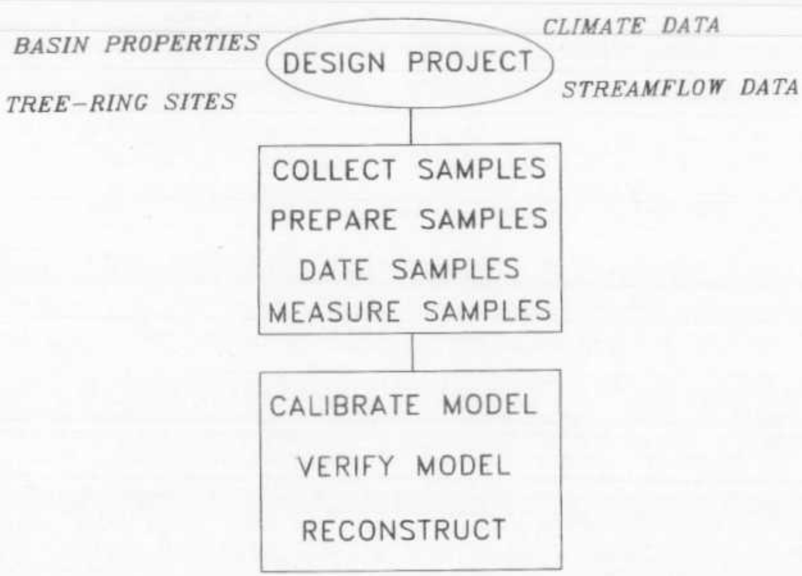

FIGURE 6.10 The major steps in a tree-ring reconstruction of streamflow.

Colorado River as a source of water for agriculture, hydroelectric power generation, and municipal and industrial uses in the southwestern United States cannot be overstated. This 1440-mile-long river flows through some of the most arid lands in the country, and its 244,000-square-mile drainage area includes parts of seven states and a small portion of Sonora and Baja California in Mexico. The Colorado has an average annual flow of just under 14 million acre-feet (maf), a small amount when compared to such rivers as the Columbia and Mississippi. In spite of this relatively low flow, more water is diverted from the basin than from any other river basin in the United States. The river is an important source of supply for southern California and, with the nearly completed Central Arizona Project, for the metropolitan areas of Phoenix and Tucson in Arizona.

Most of the flow for the Colorado originates in the river's upper basin (the area north of Lee's Ferry, Arizona), which includes some 109,300 square miles. About 85 percent comes from only 15 percent of the area—the high mountains of Colorado, Wyoming, and Utah (Stockton and Jacoby, 1976).

The tree-ring data for the study comprised 30 different sites from the major runoff-producing regions. Stockton (1975) calibrated statistical models to reconstruct annual and seasonal flow series at several gage locations in the upper basin from these tree ring data. The reconstruction for the outflow point of the upper basin—Lee's Ferry, Arizona—extends back to A.D. 1520. The period from 1906 to 1930 had the highest sustained flows in the entire reconstruction. The average annual flow, 16.2 maf, for that period was used as a basis for the Colorado River Compact. If the tree-ring reconstruction is accepted as accurate, the design period was simply not representative of the long-term flow of the river. Thus, the division of water between states of the upper and lower Colorado basins, as well as Mexico, is based on an anomalously high value and is apt to result in shortages when all of the entities involved demand their allocated share of the available water.

The terms of the Colorado River Compact specify that no less than 75 maf will be delivered at Lee's Ferry in any consecutive 10-year period (Holburt, 1982). For this reason, 10-year moving averages of the Lee's Ferry reconstruction are of particular interest. Nonoverlapping 10-year means of the reconstruction beginning in 1521, 1531, and so forth until 1951 are graphed in Figure 6.11 along with similar averages for the actual natural flow series as provided by the U.S. Bureau of Reclamation. The droughts of the 1580s through 1590s and the 1660s are again prominent—the earlier especially so for its combined intensity and duration.

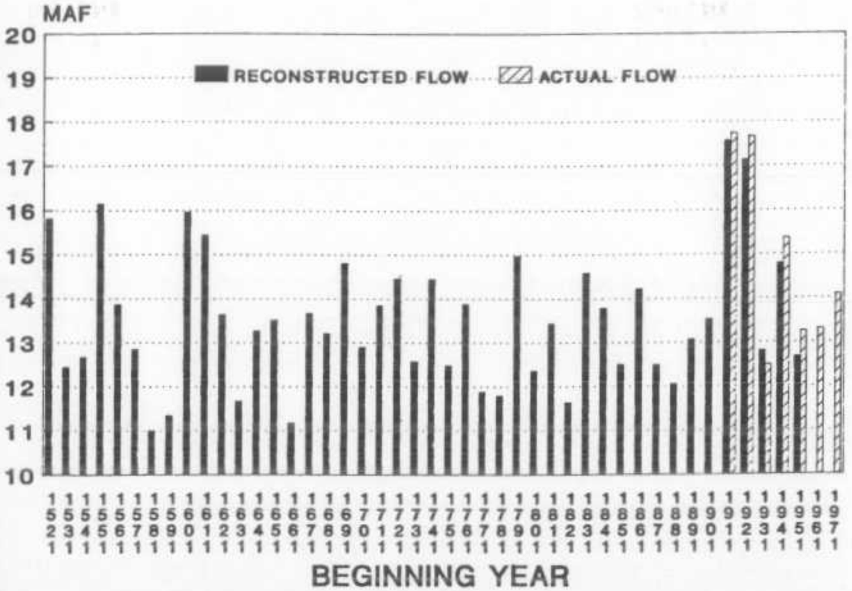

FIGURE 6.11 Bar plot of nonoverlapping 10-year means of reconstructed and actual flow at Lee's Ferry. Actual data are virgin flow obtained from the U.S. Bureau of Reclamation.

The designation of the lowest reconstructed 10-year mean depends on the yearly grouping. The second year of each decade (e.g., 1951) was used to begin each 10-year period in Figure 6.11 because the minimum flow in the actual natural-flow series happened to occur during the period 1931 to 1940. The minimum nonoverlapping 10-year-average reconstructed flow by this grouping is 11.0 maf for 1581 to 1590. In terms of running 10-year means, however, the lowest value is 9.71 maf for 1584 to 1593. Whether the implied 10-year total natural flow of 97.1 maf would lead to noncompliance with the contract terms specifying delivery of 75 maf depends, of course, on the 10-year total depletions for the period. These depletions would reduce the 97.1 maf by some unknown amount depending on water use in the upper basin.

We emphasize that data such as those plotted in Figure 6-11, while in the proper units for streamflow, are merely estimates. Such estimates represent our best possible information on what streamflow conditions may have been, but the inherent uncertainty

should always be kept in mind. The magnitude of the uncertainty for reconstructed values in individual years is appreciable: the standard error of the estimate for the Lee's Ferry reconstruction is about 2 maf. It is reasonable, however, to expect somewhat less uncertainty in values averaged over several years. For example, a simple regression of 10-year running means of observed Lee's Ferry flow against the reconstructed flow yields a standard error of 0.46 maf—only about 25 percent of the standard error of the annual reconstructed values.

Uncertainties in Regional Water Supplies

It is not unusual for metropolitan water utilities in the West to import water from regions separated by hundreds of miles. The impact of drought on water supply then depends on the synchrony of climate anomaly patterns over the various source regions. An example of an area depending on several widely separate runoff sources is metropolitan southern California.

The Los Angeles area draws much of its supply from two source regions: the upper Colorado River and northern California. We have examined jointly two hydrologic tree-ring reconstructions for information on extended low-flow periods in two source runoff areas for the Los Angeles water supply: the upper Colorado River and the Sierra Nevada of California. The corresponding tree-ring studies are by Stockton (1975), for the Colorado River at Lee's Ferry, and Earle and Fritts (1986), for the Four Rivers (Sacramento, Feather, Yuba and American) index of northern California (Figure 6.9). Both reconstructions were conducted specifically to maximize the signal for annual runoff, and both extend over several centuries: to A.D. 1520 for the Colorado River and to A.D. 1560 for the Four Rivers index.

Storage acts as a buffer against the effects of meteorological drought, and the considerable capacity of surface and underground storage in this case suggests that droughts must last several years to significantly impact water supply. We have adopted the 20-year moving average of reconstructed annual flow as the data unit to be analyzed for drought. Shorter droughts, especially those of great intensity, can, of course, cause hardship to water users not tied in to the larger storage network. A sustained deficiency of precipitation over a period of 20 years or longer, however, would likely affect even those major water utilities that have elaborate contingency plans to counter drought.

Twenty-year moving averages for both reconstructions are shown in Figure 6.12. The 1660s and 1840s droughts, referred to previously in the discussion of spatial patterns of tree-ring growth departures, are prominent in these plots. The years before A.D. 1600, however, hold by far the lowest reconstructed 20-year flows on the Colorado River. The most severe sustained droughts inferred from lowest 20-year moving average reconstructed flows were as follows for the two series:

- For the Colorado River at Lee's Ferry, flow dropped to 10.95 maf for the years 1579 through 1598.
- For the Four Rivers index, flow dropped to 13.55 maf for the years 1918 through 1937.

Figure 6.12 clearly shows that the 1579 to 1598 period was drier than any other on the Colorado. Considering that the long-term mean of the Lee's Ferry reconstruction is 13.5 maf, the most severe sustained drought for the Colorado River represents a cumulative deficiency of 51 maf over 20 years. The designation of most severe sustained droughts is more uncertain for the Four Rivers index. The Four Rivers area apparently experienced a drought in the 1840s only slightly less severe than that of the 1918 to 1937 period. Moreover, the standard error of the estimate for the annual values of the Four Rivers reconstruction is 5.5 maf, compared with 2.0 maf for the Colorado River reconstruction.

A comparison of the two curves in Figure 6.12 suggests a lack of consistent synchrony between 20-year average flow departures in the upper Colorado River basin and northern California. Annual (unsmoothed) flow series in the two basins are positively correlated, though the coefficients are small:

$r = 0.40$, actual series, 1906-1985
$r = 0.23$, reconstructed series, 1560-1961
$r = 0.37$, actual series, 1906-1961
$r = 0.25$, reconstructed series, 1906-1961

All except the 0.25 value are significant at the 95 percent confidence level. The last two coefficients listed suggest that the reconstruction may underestimate interbasin correlation. Although like-sign departures occur from time to time in the 20-year moving average curves of Figure 6.12, periods of contrast are frequent. For example, the 20-year period of highest average flow for the Four Rivers index, beginning in about 1800, was a time of below-

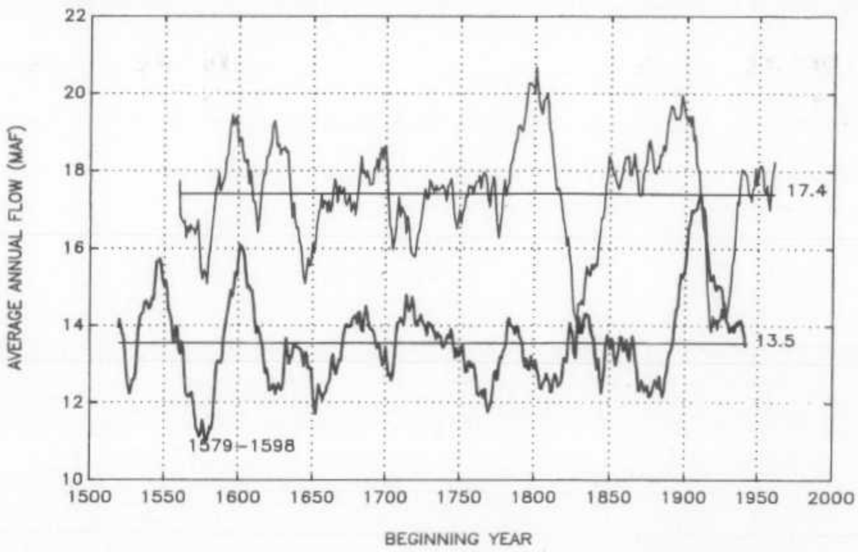

FIGURE 6.12 Time series plots of 20-year running means of reconstructed flows for the Colorado River at Lee's Ferry (lower line) and for the Four Rivers index, northern California (upper line).

average reconstructed flow for the Colorado River. On the other hand, the aforementioned 1579 to 1598 drought on the Colorado River coincided with the third lowest nonoverlapping 20-year mean flow on the Four Rivers index.

The synchrony in droughts and wet periods between the two regions can perhaps be judged more clearly from a scatter plot of the 20-year moving averages (Figure 6.13). A consistent relationship between 20-year departures in the two areas is clearly lacking. In fact, the correlation coefficient for the scatter plot is essentially zero. The lack of correlation does not mean, however, that severe droughts or wet periods have not occasionally been synchronous over the two regions. For example, the period from 1579 to 1598 was notably dry in both regions, and the period from 1904 to 1923 was notably wet in both regions. On the other hand, the years between 1918 and 1937 were a time of contrasting anomalies in terms of 20-year averages—dry in the Four Rivers index but wet in the Colorado River series. The line connecting the

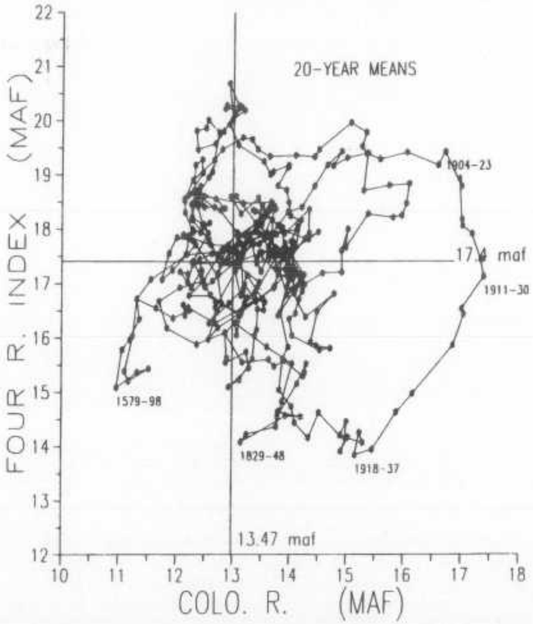

FIGURE 6.13 Scatterplot of running, 20-year means of reconstructed flow of Four Rivers against reconstructed flow of Colorado River at Lee's Ferry. Symbols are connected by lines to show development of anomalies in time. Times of selected key anomalies are annotated.

points on the scattergram indicates a transition from the 1904 to 1923 period to the 1918 to 1937 period, in which the Four Rivers index was becoming increasingly dry relative to the Colorado River series.

The tree-ring record as represented by data used in this study represents about a 450-year time window. On this time scale, moisture anomalies in the two regions are apparently neither consistently synchronous nor compensating. Climate change, whether due to increasing levels of atmospheric carbon dioxide or other influences, could conceivably produce monotonic trends in decadal rainfall totals over larger regions and on longer time scales than discernible from tree-ring data or gaged streamflow records. Indeed, the conversion of ring widths to tree-ring indices involves removal of any trend on the order of one-half the length of the tree-ring series itself, which places a practical limit on the climatic wavelengths that can be inferred. Research is currently ongoing

to make use of tree-ring specimens covering thousands of years to extend our record of climatic and hydrologic variations.

CONCLUSIONS

Major changes in global climate have occurred on geologic time scales. So far as their causes are understood, they arose from changes in external boundary conditions such as solar receipts, the gross composition of the atmosphere, and the configuration of the oceans and continents. Although these changes are usually described as occurring rather slowly—that is, over millions of years—it should be remembered that they may have occurred more rapidly in some cases but appear slow because of the coarse temporal resolution of geological records.

Within the overall cool period of the last 2.4 million years, there have been a number of short intervals (up to 15,000 years long) in which the climate has broadly resembled that of the present. The mechanisms controlling the switch between full glacial and such interglacial conditions have been subject to intense scientific interest in recent years. Although they are not fully understood, it is reasonable to state that changes in boundary conditions have played an important part in driving the recurrent pattern of glacials and interglacials. The combination of boundary conditions projected for the next few decades has not occurred before. Consequently, there is great uncertainty as to whether the climate system will continue to behave much as it has in the last 9,000 years.

The Younger Dryas episode demonstrates that major climate change (almost as big as the difference between an ice age and modern climate and covering a large region, such as the North Atlantic basin), can occur in a few decades. Very rapid but less persistent changes to conditions outside the range experienced in the last few hundred years have also taken place since the last retreat of the ice. Such changes may result entirely from the internal mechanisms of the atmosphere and oceans, or they may be caused by events such as very large explosive volcanic eruptions.

Other than the El Niño-Southern Oscillation (see Trenberth, Chapter 5), understanding of decade- to century-scale variations in climate is limited. Reconstructions of streamflow from tree-ring data indicate that such variations are of a magnitude that cannot be ignored in planning for management of water resources in the West. Reconstructions for the upper Colorado River basin and the northern Sierra Nevada of California both emphasize that hyrologic variations of the current century have been unusual in a 400-year context. The highest-flow period on the Colorado and the lowest-flow period in the Sierra Nevada are found in the current century. The modern gaged streamflow record may therefore be an unrepresentative sample for estimating water availability. The large range of departures of reconstructed flows averaged over 20-year periods also suggested that hydrologic models for annual flow simulation incorporate nonstationarity in the mean.

ACKNOWLEDGMENTS

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8

Hydrologic Implications of Climate Uncertainty in the Western United States

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By now, a vast majority of the inhabitants of the United States of America are aware of and accept the fact that levels of greenhouse gases, such as carbon dioxide, are increasing in the earth's atmosphere. Probably, most people with even a minimal education in science also accept that increased atmospheric greenhouse gas concentrations will cause additional energy retention in the earth's immediate environment—an increased greenhouse effect. However, drawing conclusions about changes in hydrologic phenomena brought about by the augmented green-house effect is not a straightforward exercise. One might logically conclude that a part of the additional energy would accelerate the hydrologic cycle: that is, there would be more precipitation, more infiltration, more evapotranspiration, and more runoff. But, heretical as it may seem, the hydrologic cycle as depicted in most basic texts does not exist. There is a myriad of paths by which a molecule of water can transit about the globe, and the likelihood of it doing so in a cyclic manner is infinitesimally small. Thus, the simplified concept of a hydrologic cycle offers little insight into the hydrologic impacts of potential climate change.

Instead of a cycle as the conceptual analog for hydrology, a random walk seems more appropriate. In the hydrologic random walk, a water molecule's passage through one of the reservoirs of the earth's hydrosphere or its transition from one reservoir to another is controlled probabilistically by the distribution of energy and mass within and among adjacent reservoirs. Hydrology is the science of understanding the aggregations of a great many molecules of water passing through and among the reservoirs. To predict the hydrologic impacts of increased atmospheric concentrations of greenhouse gases, knowledge of the partitioning of the incre-

mental energy within the various reservoirs is required. This paper explores our current ability to define this partitioning and draws conclusions about the resulting implications on the hydrology of the western United States.

To illustrate the complexity of the hydrologic random walk, it is useful to consider the concept of teleconnections (Namias, 1981), which is a statistical approach relating the magnitudes of weather or hydrologic events that occur at great distances from each other. For teleconnections to be more than a statistical oddity, they must be the result of seasonally preferred paths through the hydrologic random walk. The relation of weather patterns around the globe to an aperiodic anomalous warming of the eastern Pacific Ocean, the El Niño Southern Oscillation (ENSO), is a teleconnection that has been much explored recently. For example, as shown in Figure 8.1, Ropelewski and Halpert (1987) demonstrated a positive correlation between ENSO events and precipitation magnitudes over much of the Colorado River basin. This correlation implies that an energy exchange between the atmosphere and the Pacific Ocean can alter the probabilities of precipitation in the western United States during ENSO events.

A more explicit depiction of a preferred path of a similar or even greater spatial scale is found in the work of Koster as reported by Eagleson (1986). Figure 8.2 shows the regions where water that is evaporated in the month of March from a grid cell of 10 degrees longitude by 8 degrees latitude located in southeastern Asia is first redeposited on earth. Most of the land area under the mandate of the Bureau of Reclamation receives moisture from this cell, as does most of eastern Asia and the northern Pacific. Thus, evidence indicates a very complex system of reservoirs of moisture and energy in the oceans, in the atmosphere, and on the land that interacts with itself to define the existing climate and hydrology in the western United States.

What do we know about the response of this complex system to an increased greenhouse effect? Probably, we know best the physics of the transport of mass and energy in most reservoirs of the system. However, we know the physics only at spatial scales that are not fully compatible with the data bases and computing facilities that are available today. Climatologists and oceanographers have attempted to bridge this incompatibility by constructing mathematical general circulation models (GCMs) of the earth's atmosphere and oceans. GCMs are, at best, compromises between the sophistication of the description of the physics and the temporal and spatial scales at which transport is computed; thus,

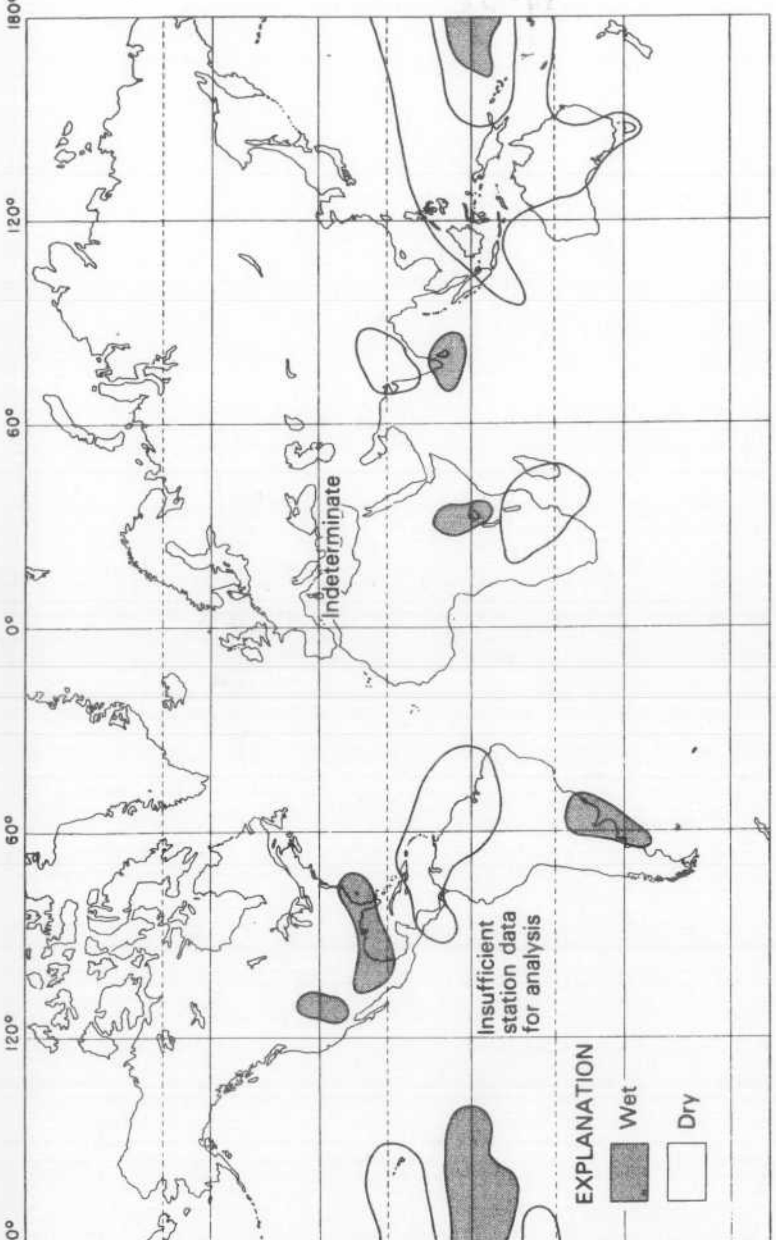

FIGURE 8.1 Regions exhibiting a consistent precipitation response to El Niño-Southern Oscillation episodes.
SOURCE: Reprinted, by permission, from Ropelewski and Halpert (1987). Copyright ©1987 by Monthly Weather Review.

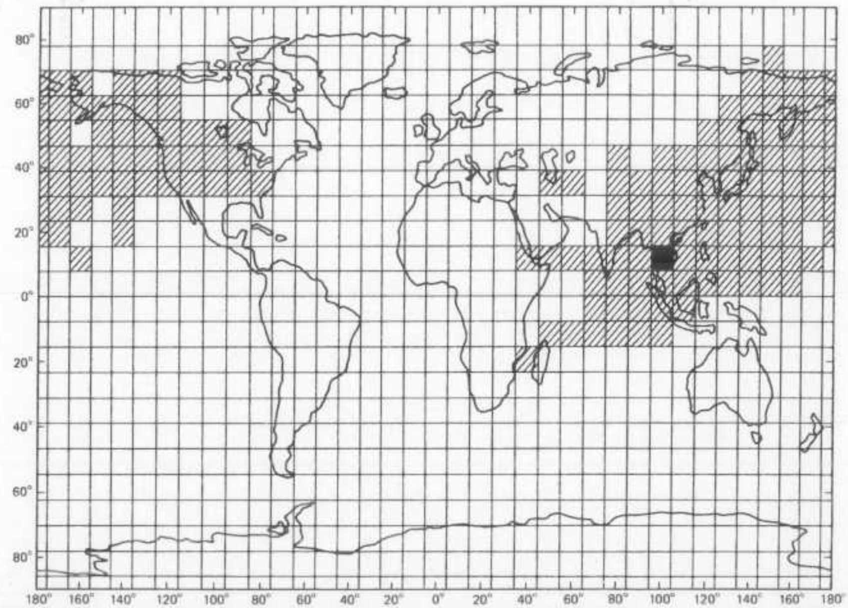

FIGURE 8.2 Region of influence of Southeast Asia March evaporation.
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they have computational grids that are several degrees in both latitude and longitude.

Information about hydrologic processes on and beneath the land surfaces of earth is poorly served by these compromises. For example, a common GCM representation of the land surface within a grid is that of a uniform soil of constant depth, the so-called bucket model, from which runoff is generated when the soil is saturated and precipitation exceeds evapotranspiration during any time step of computation. Runoff so defined is quite a different phenomenon from that recognized under the same name in hydrology. Furthermore, the spatial averaging that takes place over a grid cell yields variables that have little relevance to most problems of interest to traditional hydrologists and little applicability in water-resources decisionmaking.

To extract relevant hydrologic information from GCMs, two requirements must be met. First, outputs from the GCMs must be hydrologically meaningful. Second, there must be significant information contained in those outputs. Hydrologic models that convert GCM runoff to a meaningful variable do not currently exist; thus, GCM runoff fails the first criterion.

Other outputs from GCMs, such as precipitation, temperature, and relative humidity, might be hydrologically meaningful except for the discrepancies between their spatial scales of aggregation and the spatial resolution needed for these variables in existing hydrologic models. One approach that could resolve such discrepancies is statistical disaggregation (Valencia and Schaake, 1973). If this approach can be applied with some degree of confidence to spatial disaggregation of such GCM outputs, the outputs could meet the first criterion, whereas GCM runoff could not.

Another approach for the resolution of the scale discrepancy is the use of models of a finer scale for selected geographical regions of interest nested within a GCM (Giorgi, 1990). This approach shows great promise at the meteorological mesoscale, which is pertinent for many of the larger-scale hydrologic problems. It is conceivable that nested models and disaggregation models could be combined to address hydrologic problems of an even smaller scale.

With respect to the second criterion, quite a large body of literature exists that describes qualitatively the uncertainties inherent in climate modeling. A comprehensive review of this literature was done recently by Dickinson (1989). However, in the only attempt to date to quantify the information derived from GCMs, Moss (1991) has found that, for the grid cell highlighted in Figure 8.3, information from the Community Climate Model of the National Center for Atmospheric Research about July precipitation under current climatic conditions is limited to less than 20 percent of the information contained in 30 years of actual records. For January precipitation, the model output is limited to about 15 percent of the 30-year record. Extrapolations required to estimate future climate changes would undoubtedly degrade the resulting information below these limits. Thus, there may be some useful hydrologic information in GCMs, but our current ability to extract it is very limited.

Because of the paucity of hydrologic information that can be extracted from climate models, hydrologists generally have opted for scenario analysis (Lave and Epple, 1985) as a means to investigate the sensitivity of hydrologic systems to climate change. For example,

FIGURE 8.3 A GCM cell superimposed on the map of the State Climate Divisions.

Revelle and Waggoner (1983) assumed a scenario of a 10 percent decrease in precipitation and an increase of 2°C and used the empirical relations from Langbein and others (1949) to explore the impacts on runoff in the Colorado River basin. They found a potential decrease in average annual runoff of approximately 50 percent. However, the data used by Langbein were collected in the first half of this century, when carbon dioxide in the atmosphere was not at the levels contemplated in the climate-change scenarios. Most plants respond to increased levels of carbon dioxide by decreasing their rates of transpiration, and this feedback is not included in the work of Revelle and Waggoner (1983). Idso and Brazel (1984) estimated the vegetation effect and found that the 50 percent decrease in runoff reported earlier would become a 50 percent increase instead. Stockton (1975) has estimated the annual runoff of the upper Colorado River basin for the period 1520 to 1961 using dendrochronology and has found the mean annual runoff for this period to be approximately

13.5 million acre-feet. Figure 8.4 shows the decadal averages for the reconstructed record and the range of plus and minus 50 percent of the long-term average. It can be seen that the level of hydrologic uncertainty as depicted by the mean annual runoff, given the climate-change scenario of Revelle and Waggoner (1983) and of Idso and Brazel (1984), is greater than the decadal runoff variability experienced during at least 440 years.

Schaake (1990) has attempted to reduce this uncertainty by the use of more complex hydrologic models on the Animas River, which is a subbasin of the Colorado River basin. His results are summarized in Table 8.1. In essence, he found: (1) that an increase in precipitation would cause an increase in runoff that was greater in percentage than that of the increase in precipitation, and (2) that an increase in temperature would cause a minor decrease in annual runoff but would cause major changes in the seasonal distribution of the runoff. The second finding can be attributed to the dominance of the runoff regime in the Animas River by snow accumulation and melt. Gleick (1987) and Lettenmaier and others (1989) found similar results in the Sacramento River basin, which also is a snowmelt-dominated system.

Several other studies have been conducted using the scenario approach; Gleick (1989) provides a recent review of these. Each demonstrates, in its own way, one or more possible outcomes for the hydrologic effects of climate change. It should be reiterated that each is subject to its own inherent assumptions and should be considered as a measure of the system's sensitivity to those assumptions and not necessarily as a likely outcome of climate change. At this time, the plausibility of each scenario can only be determined subjectively, because the probability of any climate scenario cannot yet be determined.

Thus, today's state of understanding concerning the hydrologic implications of climate change is best characterized as one of uncertainty in which the level of uncertainty itself is uncertain. Because the validity of water resources decisions is very sensitive to hydrologic uncertainty, one of the first priorities of hydrologic research should be the quantification of the added uncertainty caused by an enhanced greenhouse effect. In other words, water resources planners and decisionmakers should encourage the research community to assess the level of hydrologic uncertainty while concurrently reducing it.

There are two paths for the reduction of uncertainty: (1) data collection, and (2) research. Traditionally, data collection has played the primary role in uncertainty reduction in hydrology. However, in the nonstationary world caused by climate change, the dominant role

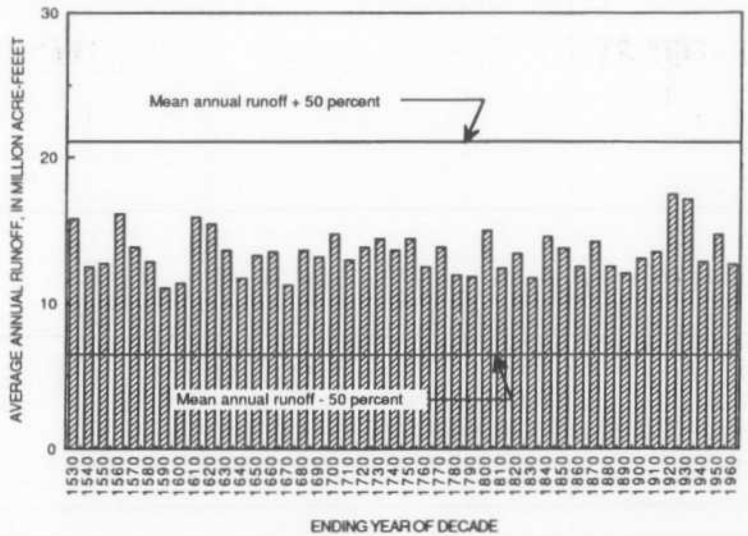

FIGURE 8.4 Reconstructed runoff for the Colorado River at Lee's Ferry.

TABLE 8.1 Sensitivity of runoff to climate change for the Animas River at Durango, Colorado.

	Period		
	Annual Average	January	June
Runoff (thousands of acre-feet)	545	12	163
Percentage runoff change for 10% increase in precipitation	19.7	17.1	12.1
Percentage runoff change for 10% increase in ETP	-7.0	3.8	8.9
Percentage runoff change for 2°C temperature increase	-2.1	37.4	-26.8
Percentage runoff change for 10% increase in ETP and 2°C temperature increase	-8.6	22.9	-30.4

SOURCE: Schaake, 1990.

of data must be reduced (Moss and Lins, 1989), because the information content of the raw data degrades with time. In other words, the hydrologic processes operational at the time that the data were collected are subsequently modified by the climate changes. Thus, yesterday's data lose their relevance to today's circumstances unless sufficient understanding of the climate-hydrology interactions is available to capture the information in yesterday's data and apply it to today's situation. The current level of understanding of hydroclimatology is not sufficient to perform this act of information retention. Therefore, increased support for research in hydroclimatology is a prerequisite to uncertainty reduction. Nevertheless, data collection is a necessity as well. Research without supporting data is a tenuous approach at best; furthermore, the data will be valuable in their own right once sufficient research is done so that they can be properly interpreted.

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11

Economic Consequences of Climate Variability on Water in the West

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The economic impacts of hydrologic extremes and variability on specific regions depend on the nature of the economy, the slack in the existing water-supply system, and society's ability to anticipate and adapt to hydrologic change. Demand management and water marketing are potentially important tools for responding to drought and long-term reductions in supply.

A case study of the Missouri River basin illustrates the possible impacts of a general warming on the availability of water within one of the West's principal river basins and indicates how management changes and a reallocation of supplies would help the region adapt to a sizable reduction in streamflow.

Hydrologic extremes have long posed risks to settlements in the western United States. A 5-year drought in the twelfth century may have caused the prehistoric Anasazi people to abandon the Colorado plateau (Kneese and Bonem, 1986). Twice within the last century prolonged drought forced tens of thousands of desperate families to flee the semiarid plains in search of more promising economic opportunities. And currently, a multiyear drought extending from southern California to the Missouri River basin is exacting a toll on a variety of water users.

The temporary transformation of the Trinity River in Texas from a small river to a mile-wide flood in the spring of 1990 provided a recent reminder of what can happen when too much water arrives within too short a time. Even though California has about six million acre-feet of flood control storage and 6,000 miles of levees, floods may pose a bigger problem to the state than earthquakes (Hartshorn, 1986). Floods have consistently been the nation's most deadly atmospheric hazard in recent decades; they accounted for 61 percent of all presidential disaster declarations in the decade starting in April 1974 (Riebsame et al., 1986).

CHANGES IN VULNERABILITY TO HYDROLOGIC VARIABILITY

Factors Tending to Reduce Vulnerability

The susceptibility of the West's economy to hydrologic extremes has changed over time. A decline in the economy's dependence on water and an increase in the control over supplies have tended to make the West less sensitive to changes in water supplies. Water's influence on economic development generally weakened during the last century. Development of steam engines, internal combustion motors, and electricity generation and transmission reduced the significance of on-site water power. Expansion of railroads, highways, and air transport diminished the importance of water-based transport. Water intensive industries such as irrigated agriculture declined in relative importance, and industries in general learned to prosper with less water (National Water Commission, 1973).

The tremendous expansion of the infrastructure to store and transport water and to tap ground water supplies also has tended to reduce the susceptibility of the nation's economy to climate variability. More than 63,000 dams with 869 million acre-feet of storage are included in the 1982 inventory of the nation's dams. More than three-fourths of these dams and two-thirds of the storage were completed since 1945 (U.S. Army Corps of Engineers, 1982).[1] About 47 percent of these dams and 55 percent of the storage are in the 17 western states, giving the region considerable capacity to prevent floods and to supply water during drought. Ground water also provides an important buffer against fluctuations in surface supplies in many areas of the West. Ground water use was essentially limited to areas with low pumping depths or artesian pressure until technological advances in the 1930s made it feasible to pump water from much greater depths. Water stored within deeper aquifers is less susceptible to climate variations, but the economies of some areas have become dependent on the use of nonrenewable ground water supplies.

Factors Tending to Increase Vulnerability

Countering these changes are several trends tending to make the

West more susceptible to hydrologic fluctuations. At least two factors are increasing the costs associated with drought.

First, demands on the resource have increased, making water more valuable and the competition for supplies during drought more intense. Nationally, offstream water use rose from about 40 billion gallons per day (bgd) in 1900, to 180 bgd in 1950, to 440 bgd in 1980 (Picton, 1960; Solley, Merk, and Pierce, 1988). Although natural supplies are much more sparse in the West, nearly half of the nation's fresh water withdrawals are now in the 17 western states.

Second, the rate of construction of reservoirs to assure water supplies has decreased since 1970 and is likely to continue declining. A basic principle of reservoir planning is that the risk of deficiency increases if the storage period (that is, available reservoir storage divided by average daily withdrawals) is not increased as withdrawals increase. The storage period rose from 204 days in 1960 to 216 days in 1970, and it had increased for at least six consecutive decades prior to 1970. By 1980, however, it had fallen to 201 days (USGS, 1984). Moreover, unless withdrawals continue to decline as they did from 1980 to 1985, the storage period is likely to continue to fall for two reasons: (1) the high economic and environmental costs of developing new supplies with additional storage, and (2) the adverse impacts of sedimentation on existing storage. The costs of water supply projects have increased sharply in recent decades, and continued increases are inevitable for three reasons: (1) the best reservoir sites have already been developed; (2) as storage capacity on a stream increases, the quantity of water that can be supplied with a high degree of probability grows only at a diminishing rate; and (3) the opportunity costs of storing and diverting water rise as society places higher values on instream flows. While the data on sedimentation rates for most dams are poor or nonexistent, one estimate suggests annual sediment losses total about 1.4 to 1.5 million acre-feet (Guldin, 1989). Over a decade, this loss is equivalent to about two percent of the nation's aggregate reservoir storage.

Actual flood damages also have been rising over time. Increased development and rising real property values in the flood plains together with upstream developments that increase runoff rates and flood peak frequencies have resulted in greater flood losses despite a growing capacity to regulate intertemporal flows. In the absence of better preventive measures, flood losses are likely to continue rising because urban expansion within the flood plains is increasing at 2 percent per year (Schilling, 1987).

Uncertainties of Climate Change

Past trends may provide a poor guide to the economic implications of future climate variability in a world undergoing anthropogenically induced climate change. As other papers presented at this colloquium indicate, a greenhouse warming would accelerate the global hydrologic cycle and significantly increase the uncertainty as to the water supplies of specific regions. Regional impacts are likely to include changes in precipitation and runoff patterns, evapotranspiration rates, and the frequency and intensity of storms. Even the direction of precipitation and runoff changes are uncertain. Higher temperatures, however, are likely to have particularly large and adverse impacts on annual runoff in arid areas where changes in precipitation and evaporation have amplified effects on runoff. Seasonal streamflow patterns would also be affected, especially in areas where precipitation currently comes largely in the form of winter snowfall and runoff comes largely from spring and summer snowmelt. These conditions characterize much of the West.

ECONOMIC SENSITIVITY

Existing water use patterns, infrastructure, and management practices reflect past climate and water availability. The economic consequences of adjusting to any given climate change would depend on the nature of the economy and its dependence on water supplies, the slack in the supply system, and society's ability to anticipate and adapt to hydrologic change. Effective adaptation to drought involves curbing excessive and low-value uses through demand management and transferring scarce supplies to uses for which the losses from inadequate supplies would be greatest.

Nature of the Economy

Agriculture is one of the most sensitive of human activities to climate conditions and variability. Dryland farming is highly dependent on the timely availability of water. Too much water can make it difficult to plant in the spring or to harvest in the fall. And too little water can reduce or even eliminate yields. Irrigation reduces susceptibility to variations in rainfall unless irrigators depend on fully allocated surface water and must share in any

shortfalls. Ground water supplies are less susceptible to drought than surface water, although nonrenewable irrigation supplies might be mined faster under a hotter and drier climate.

Agriculture is certainly not the only sector to be affected by drought. A major drought is likely to affect adversely all instream and offstream water users. The impact on particular sectors would depend in part on the institutional arrangements for allocating scarce supplies. Historically, western water law strongly favored offstream users at the expense of instream users. Thus, reservoir and streamflow levels were drawn down to the detriment of recreation, fish and wildlife, and hydropower. The balance has shifted somewhat in recent years as a result of state and federal legislation and judicial decisions protecting environmental interests such as wild and scenic rivers, unique ecological environments such as Mono Lake, and endangered species. Drought may also adversely impact the forests and the economic interests dependent upon them by increasing the risks of fire, disease, and pest damage.

The overall losses associated with the 1976-1977 drought in California have been estimated at $2,663 million. Agriculture, with losses estimated at $1,475 million over the two years, accounted for more than half of the total; livestock accounted for more than half of these agricultural losses. Energy costs increased by more than $450 million as a result of the drought. And timber interests lost $280 million to fire and $390 million to insect damage (Association of California Water Agencies, 1989). It is too early to know the extent of the economic impacts of the drought that started in 1987 and is now well into its fourth year in California.

Slack in the System

A region's vulnerability to climate variability depends in part on the amount of slack between water supplies and demand and the robustness and resilience of the supply system. When supplies are stretched to meet demand under normal hydrologic conditions, even a mild drought requires adjustments in water use. Water resource systems traditionally have been designed to be robust (able to respond to the range of uncertainties associated with future variability) and resilient (able to operate under a range of conditions and to return to designed performance levels quickly in the event of failure). The recent decline in the storage period noted above suggests a decline in the overall robustness of the nation's water supplies. And the rising costs of and prevailing skepticism toward new water projects suggests that the tradition of building large redundancy into water supply and control projects may be a thing of the past. Moreover, the existing systems were designed and are operated assuming future levels and patterns of precipitation and runoff will be similar to those experienced in the past. The prospect of long-term climate change poses new risks and challenges for managing these systems and raises questions about their vulnerability to climate change.

Gleick (1990) uses five indicators of a region's vulnerability to climate change. These include the ratios of storage capacity and consumptive use to renewable supplies, measures of a region's dependence on hydroelectricity and ground water overdrafts, and a measure of streamflow variability. The critical values that Gleick designates as indicating vulnerability as well as the values of the indicators for the nine principal water resource basins in the western United States are presented in Table 11.1. All nine basins are vulnerable on at least two of the five indicators. The Great Basin exceeds the critical limits on all five criteria and California and the Missouri River basin are vulnerable on four counts. The Missouri, for example, appears to have plentiful storage (equivalent to 112 percent of its mean annual renewable supply). But a relatively high ratio of consumptive use to renewable supplies, a high degree of reliance on hydroelectric power, high rates of ground water overdraft, and high streamflow variability all suggest the region is vulnerable to the hydrologic uncertainties associated with climate change.

Improved Management[2]

Seeking ways to improve management of the existing infrastructure is always prudent; management improvements assume greater importance in view of the vulnerability of water resource systems, the limitations on structural responses, and the prospect of climate change. The economic impacts of future hydrologic change are likely to depend even more than in the past on the ability to anticipate and adapt to these changes.

Joint management of water supply systems that are currently managed independently with separate operating rules and objectives may make it possible to improve significantly the supply capabilities of each system. Integration of the three principal water supply agencies in the Washington, D.C. area illustrates the potential advantages of joint operation of facilities. The combined

TABLE 11.1 Indicators of Vulnerability to Climatic Conditions.

Measure of:	Storage[1]	Demand[2]	Hyrdo[3]	Overdraft[4]	Variability[5]
Water Resource Region					
Missouri	1.12	.29	.25	.25	4.22
Arkansas-White-Red	0.45	.17	.10	.62	5.59
Texas-Gulf	0.61	0.23	0.01	0.77	9.90
Rio Grande	1.89	0.64	0.09	0.28	22.00
Upper Colorado	2.61	0.33	0.04	0.00	4.00
Lower Colorado	4.22	0.96	0.27	0.48	1.42
Great Basin	0.35	0.49	0.25	0.42	3.92
Pacific Northwest	0.19	0.04	0.93	0.08	1.92
California	0.42	0.29	0.30	0.12	4.48
Critical values	0.6	0.2	0.25	0.25	3

[1] Measure of storage. Ratio of maximum basin storage volume to total basin annual mean renewable supply as of 1985. Regions with values below 0.6 have small relative reservoir storage volumes. Large reservoir storage volumes provide protection from floods and act as a buffer against shortages.

[2] Measure of demand. Ratio of basin consumptive depletions (including consumptive use, water transfers, evaporation, and ground water overdraft) to total basin annual mean renewable supply as of 1985. Water is considered a decisive factor for economic development in regions with values above 0.20.

[3] Measure of dependence on hydroelectricity. Ratio of electricity supplied by hydroelectric facilities to total basin electricity production as of 1975. Regions with values 0.25 or above have a high dependence on hydroelectricity.

[4] Measure of groundwater vulnerability. Ratio of annual ground water overdraft to total ground water withdrawals as of 1975. Regions with values of 0.25 or above already have ground water supply problems.

[5] Measure of streamflow variability. Ratio of 5 percent exceedance flow to 95 percent exceedance flow. Values of 3 or above suggest high streamflow variability.

SOURCE: Gleick, 1990.

drought condition water yield of the three systems was increased more than 30 percent at a cost saving of between $200 million to $1 billion compared to the proposed structural alternatives. Although the specific circumstances in this case are unique, Sheer's

(1986) studies suggest major benefits from improved management are also possible in areas with very different characteristics.

The obstacles to integrated management are largely institutional. Separate ownership of water supply systems, multistate jurisdictions, and state laws and administrative practices all hinder reform. Officials in the principal federal water construction agencies have at least begun to talk about the need for change. The Bureau of Reclamation's *Assessment 1987* (DOI, 1987) concludes that "the Bureau's mission must change from one based on federally supported construction to one based on effective and environmentally sensitive resource management." A recent paper by three senior members of the U.S. Army Institute for Water Resources advocates greater emphasis on management measures to meet the problems caused by extreme events and the uncertainties stemming from the prospect of climate change (Hanchey et al., 1987).

Demand Management

Traditionally, water planners adopted a supply-side approach to provide for growing water demands. Offstream water use was projected to grow approximately in step with population and economic growth. These projections were treated as virtual requirements to be supplied with little regard for cost. This approach may have approximated an efficient strategy when the costs of supplies were low and streamflows were sufficient to meet all demands. When large quantities of water can be developed at relatively low cost and when withdrawing water from a stream does not significantly alter its availability for other users, it may be reasonable to assume that the benefits of a water-supply project exceed its costs. These conditions, however, no longer characterize the situation in the West or even in the rest of the nation.

The need to manage the demand for water has gained much wider acceptance within the last decade or so, but there is less agreement as to how it should be done. Regulatory measures such as restrictions on watering lawns and washing cars and sidewalks are common means of reducing water use during drought. Less common and more controversial is the use of regulations such as imposing water conservation standards for toilets, showerheads, and water-using appliances to curb the long-term growth of demand. Some local and state governments have already mandated water conservation measures, and legislation under consideration in the Congress calls for national standards designed to reduce water use.

Water prices also influence use. Planners, however, have traditionally assumed that the demand for water is unresponsive to price (that is, perfectly inelastic with respect to price). Prices rarely reflect the full cost of water use. Indeed, water has been treated as a free resource for which there has been no charge for withdrawing water from or for discharging pollutants into a lake or stream. Water prices are set to cover the costs of delivery and treatment, but even these costs are sometimes subsidized. Wahl (1989) estimates that federally-supplied irrigation water receives a subsidy equivalent to 80 percent of the economic costs of developing supplies and delivering them to an irrigation district. The urban water supply industry usually sets rates just high enough to cover average costs including a return to capital. Average cost pricing in a rising cost industry such as water results in prices below marginal costs. These low prices encourage consumption in excess of socially efficient levels. Efficient pricing would set price equal to marginal social cost to limit use to the point where the benefits derived from use of the last unit are equal to the costs of producing that unit.

Water Marketing

Water is a scarce resource in the United States, and it is almost certain to become scarcer as the supply and demand for the resource continue to change over time. Making the best use of the West's water requires an efficient way to reallocate scarce supplies in response to changing supply and demand conditions. In the United States, markets are the usual mechanism for allocating scarce resources. Well functioning markets allocate scarce resources to their highest-value uses and they provide incentives to conserve and develop new supplies. Water markets, however, are generally crude and are relatively uncommon.

The nature of the resource as well as government regulations pose problems for developing efficient water markets. Efficient markets must satisfy two conditions, both of which may be difficult to meet for water resources. There must be well-defined, transferable property rights and the buyer and seller must bear the full costs of the transaction. It can be difficult to establish property rights over ground and surface waters that are fugitive in time and space. Supplies may be common property resources that belong to no one until they are extracted for use. When ownership is only established by extraction, the individual does not pay the full costs of that use and there is an incentive to overuse the resource. Transferring water from one use or location to another is likely to affect third parties by altering the quantity, quality, timing, or location of water available to others. Another obstacle to the development of efficient water markets is that some of the services provided by water, such as the amenities of a free-flowing stream, are public goods that are usually not marketed. Furthermore, water utilities tend to be natural monopolies that have their prices set by regulatory agencies and utility managers rather than by the interaction of supply and demand (Frederick and Kneese, 1990).

In spite of these difficulties, water marketing does occur in the West, and with more appropriate state and federal policies marketing could play a much greater role in allocating supplies and encouraging conservation. Transaction costs are often unnecessarily high because of long delays, uncertainties, and legal fees. And the introduction of marginal cost pricing by utilities would curb use and provide investment funds to repair inefficient supply systems.

IMPLICATIONS OF A HOTTER AND DRIER CLIMATE: A CASE STUDY OF THE MISSOURI RIVER BASIN

The following case study of the Missouri River basin illustrates the possible impacts of a general warming on the availability of water within one of the West's principal river basins and indicates how management changes and a reallocation of supplies among alternative uses would help the region adapt to such hydrologic changes. Although the impacts of a global warming on the Missouri River basin are unknown, global climate model results suggest that the basin might become hotter and drier. The decade starting in 1931 was such a period within the basin. Superimposing the climate of that decade on the basin as it exists today provides some idea of the water issues that might arise under such a climate.

If the climate of the 1931-1940 analog period became the norm, runoff and evaporation rates would differ from those of the current climate. Estimates of the impact of these differences on the basin's renewable water supplies are presented in Table 11.2.[3] The mean assessed total streamflow represents the renewable supply available before consumptive use. Renewable supplies under the analog climate are only 69 percent of the long-term mean at the outflow point of the basin (subregion 1011), and they range from 64 to 99 percent measured at the outflow points of the various water resource subregions.

TABLE 11.2 Adjustments in 1985 mean assessed total streamflows of the Missouri River basin under the 1931-1940 analog climate.

Subregion	1985 mean assessed total streamflow with control climate[1]	Reductions in streamflows under the analog climate[2]: Reductions in runoff	Increased evaporation	Assessed total streamflow with the analog climate	Analog as a percent of control flows (in percent)
	(------------millions of gallons per day			------------)	
1001	7,632	1,829	49	5,754	75
02	6,071	1,370	15	4,686	77
03	6,961	1,686	48	5,227	75
04	9,806	2,179	8	7,619	78
05	18,204	4,706	185	13,313	73
06	20,692	5,822	190	14,680	71
07	3,963	20	19	3,924	99
08	9,746	2,926	26	6,794	70
09	34,969	10,940	216	23,813	68
10	6,099	2,169	39	3,891	64
11	56,634	17,129	304	39,201	69

1 Total assessed streamflow is the flow at the outflow point of the subbasin that would be available if (a) consumption were eliminated, (b) estimated 1985 water transfer and reservoir practices were continued, and (c) ground water mining were discontinued. This measure takes account of average evaporation under long-term climatic conditions.

2 These reductions in streamflows are the result of decreased runoff (or increased evaporation) within the hydrologic unit and within all upstream hydrologic units.

The analog climate would also affect water demand. The demand for irrigation and domestic water, especially for lawn watering, would probably rise as a result of the hotter and drier conditions. Quantification of the changes in water demand would be highly speculative, and the subsequent analysis assumes that consumptive uses are unchanged by the analog climate.[4] To the extent that this omission understates the competition for water, the analysis may understate the water problems likely to emerge under the analog climate.

Water is a scarce resource in the Missouri basin even in the absence of any anthropogenically-induced climate change. Society has placed increasing values on instream water uses such as recreation and protection of fish and wildlife habitats in recent decades. The rising demand for these very water-intensive uses in combination with the recent drought within the region have contributed to growing conflicts over water use in the basin. Streamflows during the 1988-1989 drought, which has aggravated water conflicts in the region, exceeded the mean flows during the analog period by 16 to 23 percent at the gauging stations used to reconstruct the analog flows. These conflicts have been particularly evident in the management of the main stem of the river and in the opposition to several water projects proposed for the basin. The U.S. Army Corps of Engineers is under pressure from the upper basin states of North and South Dakota, Wyoming, and Montana to give greater weight to the economic, recreational, and environmental values within the upper basin that are affected by management of the main stem reservoirs. Several proposed water projects including Two Forks Dam in Colorado, Deer Creek Dam in Wyoming, and Catherland irrigation project in Nebraska have encountered strong opposition from environmentalists.

Table 11.3 provides an indication of the adequacy of mean assessed total streamflows to supply 1985 consumptive uses and "desired" instream flows under the current and analog climates.[5] Total use, defined as the sum of cumulative consumptive use and "desired" instream flows, exceeds the mean assessed total streamflow under the current climate in two of the eleven subregions. Under the analog climate, total use exceeds these streamflows by at least seven percent in eight of the subregions; even in the other three subregions, total use is 94 percent or higher of mean assessed total streamflow. When total use exceeds mean assessed total streamflow, then ground water supplies are being mined and/or desired instream flows are not being met.

The amount of water actually available to meet instream uses is derived by subtracting consumptive use and adding ground water

TABLE 11.3 Water use as a percent of mean assessed total streamflow in the Missouri River basin under the current and analog climate.

	Current Climate			Analog Climate		
Subregion	Cumulative Consumptive Use	Desired Instream Flow	Total Use	Cumulative Consumptive Use	Desired Instream Flow	Total Use
1001	13	60	73	18	79	96
02	12	60	72	16	78	94
03	12	60	72	16	80	96
04	18	75	93	23	97	119
05	18	61	78	24	83	107
06	16	61	77	23	85	109
07	76	55	130	77	55	132
08	52	34	86	74	48	123
09	25	60	85	37	88	125
10	50	61	111	79	95	174
11	21	60	81	31	87	117

SOURCE: Frederick, 1990.

overdrafts to assessed total streamflow. This quantity is the current streamflow. Table 11.4 shows desired instream flows as a percentage of current streamflow under the current and the analog climates. Under the analog climate, instream flows are generally well below desired levels as estimated in the Second National Water Assessment. The desired flows would exceed the actual flows by 25 percent or more for sustained periods in five subregions under the analog climate. The values that would be lost are not easily estimated, but they are likely to be high. Moreover, conflicts as to the preferred timing of flows for aquatic habitat, navigation, hydropower, and other uses increase as the resource becomes scarcer.

Preliminary results from an ongoing study by the U.S. Army Corps of Engineers (1990) indicate opportunities for mitigating the overall costs of low-flow conditions within the Missouri basin. A repeat of the 1931-1940 climate would have major impacts on water users in the Missouri. Under current operating criteria for the 6 main stem reservoirs operated by the U.S. Army Corps of Engineers, the navigation season would be reduced from its normal of eight months to about five months during six of the ten years despite the relatively high priority navigation receives in the management of the river. Hydroelectric power production would decline to about half

TABLE 11.4 Desired instream flow as a percent of current streamflow in the Missouri River basin under the current and control climates.

	Current Climate	Analog Climate
1001	69	
02	68	92
03	68	95
04	91	125
05	74	109
06	72	111
07	156	160
08	59	125
09	77	131
10	80	153
11	72	114

SOURCE: Frederick, 1990.

its normal level and the reservoirs would contain less than half their normal quantities of water during these years. These outcomes implyprofound negative implications for the recreational services as well as the fish and wildlife habitat provided by these reservoirs.

Table 11.5 presents preliminary estimates of the average annual benefits by principal use categories derived from the operations of the Missouri main stem system under existing operating criteria and historical streamflows. The large water flows required to support navigation and the high priority navigation receives in the current operating scheme are in striking contrast to the relatively small contribution navigation makes to the overall benefits from the system. Missouri River navigation accounts for less than 2 percent of total system benefits. Even when the contribution to traffic on the Mississippi River is included, navigation accounts for less than 3 percent of total annual benefits. In contrast, hydropower provides 58 percent; flood control a total of 16 percent; water supplies within the lower basin states of Iowa, Kansas, Missouri, and Nebraska 11 percent; and upper basin reservoir recreation 8 percent of the overall benefits.

Even during periods of average or above-average flow, conflicts may emerge among alternative operating criteria. For instance, maintaining navigation flows may conflict with the interests of the upper basin in maintaining high and relatively stable lake levels and with power production at Gavins Point, where releases in support of navigation may exceed the capacity of the power plants. As more space

TABLE 11.5 Estimated Annual Benefits of Missouri Main Stem System Operations.

	Millions of dollars	Percent of totals
Hydropower	470	58
Flood control (Missouri River)	95	12
Flood control (Mississippi River)	36	4
Water supply (downstream)	93	11
Water supply (reservoir)	N/E[2]	—
Recreation (reservoir)	67	8
Recreation (downstream)	3	a[3]
Navigation (Missouri River)	14	2
Navigation (Mississippi River)	6	1
Other[1]	30	4
Total	814	100

[1] The U.S. Army Corps of Engineers lists total benefits of system operations at $814 million but they itemize only $784 million of these.

[2] N/E indicates no estimate available.

[3] a indicates less than 0.5 percent.

SOURCE: U.S. Army Corps of Engineers, 1990.

is devoted to flood control, reservoir levels may be subjected to wider seasonal fluctuations and less storage is available for protection against drought. Nevertheless, these conflicts pale in comparison to those that emerge under drought conditions.

The guidelines for managing the main stem reservoirs have come under attack during the recent drought and are currently under review. Table 11.6 compares the differences between the preliminary average annual benefits for the various users (power, reservoir recreation, downstream recreation, water supply, navigation on the Missouri, navigation on the Mississippi, and flood control on the Mississippi) when selected operating criteria are varied from the base case reflecting current policy. These preliminary results provide strong

TABLE 11.6 Comparative analysis of annual incremental benefits for alternative operating criteria for the main stem of the Missouri River[1] (millions of dollars).

Alternative	Power	Recreation		Water	Navigation		Flood Control	Total
		Reservoir	Downstream	Supply	Missouri	Mississippi	Mississippi	
Base Case	0	0	0	0	0	0	0	0
A	2.35	0.20	-0.03	70.31	-0.18	2.91	0.08	75.65
B	4.80	3.41	-0.03	70.10	-0.44	3.55	0.11	81.51
C	14.57	3.40	-0.26	70.31	-0.51	1.07	0.09	88.67
D	23.01	3.45	-0.23	70.28	-0.54	-0.63	0.13	95.47
E	34.56	3.91	-0.27	57.31	-1.17	-3.80	0.21	90.75
F	42.79	3.91	-0.32	54.48	-1.70	-2.51	0.39	97.04

[1] The dollar values represent the differences in the average annual benefits or costs when each alternative is compared to the base case. The annual averages are derived by simulating the hydro-logic record from 1898 to 1989 with the existing infrastructure and water demands.

SOURCE: U.S. Army Corps of Engineers, 1990.

NOTES TO TABLE 11.6:

Explanation of Alternative Operating Criteria Base Case:

(1) System storage is divided such that:

- the first 18.3 maf is for the permanent pool
- the next 39.3 maf is for carry over multiple use
- the next 11.6 maf is for annual flood control and multiple use
- the top 4.7 maf is for exclusive flood control.

(2) Length of navigation season: the current rules for determining the length of the navigation season are in effect. The navigation season is curtailed if system storage on July 1 is less than 41 maf.

(3) Minimum winter season release rate is 6,000 cfs.

(4) Minimum summer release rate is 6,000 cfs.

Variations from the Base Case incorporated in the alternatives.

Alternative A

(3) Minimum winter releases 12,000 cfs.

(4) Minimum summer releases 18,000 cfs.

Alternative B

(1) Permanent pool storage increased to 31.0 maf.

(2) Changes in navigation rule curve with the season curtailed if storage is less than 41 maf on July 1.

(3) Same as A.

(4) Minimum summer releases 12,000 cfs.

NOTES TO TABLE 11.6 (continued)

Alternative C
(1) Same as B.
(2) Changes in navigation rule curve with the season curtailed if storage is less than 54 maf on July 1.
(3) Same as A.
(4) Same as A.

Alternative D
(1) Same as B.
(2) Changes in navigation rule curve from Alternative C with the season curtailed if storage is less than 54 maf on July 1.
(3) Same as A.
(4) Same as A.

Alternative E
(1) Permanent pool storage is increased to 44 maf.
(2) Changes in navigation rule curve with the season curtailed if storage is less than 58 maf on July 1.
(3) Minimum summer releases of 9,000 cfs.
(4) Same as B.

Alternative F
(1) Same as E.
(2) Changes in navigation rule curve from Alternative E with the season curtailed if storage is less than 58 maf on July 1.
(3) Same as E.
(4) Same as A.

signals as to the types of changes in operating criteria that would increase the benefits the nation derives from the Missouri River main stem reservoirs. Some of the more promising changes are:

- Increasing minimum winter and summer releases (Alternative A) adds nearly $76 million to the average annual system benefits. Most of these benefits accrue to lower basin communities that would have greater security in their water supplies.
- Increasing the size of the permanent pool (the minimum level of water that is maintained in the reservoirs for fish and wildlife, recreation, operation of hydropower generating units, and municipal, industrial, and agricultural water-supply intakes) and curtailing navigation flows sooner when reservoir levels are low (Alternatives B through F) increase the benefits from hydropower production and reservoir recreation in the upper basin. The dollar value of the adverse effects on navigation of increasing the permanent pool and altering other operating criteria that currently favor navigation are overwhelmed by the positive impacts on power, water supplies, and reservoir recreation.

The results summarized in Table 11.6, which are based on simulations for the entire hydrologic record from 1898 to 1989, suggest the potential benefits of alternative management criteria even in the absence of climate change. The alternative operating criteria are designed to deal with conflicts that emerge during relatively low-flow periods, and the largest gains in annual benefits occur during such periods. Consequently, under a scenario in which the climate of the 1931-1940 decade becomes the norm, the annual incremental benefits of the alternative operating criteria would be much higher than the values presented in Table 11.6.

NOTES

1. The inventory only includes dams that were at least 6 feet in height with a storage capacity of at least 25 acre-feet or at least 25 feet in height with a capacity of 15 acre-feet.

2. The next two sections draw on Frederick and Gleick, 1989.

3. The methodology underlying these estimates is described in Frederick (1990). In brief, the estimates start from data in the Second National Water Assessment (U.S. Water Resources Council,

1978) for mean natural streamflows (flows in the absence of any diversions, man-made reservoirs, and consumptive use) and total assessed streamflows as of 1985 (equal to natural flow minus net evaporation from manmade reservoirs and net exports) for the eleven water resource subregions within the Missouri basin. The adjustments to runoff are based on the differences between observed flows in the 1951-1980 control period and the 1931-1940 analog period at specified gaging stations. Streamflow data going back to 1931 are available for hundreds of gaging stations in the Missouri basin. At most of these stations, however, measured flows are not a reflection of natural streamflows; they have been altered by diversions, dams, or other human impacts. Consequently, flows at seven gaging stations within the basin that were unaffected by human impacts are used as proxies to estimate the changes in natural streamflows attributable to the analog climate. The differences between the reconstructed flows during the 1931-1940 analog and the 1951-1980 control periods capture the effects of changes in precipitation and evaporation from land surfaces. The impacts of temperature and other climatic changes on reservoir evaporation are based on estimates of net evaporation from the six large reservoirs in the main stem of the Missouri during the two periods. The estimated average change in net evaporation rates from these reservoirs is used to estimate evaporation from reservoirs throughout the basin.

4. The impacts of the analog climate on water withdrawals and consumptive use are examined in Frederick (1990).

5. The estimates of "desired" instream flows are from the Second National Water Assessment. The assessment suggests that desired instream flows are "that amount of water flowing through a natural stream channel needed to sustain the instream values at an acceptable level. Values of instream flows relate to uses made of water in the stream channel that include fish and wildlife population maintenance, outdoor recreation activities, navigation, hydroelectric generation, waste assimilation (sometimes termed water quality), conveyance to downstream points of diversion, and ecosystem maintenance that includes freshwater recruitment to the estuaries and riparian vegetation and flood-plain wetlands" (U.S. Water Resources Council, 1987). Fish and wildlife were determined to be the dominant use because the flows that would ensure full fish and wildlife benefits would also provide for all other instream values. The desired instream flows in the assessment are (conservative on the side of identifying more water for instream uses than further study might reveal to be justified" (Bayha, 1978).

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12

Western Water Law, Global Climate Change, and Risk Allocation

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For behold, The Lord, the Lord of Hosts doth take away from Jerusalem and from Judah the stay and the staff and the whole stay of health, and the whole stay of water . . . I will command the clouds that they rain no rain upon it.

—*Isaiah, Books 3 and 5*

INTRODUCTION: WHAT THE DOOMSAYERS SAY

Both the urban and rural West are extremely vulnerable to the predicted adverse consequences of global warming (EPA, 1988). Coastal dwellers along the Pacific Ocean face rising sea levels and the loss of littoral land. Estuarine areas face the risk of destruction from sea level rises as the vital balance between fresh water and salt water will be destroyed. Regional fresh water supplies will be adversely affected in difficult-to-predict ways. The head of the Advanced Study Program at the National Center for Atmospheric Research advises that the change will not be a simple shift to a warmer but stable climate. Instead, we must plan for a new climate each decade. The new climate will bring both surface temperature increases and large year-to-year weather variations (Firor, 1990b). Urban areas that survive sea-level rises will probably face severe water shortages as spring runoffs decline and forests die.

Both farmers and wildlife will suffer from the heightened competition for diminished supplies. In California, for example, there may be less snowpack, higher winter runoff, and lower spring and summer runoff. Annual deliveries to the State Water Project could decline by 7 to 15 percent (EPA, 1988). At the same time, the demand for electricity will increase by 4 to 6 percent over the increase that would occur without global warming. The growing competition between municipal and industrial water users and agricultural water users will exacerbate existing supply shortfalls in populous arid areas, and cities may use their political power at both the state and federal level to bar all but the most essential crops from being irrigated. Simultaneously, the efforts to allocate more water to in-situ uses that began in the 1970s may literally evaporate. A recent global warming disaster scenario includes the prediction that "[i]n northern California, low water levels and high temperatures deoxygenated Tule Lake, inducing epidemics of botulism that eventually killed off immense flocks of ducks and geese that had made Tule the greatest single gathering around the world for migratory waterfowl" (Oppenheimer and Boyle, 1990).

GLOBAL WARMING RESPONSE STRATEGIES: WHAT SHOULD WE BE DOING?

Three interrelated responses to global climate change have been identified: (1) further research, (2) adaptation to temperature rises, and (3) the reduction of the root causes of the warming (resource demand). The merits of the first option are a given (Guruswamy, 1990). The current debate centers on the comparative merits of the second two options. Carbon dioxide and other greenhouse gases must be reduced to slow the warming, but implementing the third option will require a radical change in energy generation and consumption and thus a radical shift in the economic and social organization of all countries.

Climates have historically varied throughout the world, and civilizations accepted variations more or less as fate. In the past, the causes of climate change were unknown natural phenomena rather than human activities; man did not try to manage climate change. However, the legacy of the enlightenment is that climate can be adapted to man through technological progress. The entire settlement of the West can be understood as a living example of this faith. We have refused to accommodate to the limitations of aridity and have sought to turn deserts into gardens for all who would cultivate them.

Global warming is forcing a modest reexamination of this practice. Most moderate alarmists counsel adoption of the second strategy: the decade-by-decade adoption of flexible response strategies to prepare us to live with long-term change. Water shortages are one very important category of the full range of possible adverse

effects that can be addressed through adaptation. If we can adapt to water shortages, the adaptation will represent the first major reversal of faith in technological progress as the solution to the limitations of nature.

Ultimately, adaption to a changing climate is at best a temporary strategy and is not a substitute for more fundamental shifts in resource use. Globally, the answer lies in shifting from nonrenewable to renewable energy sources and in curbing explosive population growth (Firor, 1990a). In the West, the answer lies in confronting the relationship between water demand and urban growth. In all the major arid states, unlimited population growth is taken as an article of faith and the function of water policy is to supply all the water necessary to accommodate this growth. Many serious observers of the West think that the question is backwards. We should first set growth limits and use them to temper water demands to the more realistic use of available, possibly diminishing supplies. The Bureau of Reclamation cannot do this alone; nevertheless, the global warming debate may place the Bureau at the center of debate about the future of land use in the West. What happens in Fresno is related to the anti-growth debate in Los Angeles.

As the major federal water manager in the West, the Bureau of Reclamation will be affected by global warming-induced water shortages. Flexible adaptation strategies will require the ability to capture and store decreased rainfall and snowfall and to move available, reduced supplies to the areas of greatest demand with speed. However, existing technical and institutional barriers may make this adaptation difficult. This paper addresses the capacity of state water law and federal reclamation law to adapt to the possibilities of shortages as normal rather than abnormal events. It does not address the strategies needed to achieve a new energy balance. Rather, it assumes that the West faces a substantially increased risk of water shortages and speculates about how the existing law of prior appropriation will respond to these shortages, when and if they occur, as well as the likely effect of recent trends in western water law on global warming adaptation. The basic conclusion is that the law of prior appropriation is not well suited in practice to achieve an optimum allocation in times of shortages because of the gap between priority rights holders and demand, but that reallocation trends currently underway can form the basis for a western global warming adaptation strategy.

PRIOR APPROPRIATION: IS IT A RISK MANAGEMENT SYSTEM?

In theory, state and federal reclamation law have a great capacity to respond to global warming-induced water shortages because the function of western water law has been to allocate a scarce resource among competing users in times of shortage. The law of prior appropriation was developed to allocate water among California miners and to distribute water throughout the West. The law has endured in the face of sharp criticisms about its efficiency (Reisner and Bates, 1989) and equity (Freyfogle, 1986) because it has been able to accommodate changing use demands—by adding indefinitely to the classes of claimants eligible to acquire water rights and by allowing water to be shifted among uses. Irrigators, hydroelectric generators, cities, recreationists, and spokespersons for fish and wildlife have all been accommodated. Thus, the law of prior appropriation, supplemented by federal and state reservoir management, is a potential complete risk allocation strategy.

There are two major problems with the use of prior appropriation for risk allocation. First, the law has never been used for this function. As a result, there are major political, institutional, and legal barriers to its use to declare winners and losers, which must be done if water is to be allocated in times of severe shortages. Second, the risk allocation schedules produced by the strict application of prior appropriation will be widely perceived as perverse. The highest priorities are often the lowest-valued uses. For example, the highest priority on the Colorado River remains irrigation, although the highest values of water are for municipal and industrial supplies and the enhancement of environmental values. Perverse priorities are not an absolute barrier because water can be voluntarily reallocated. However, we are just starting to market water on a large scale, and the jury is out on the success of this method of reallocation.

Prior appropriation allocates the risks of shortages by a simple principle: priority of use. The question is whether the magnitude of the global climate change risks can be allocated within the framework of prior appropriation. Western water law is premised on shortages and priority schedules that provide clear risk allocation schemes. But we do not expect the risks to occur with any regularity. The whole thrust of federal and state water policy has been to reduce the risk of shortages to as close to zero as possible by the construction of large carryover storage facilities. In some places, such as California, ground water pumping serves the same back-up function. Thus, we expect that reservoirs and ground water will avoid all but the mildest forms of rationing during droughts. States have tried to accommodate unlimited growth on a limited water budget by providing ample margins of safety against shortages. When water deliveries have been reduced or stopped according to a strict priority schedule, the losers have generally been small farmers, Indian tribes, and fish and wildlife. Most irrigators have been buffered by the harshness of prior appropriation by both carryover storage and formal and informal mechanisms that share the burdens of shortages by pro rata rather than pro tanto delivery reductions. Thus, although the law of prior appropriation is a risk allocation mechanism, the expectation that it will be used for this purpose is low.

The strong expectations of user security will impede the Bureau of Reclamation should it seek to introduce flexibility (e.g., reallocation) into its mission. Historically, that mission has been to support local users by reducing the risks of shortages to as close to zero as possible by providing sufficient carryover storage to keep water flowing downstream from its reservoirs during dry years and to deliver water to the beneficiaries of the original project at subsidized rates. Our model of natural disaster is the seven-year cycle of plenty and famine experienced by Egypt in the book of Genesis rather than Anasazi long-term drought scenarios. Just as the Pharaoh heeded Joseph's advice and stored the harvests of plenty, so too has the Bureau of Reclamation heeded the vision of scientists and western promoters and stored spring runoffs in wet years to provide reserves for dry years. The faith in our ability to reduce the risks of shortages has powerful and insufficiently noted influence on the western water law. Fear of shortage has been used as the rationale for large projects and has crowded other adaptation strategies off of the political agenda (Stegner, 1986).

The issue that prior appropriation poses for global warming adjustment strategies is how flexible the system will be in shifting water to areas of greatest need and in promoting maximum access to a scarce resource. Global warming adaptations will place a premium on both technical and allocative efficiency. Users in water-short areas will have to conserve existing supplies by using less, and they will face increased pressures for reallocation. Economists have long criticized western water law because it ignores higher, alternative values of water. Many western water observers argue that the historic allocation pattern is grossly inefficient. Too much water is used to grow surplus or lowvalued crops, and too much water is wasted (Reisner and Bates, 1990). In almost all western areas, agriculture preceded urbanization. Thus, agricultural users hold the most senior water rights. For most of this century, water allocation has been relatively static because the three major uses—agriculture, hydroelectric power generation, and municipal and industrial consumption—were able to share the available water budget without unduly disrupting each other.

Until recently, there was a widespread perception that the allocation of western water was eternal, but the system was never completely static. It contained reallocation mechanisms that allowed minor adjustments, though, in general, prior appropriation remained watershed-based in practice. Transfers were the exception rather than the norm (although marginal agricultural areas did shift to urban uses). Today, the exception may become the norm. There is a growing consensus in the water community that water needs to be reallocated from irrigated agriculture to municipal, industrial, and instream uses to protect a broad range of environmental and recreational values. Water marketing has been endorsed by the national environmental community as well as by urban suppliers. Transfers can be used to meet both urban and environmental demands with minimum disruption for existing users.

Prior appropriation contains two principles that could become the basis for global climate adaptation. Appropriative rights are usufructuary property rights. The original Edenic vision of the West as a land of small irrigators assumed that water rights should be tied to the soil. However, most states have rejected the appurtenancy principle, and have made water rights transferable property rights. In addition, water has a social value; it can only be used for a beneficial purpose. In this century, beneficial use has been defined only as nonwasteful use. Waste has long been defined by local custom, with the result that few irrigation practices are found to be nonbeneficial. A redefined concept of beneficial use could play a larger role in the future. For example, beneficial use could be defined as efficient use; the beneficial use doctrine would then form the basis for requiring substantial water conservation measures. The operating criteria imposed on the Newlands Project in the Truckee-Carson basin of western Nevada is a possible model of how beneficial use can form the theoretical basis for increased farm and urban water conservation requirements (DOI, 1966). The beneficial use doctrine can be complemented by the public trust doctrine. In California, this doctrine has been used to reallocate vested rights to trust purposes, which include environmental protection. For example, some commentators have argued that the public trust requires reductions in water use and the reallocation of water to dilution flows to redress the adverse effects of agricultural runoff. Water marketing has been endorsed by the national environmental community as well as by urban suppliers. Transfers can be used for both urban and environmental purposes with minimum disruption for existing users. Water marketing could be the cornerstone of an adaptive strategy because water can be shifted to areas of highest demand regardless of its original priority and use. The agreement between the Imperial Irrigation District (IID) and the Metropolitan Water District (MWD) of Southern California could be a model of future transfers. The MWD has paid the IID $120 million to save 100,000 acre-feet of water, which will be added to Los Angeles's lower priority on the Colorado River for the next 30 years, and this is only IID's first trip to the fat farm. Overall, however, we now have more water market theory than we have water markets, largely because proponents have underestimated the complexity of water transfers.

The transfer debate centers on two related questions. The first question is, what are the barriers to transfers? Although most western water rights are transferable, the transaction costs of a transfer can be high. The vested rights of third parties must be protected under state law, and in an increasing number of states transfers are subject to public interest review. These barriers are not insurmountable, however. A comprehensive survey of water transfers in six western states (University of Colorado School of Law, 1990) illustrates that a variety of transfers occur both among similar users and from existing to new users. The transaction costs vary from minimal to very high in Colorado, but in all states transfers are generally supported by state law and are taking place. The second question in the transfer debate is, what is the relevant range of third party interests with a stake in the transfer? In past decades, states have begun to include a variety of previously excluded interests in the allocation and transfer process. Environmental representatives, Indian tribes, ethnic communities, and areas of origin now have a greater stake in water allocation processes than they have had in the past. The net result of these developments is to complicate water transfers. As Professor Joseph L. Sax of the University of California, Berkeley, has observed, water transfers are more like diplomatic negotiations than commercial transactions. The expanded compass of protected interests is legitimate; however, it poses new challenges to the water community to distinguish between good and bad transfer barriers (National Research Council, 1992).

BUREAU OF RECLAMATION RESOURCES

Transfers

The 27 million acre-feet of water that the Bureau of Reclamation supplies to farmers throughout the West have been targeted for a starring role in water marketing. Federal reclamation projects have been identified as a major source of water for municipal, industrial, and environmental uses. Reclamation projects use large amounts of subsidized water, often at low technical efficiencies. However, the Bureau faces two major institutional barriers to reallocating the supplies that it controls to adapt to global warming. First, reclamation law creates strong expectations that the original project beneficiaries will be the eternal beneficiaries of project water; every proposed transfer or conservation requirement will be met with substantial, although not insurmountable, opposition. Second, the Bureau's attempt to recast its mission as that of a multiple-purpose manager to deflect criticism that it has helped pollute western waters and degrade or destroy prime fish and wildlife habitats may be inconsistent with global climate change adaptation.

Efforts to promote efficiency through cost increases and conservation plans have not been aggressively pursued, although a court has held that there is no constitutional right to federally subsidized water.[1] Water marketing advocates argue that voluntary transfers may overcome resistance to transfers and "can be as effective as appropriate pricing in leading to efficient use of water" (Wahl, 1989). However, there are many legal and political barriers to the movement of Bureau of Reclamation water away from the original projects. Federal reclamation law was designed to promote family farms. The legacy of this largely unsuccessful experiment is that the law provides no incentives for transfers. As a leading expert has concluded, "Reclamation law is devoid of any explicit Bureau [of Reclamation] water transfer policy" (Driver, 1987).

Transfers of project water may take place both under federal and state law, but the prevailing assumption is that they will be the exception rather than the rule. Section 8 of the Reclamation Act of 1902 provides "[t]hat nothing in this Act shall be construed as affecting or intended to affect or to in any way interfere with the laws of any State or Territory relating to the control, appropriation, use or distribution of water in irrigation, or any vested right acquired thereunder, and the Secretary of the Interior, in carrying out the provisions of this Act, shall proceed in conformity with such laws."[2] Section 8 was initially construed to mean that the Bureau of Reclamation is "simply a carrier and distributor of water . . . with the right to receive the sums stipulated in the contracts as reimbursement for the cost of construction and annual charges for operation and maintenance of the works."[3] However, in the wake of the New Deal expansion of federal powers, the Supreme Court held that Congress may preempt state law.[4] The Court adhered to these cases in *California v. United States*,[5] but in 1983 the Court again described federal ownership of rights as "at most nominal" because the beneficial interest was held by owners of project land.[6]

Section 8 of the Reclamation Act of 1902 further provides that "[t]he right to the use of water acquired under the provision of this Act shall be appurtenant to the land irrigated, and beneficial use shall be the basis, the measure, and the limit of the right."[7] Section 8 also requires that the Secretary of the Interior proceed in conformity with state law in "the control, appropriation, use, or distribution of water used in irrigation, or any vested right acquired thereunder." The Reclamation Projects Act of 1939 allows the U.S. Army Corps of Engineers and the Bureau of Reclamation to impound water for municipal and industrial use.

The net effect of Section 8 is that project water based on state water rights cannot be reallocated by the federal government alone unless Congress has preempted state law. Individual Bureau of Reclamation project contracts may present additional problems. For example, all projects generate return flows, but control of these flows varies. Some contracts give the United States control over the flows for project use; other contracts give the district power to use them within the district or, in the case of the Central Arizona Project, to sell the flows.

Recent changes in Bureau of Reclamation policy indicate a greater receptivity to transfers, but the new policies do not eliminate the long-standing bias toward appurtenancy in federal reclamation law. Late in 1988, the Bureau, in its new management mode (as opposed to its engineering mode), announced a seven-principle transfer policy. The policy does not amount to a radical switch to water marketing. It reaffirms traditional Bureau deference to state law and generally announces a reactive, rather than a proactive, position on transfers. For example, the Bureau will become involved only where there is a potential effect on federal projects and services and the transfer has been requested by an appropriate nonfederal political authority. Transfer agreements that are part of an Indian water rights settlement (of which there are many, either negotiated or being negotiated) is the major exception to this passive stance. The policy reaffirms the protection of third party interests and the mitigation of adverse environmental effects. Water will not be transferred unless third party effects can be avoided or mitigated. The policy only touches on the volatile issue of subsidy recapture. The issue is whether project beneficiaries can receive the current market value of subsidized water or whether the government should recapture some or all of the increment of value added by decades of underpriced water. The policy states only that transfers will not be burdened with costs beyond those actually incurred. This response seems inadequate, although most analysts argue that subsidy recapture should be subordinated to the removal of transfer restrictions. Still, subsidy recapture will be an issue in both contract renewals and transfers.

Reservoir Operation

The Bureau of Reclamation operates carryover storage reservoirs throughout the West. Bureau operations are subject to varying levels of discretion that may change as the result of severe shortages caused by global climate change. Ironically, global climate change may constrain the Bureau's operating discretion more than it is now. Projects may actually have to be operated to meet legally binding allocations rather than to maximize power revenues. Bureau projects are subject to a complex state and federal scheme of priorities and preferences, and these priorities and preferences vary from reservoir to reservoir. The legal position of the Bureau is not clear. The orthodox analysis is that the Bureau is only a carrier for water allocated by state law. Section 8 of the Reclamation Act requires that the Bureau perfect project water rights under state law. This analysis was developed at a time when the Bureau's constitutional powers were not as broad as they are now and the Bureau operated smaller-scale projects. Congress may preempt state law and delegate to the Bureau the power to allocate water as it chooses.[8] Thus, the modern rule is that the Bureau must presumptively follow state law unless Congress has chosen to preempt it.

The carrier analysis works to structure the operation of small Bureau of Reclamation reservoirs; the Bureau stores the maximum amount of water possible during the spring runoff and answers calls during the irrigation season, refusing to honor a call only if there is not enough to satisfy senior water rights holders. The carrier analogy may also be legally correct for large, multipurpose reservoirs, too, but it is often irrelevant. The amount of water available gives the Bureau considerable discretion to operate the reservoir. As long as supplies are relatively abundant over a three- or 4-year period, there is usually a difference between the de jure operating rules and the de facto operating procedures.

Glen Canyon Dam's operation provides an example of the changes in operating procedures that severe shortages must produce.[9] Glen Canyon Dam is the linchpin of Colorado River management because it enables the upper Colorado River basin states to store sufficient water to meet their 10-year delivery obligation to the lower basin states. Paradoxically, the Law of the River controls the yearly operation of the dam but does not constrain daily operations for power generation. The reason is that the Law of the River only affects power generation in the case of long-term, extreme water shortages while reservoir law specifies annual fill targets. The dam was constructed as part of the Colorado River Storage Project Act to provide a large reserve to enable the upper basin to withstand prolonged periods of drought and meet its obligations under the 1922 Colorado River Compact to deliver 7.5 million acre-feet to the lower basin every ten years. Because the irrigation and other projects along the upper Colorado River could never pass a clean benefit-cost analysis and could not be subsidized by the beneficiaries, the upper basin states used power revenues from the storage projects to cover a large percentage of the repayment obligations. Glen Canyon Dam is presently operated to maximize power revenues, although hydroelectric generation is a low priority use on the river. In theory, Glen Canyon Dam is controlled by the Law of the River, a complex mass of compacts, international agreements, statutes, judicial decrees, and informal operating procedures. In practice, however, it is controlled by the Bureau of Reclamation and Western Area Power Administration operators, who manage the dam like an automatic bank teller machine for the southwest power grid. There is concern about the adverse effects of pulsating flows on the riverine environment of the Grand Canyon, but global warming could affect the dam's virtually unrestricted use for power generation in other ways. The Law of the River is largely irrelevant to day-to-day operations because it is only a law of mass allocations between regions and among states. The compacts that form the core of the law reflect the prevailing water use values at the time of their negotiation: irrigation and municipal and industrial use, as well as conservation storage to meet the demands for these uses in times of shortage.

The negotiators of the 1922 Colorado River Compact assumed that they were allocating an average annual flow at Lee's Ferry, Arizona, of 16 million acre-feet. Article III of the compact apportioned "in perpetuity" the "exclusive beneficial consumptive use" of 7.5 million acre-feet to each basin. The lower basin was given the additional right to the assumed one million acre-feet surplus. In anticipation of the assertion of claims by Mexico, the Mexican burden was divided equally between the two basins. The power of the lower basin was augmented by two provisions of Article III. The first provides that the upper basin states will not cause the flow at Lee's Ferry to be depleted by 75 million acre-feet for any consecutive 10-year period, the second provides that the upper basin states cannot withhold the delivery of water "which cannot reasonably be applied to domestic and agricultural use." A reciprocal duty on the lower basin not to demand deliveries on the same condition is meaningless, because the lower basin puts all its entitlement to domestic and agricultural use. The only mention of power is in Article IV, which subordinates the use of the river for navigation to "domestic, agricultural and power purposes."

The relationship between power generation and other uses of the river has been the subject of some speculation among commentators, but there has not yet been a conflict that tests the relationship. The upper basin's 10-year delivery obligation is absolute, thus, the upper basin states are precluded from objecting to the use of this water for power generation before it is consumed by the lower basin states. To establish the relationship between power generation and other river uses, there would have to be a prolonged drought making it impossible for the upper basin to meet its 10-year delivery obligations, and the lower basin states would have to demand the release of water for power generation. The late Dean Meyers suggested that if lower basin consumptive demands are met, Article III (e) prohibits the lower basin from demanding water solely for power generation, because the compact expresses a clear preference for domestic and agricultural uses over power generation (Meyers, 1966).

Prolonged warming may create the Anasazi scenarios that river watchers fear. If downstream priority right holders—the several large irrigation districts along the Colorado River in Arizona and California—make a call that triggers the 10-year obligation, however it is defined, the Bureau would have to let water flow through the dam to serve these priority uses, regardless of power contracts. Similarly, the 10-year obligation may be a basis for the upper basin states to require that water not needed for immediate downstream priority uses be stored in Glen Canyon Dam as a reserve against their 75-million-per-decade delivery obligation (Getches, 1985).

New Interests

Management of the Colorado under drought conditions is further complicated by the recent efforts to accommodate new interests. The post-Colorado River Compact experience with the accommodation of new interests contains mixed lessons for global warming scenarios. Three major classes of uses were traditionally excluded by reclamation-era allocations: recreation, environmental quality preservation (including public health and fish and wildlife habitat enhancement), and Indian claims. Most of the major developments in water law have revolved around the incorporation of these values at the federal and state levels.

In 1922, the full range of relevant interests was not represented in the negotiations. The two most obvious exclusions were Indian tribes and the government of Mexico. Both of these claimants have been accommodated by superimposing new rights onto the original mass allocation. Under the Supreme Court's *Winters* doctrine, Indian tribes have been given priority to large amounts of water.[10] Federal reserved rights may also be claimed by federal land management agencies, and there is an argument that the Grand Canyon National Park enabling legislation allows the National Park Service to assert a federal reserved water right to protect the ecological integrity of the canyon. These rights are assumed by the state in which the reservation lies. Likewise, the government of Mexico obtained quality rights by treaty and quality rights by subsequent international agreements.

The accommodation of newer resource values—the use of the river for habitat maintenance, recreation, and the stabilization of riparian corridors such as the Grand Canyon—has proved more difficult. These interests can be recognized through the creation of new rights, but their protection requires management of the river. The web of interconnected statutes, international agreements, and cases that make up the Law of the River is not designed to manage the river for the full range of resource values. All states have resisted management because of a fear that it will dilute their mass allocation consumptive use rights. This defect in the Law of the River is becoming more acute as new values assert themselves.

New values are incorporated in federal statutes passed after the 1922 compact and the Boulder Canyon Project Act, but these new statutes are not well integrated into the Law of the River. In the 1960s, Congress began to enact a number of national environmental statutes. The two most relevant for the Colorado River are the Clean Water Act and the Endangered Species Act. These statutes superimpose environmental protection mandates onto existing water allocation regimes without specifying the extent to which prior allocations are modified, but the few court cases involving these statutes suggest that existing allocations must be accommodated to accomplish the federal objectives.

Indian water rights are protected under the *Winters* doctrine. Indians assert large claims to both surface and ground water. The issue with respect to Indian water rights is the range of purposes for which the water can be used. Western water users take the pastoral people analysis of *Winters* literally, arguing that these rights are restricted for agricultural use on reservations. The Indian tribes generally claim the right to the full range of modern beneficial water uses and the right to lease water off the reservation. Off-reservation use has been allowed on an ad hoc basis in recent Indian water rights settlements. Thus, Indian water rights can be added to the pool of water available to respond to global warming-induced demands.

Recreational and environmental uses are at risk because they are junior in fact and in law. These uses are just beginning to get rights status under state law. Generally, under federal law they are protected as regulatory property rights. When they are recognized, they have a low de facto or de jure priority. Thus, they would probably be the first to be curtailed in a global warming management scenario. The recent incorporation of environmental values on the Colorado River illustrates their fragile legal status (Goldenman, 1990) and the challenges ahead for the Bureau of Reclamation to assure that global warming does not destroy the gains made as a result of the recognition of the value of protecting, to the maximum extent possible, natural environments.

CONCLUSION

Global warming may be the most serious environmental threat facing the West. If, as many believe, global warming is occurring, there is increased urgency to begin the necessary modification of our historic water allocation policies, which are premised on an

unlimited ability to outwit nature to accommodate all people attracted to the West. Federal and state western water managers are presented with a unique opportunity to begin the task of designing a set of water allocation institutions that will allow the modern West to continue as a viable region, even as aridity becomes an operational fact of daily life.

NOTES

1. *Peterson* v. *United States Department of the Interior*, 899 F.2d 799, U.S. Court of Appeals (1990).

2. 33 U.S.C. Section 383 (1986).

3. Ickes v. *Fox*, 300 U.S. 82 (1937).

4. Ivanhoe Irrigation Dist. v. *McCracken*, 257 U.S. 275 (1958) (*acreage limitation*); *City of Fresno* v. *California*, 372 U.S. 672 (1963) (*federal preference for irrigation*); and *Arizona* v. *California*, 373 U.S. 546 (1963) (*federal allocation in times of shortage*).

5. 438 U.S. 645 (1978).

6. *Nevada* v. *United States*, 463 U.S. 110, 126 (1983).

7. 43 U.S.C. 383 (1986).

8. *Arizona* v. *California*, 363 U.S. 546 (1963).

9. This portion of the paper is drawn from Ingram, Tarlock, and Oggins, 1991.

10. *Winters* v. *United States*, 107 U.S. 564 (1908).

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