PROJECTED EFFECTS OF CLIMATIC VARIATION UPON WATER AVAILABILITY IN WESTERN UNITED STATES

Final Report

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Principal Investigator:

Charles W. Stockton
Laboratory of Tree-Ring Research
University of Arizona
Tucson, Arizona 85721

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Background

The earth's climate is dynamic, and understanding its variability is vital in today's technologically advanced society. This is especially true in the field of water resources where the narrowing gap between water supplies and demands exaggerates the effects of droughts, while greater urbanization and development increases the potential for flood damage. Even subtle shifts from the present climatic norm could have serious consequences, yet surprisingly little is known about what those consequences might be.

While climatologists have been investigating climatic variation and trends for some time, the hydrologic literature has few precedents for such studies. In fact, not all hydrologists would agree to its necessity, stating that climate is, almost by definition, invariant over the 50 to 100-year lifetime of most water resources projects. The U.S. Water Resources Council (WRC) sums up this position, in their widely used Guidelines for Determining Flood Flow Frequency ". . .available evidence indicates that major changes occur in time scales involving thousands of years. In hydrologic analysis it is conventional to assume flood flows are not affected by climatic trends or cycles" (WRC, 1977).

Although this convention may have had some pragmatic justification in the past there is increasing evidence that it may be outmoded for water resources planning during the next century. Recent "state-of-the-art" reports by the U.S. Environmental Protection Agency (Seidel and Keyes, 1983) and the National Research Council (NRC, 1983) leave little doubt that global warming will occur during the next 50-100 years due to increases in atmospheric carbon dioxide related to the combustion of fossil fuels. In addition to CO_2, other infrared absorbing gases are also increasing. These include, among others, methane, nitrous oxide and the chlorofluorocarbons (Machta, 1983). Although the NRC report was less pessimistic than that of the EPA, both agreed on the inevitability of climatic warming, given present upward trends in atmospheric CO_2 and other "greenhouse" gases.

An early review by Schneider (1975) showed that predictions of global surface temperature increase due to a doubling of pre-industrial CO_2 levels ranged widely, from 0.7^{o} to an extreme of 9.6^{o}C. Schneider gives the best estimate as between 1.5^{o} and 3^{o}C, and more recent estimates are roughly in this medium range. Budyko (1982) also anticipated a change of 2.5^{o} to 3^{o}, while Flohn (1981) predicted a 4^{o} to 5^{o}C rise in average global temperature, the higher estimate being due in part to his consideration of the effect of other infrared absorbing gases.

Global warming would not affect all parts of the world equally, thus creating a complicated problem in determining the geographic distribution of temperature and precipitation changes that would result from altered circulation patterns. Manabe and Wetherald (1980) used a mathematical circulation model to determine the latitudinal variation of the difference between precipitation and evaporation. From 38^{o} to about 50^{o} north latitude, this difference shows a marked decrease when CO_2 concentration is doubled. A similar conclusion is reached by Kellog (1978), who derived his scenario from an analogy with climate during the hypsithermal period of maximum warming about 5,000 years B.P. Flohn (1981) combined mathematical models with evaluation of past climates and projected a temperature increase of about 3^{o}C to 7^{o}C, coupled with a decrease in precipitation of 10% to 20% between 38^{o} - 42^{o} north latitudes.

Smagorinsky (1983) summarized the likely effects of a doubling in atmospheric CO_2 on climate in the recent National Research Council report. Some pertinent points are listed below.

1. An equilibrium global warming of near $3^{o} \pm 1.5^{o}C$.
2. Increases in surface air temperatures would vary significantly with latitude and over the seasons.
3. Warming would be 2-3 times greater over polar regions as over the tropics and significantly greater over the Arctic than the Antarctic.
4. Temperature increases would have large seasonal variations over the Arctic -- minimum in summer and maximum in winter. Smaller seasonal variations would occur equatorward of 45^{o}.

The effect that the projected climatic changes might have on surface water supplies, especially in water-short regions such as the southwestern United States, is a point of major concern. In one of the most comprehensive studies to date, Stockton and Boggess (1979) determined the effect of four possible climatic change scenarios (average present temperature $\pm$ $2^{o}C$ combined with average present precipitation $\pm$ 10%) on water supplies of the 18 water resource regions of the coterminous United States as designated by the U.S. Water Resources Council (WRC, 1978). They found that the most severe scenario ($+2^{o}$ temperature combined with -10% precipitation), would have serious effects on all regions west of the 100th meridian except for the water-rich Pacific Northwest and the Great Basin where demand is low and groundwater reserves are relatively high. The humid East would not be seriously affected by such a change. Revelle and Waggoner (1983), writing in the National Research Council Report, essentially corroborated the conclusions of Stockton and Boggess (1979). In a more detailed study of the Colorado River, Revelle and Waggoner (1983) suggest that annual flows, based on 1931-1976 averages, would be reduced about 40% by a combined $2^{o}C$ increase in temperature and 10% decrease in precipitation. In a similar analysis Stockton, Quinlan and Boggess (1984) reported that the same scenario would cause a 30% reduction in flow for selected sub-basins of the Upper Rio Grande.

In the work reported here, we have enlarged upon our earlier study which was done for the U.S. Army Corps of Engineers (Stockton and Boggess, 1979). We have attempted to quantify our earlier estimates and to consider the combined effects of a climatic change and drought patterns that have been established from historic records and data derived from tree-ring chronologies. As part of the drought studies, the available data base has been greatly strengthened by new chronologies established for sites in and along the western flanks of the Great Plains.

As a pilot operation for the overall study, a detailed analysis was made of the Upper Rio Grande region. An in-depth study was also made of the Great Basin Region with supplementary support being furnished by the U. S. Geological Survey. These detailed studies provided the basis for Master's thesis by two University of Arizona graduate students. (Quinlan, Peter T., 1982. Climatic Change and Water Availability in the Rio Grande and Pecos River Basins. Flaschka, Irmgard, 1984. Climatic Change and Water Supply in the Great Basin.)

Research Plan and Methods

Analyses were carried out on a sub-regional basis, using regions and subregions designated by the Water Resources Council. Regions are drainage areas of major rivers or the combined drainage areas for a series of streams. Subregions are drainage areas of smaller streams (Figure 1).

We have relied heavily on data gathered by the WRC for its Second National Water Assessment (WRC 1978) as a basis for our projections. That assessment identified subregions where streamflow would be inadequate by

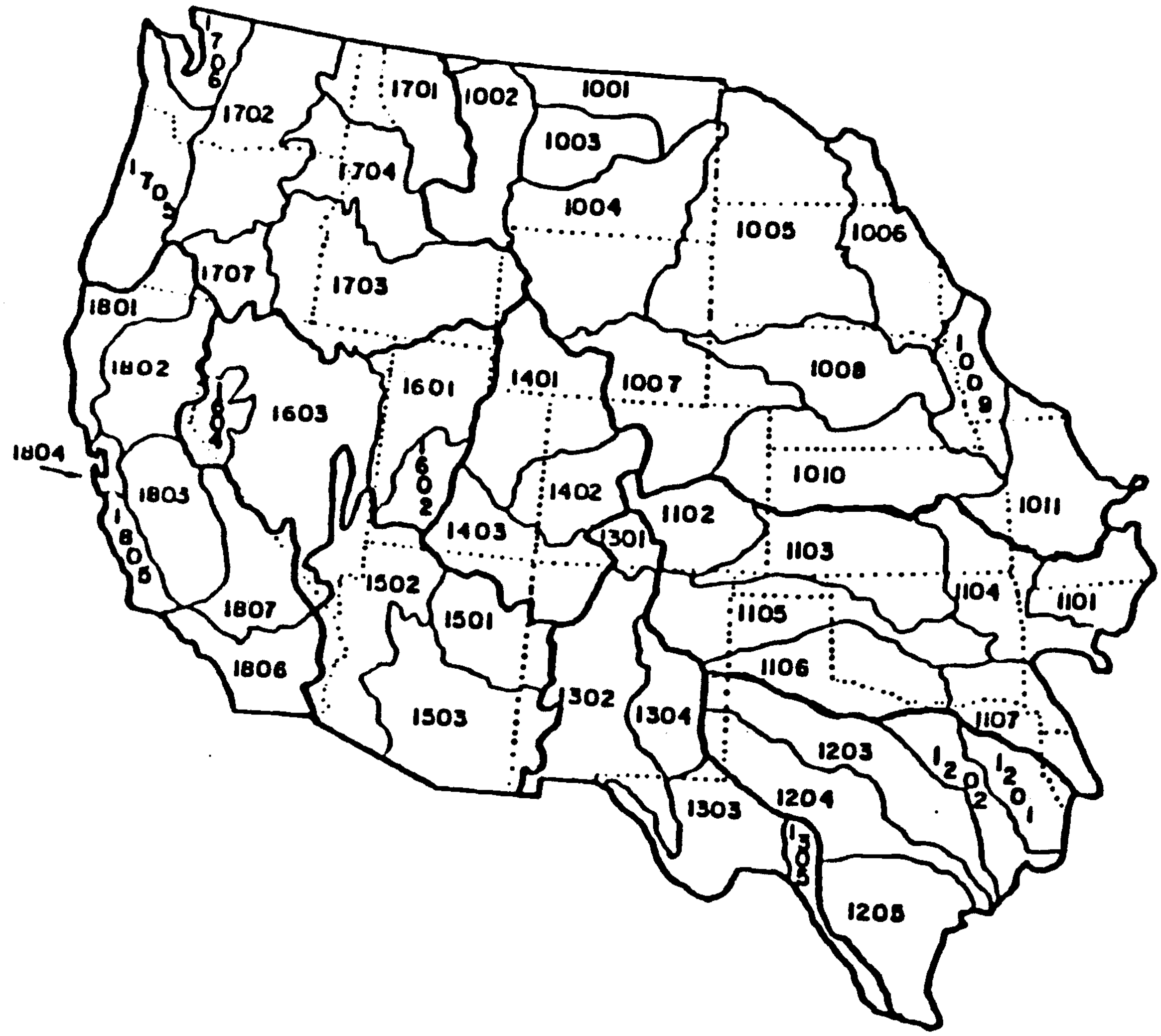

FIGURE 1. Water Resources Regions (heavy lines) and Sub-regions for the Western United States as designated by the U.S. Water Resources Council. Regions included are Pacific Northwest, California, Great Basin, Upper Colorado, Lower Colorado, Rio Grande, Texas Gulf, Arkansas-White-Red and Missouri Basin.

the year 2000. The term "inadequate" was defined as 70% or greater depletion of streamflow -- a general cutoff level for supporting good survival habitat for most aquatic life (instream requirements).

The WRC projections of future water availability assumed that natural runoff (Natural runoff = precipitation - evapotranspiration) would be the same as at the present (based on data available through 1975). We have made similar projections of streamflow for the year 2000, but under two scenarios of climatic change:

1) an increase of 2°C in mean annual temperature.
2) an increase of 2°C in mean annual temperature accompanied by a 10 percent decrease in average annual precipitation.

Our use of a postulated 2°C temperature increase is conservative as far as most model projections are concerned. It is less than the predicted global average (Hansen _et al._ 1981) and more importantly, perhaps, is the fact that considerably greater increases, as much as twice the global average, are predicted for temperate regions of the Northern Hemisphere (Kellog and Schware, 1982). The assumed precipitation decrease was arbitrary, but is also conservative considering that it represents a smaller anomaly than has been sustained in 10-year averages for some of the drier decades during the past century.

Model Development

Since our basic objective was to determine the effects of changes in average annual temperatures and precipitation on surface water yields, a model had to be developed that would adequately express gaged values for streamflow in terms of the same parameters. Once developed, the projected climatic changes could be used as inputs to the model and their effects on streamflow determined.

In line with the above constraints, an empirical climatic water balance approach was used to develop regional or subregional water budgets. In general this is a bookkeeping procedure where the water supply (Precipitation) is balanced against the climatic demand for water (Potential Evapotranspiration). Potential evapotranspiration is a theoretical term defined by Thornthwaite and Mather (1955) as the water loss from a large, homogeneous, vegetation covered area (albedo from 22 to 25%) that never suffers from a shortage of water. Potential evapotranspiration is essentially energy dependent and is not a function of soil type, vegetation, soil moisture, etc. Actual evapotranspiration, in contrast, is related to all these factors as well as climate (Mather, 1978).

During periods when precipitation exceeds potential evapotranspiration, moisture is stored in the soil profile until its storage capacity is satisfied. A surplus then occurs which may infiltrate to the water table or be discharge directly as runoff. In like manner, when potential evapotranspiration exceeds precipitation, moisture is withdrawn from soil storage by growing plants and evaporates directly to the atmosphere. This creates a moisture deficit.

The above relationship can be expressed by the generalized formula:

$$S = P - E - (W_2 - W_1) \quad \text{where} \tag{1}$$

S = Moisture surplus (includes both runoff and infiltration)
P = Monthly precipitation
E = Evapotranspiration
W_2 = Soil moisture content for present month
W_1 = Soil moisture content for preceding month

Equations governing the above relationships are developed and discussed in detail by Sellers (1965; pp. 175-177). In most cases precipitation is the only known value in the equation and the others must be developed empirically or given a "best estimate".

Potential Evapotranspiration. Actual evapotranspiration (ET) is limited by available mositure; its upper limit is the Potential Evapotranspiration (PE). In water balance models, the determination of PE is the first step in estimating evaporation losses. This is not an easy task as evidenced by the many methods available, ranging from physical measuring devices, to empirical formulas, to complicated, theorectically-based methods requiring detailed (and often unavailable) data. The "mean temperature" methods such as that described by Thornthwaite (1948) are perhaps the most widely used, largely because they are simple and the input data are readily available. Unfortunately these methods, largely developed in humid regions, do not accurately predict ET for arid climates. For instance, the Thornthwaite method may underestimate ET up to 50% in arid regions (Cruff and Thompson, 1967; Sellers, 1964; Van Hylckama, 1980).

An underlying problem is the complexity of the evaporation process which is proportional to the vapor pressure gradient between an evaporating surface and the atmosphere, along with a source of energy. Although the gradient is closely related to temperature as a source of energy, other physical and climatic factors play important roles. Thus the implicit relationship between temperature and ET, assumed in the application of most water balance models, has been widely questioned. At the same time it is reasonable to assume that temperature may vary in tandem with other climatic factors that influence evaporation. This suggests that temperature may be a good indicator of evaporation because both are symptomatic of the same underlying climatic variations.

We tested the idea that temperature and evaporation may co-vary by analyzing climatic and pan evaporation data at both Winnemucca and Salt Lake City. Table 1 shows correlations between actual (pan) evaporation and other available climatic parameters for the months of June and July, 1950-1980.

Many of the climatic parameters show a strong interrelationship in June but fewer for July. Wind speed, though an important theoretical consideration, shows no correlation to actual ET, probably because average monthly wind speed shows little year-to-year variation and does not truly convey the actual windiness occurring throughout the month. Relative humidity (RH) is very important factor in both months, and would probably be the strongest predictor of ET. Unfortunately, RH data are rarely available. Clearness of sky, an indicator of available solar radiation, is well correlated at both stations in June, but not in July. Correlations for temperature and precipitation decrease for July as well.

The general lessening of the relationships among all the variables in July may be due to the different weather patterns in that month. The tail end of Pacific frontal systems often persist into June. Large-scale storm systems result in days of cloudy, cool, rainy weather. The number of storms in a month is thus a major determinant of T, P and percent sunshine. But in July, convective storms become dominant; a typical day might be hot with a heavy afternoon thundershower. The consistent weather patterns found in June do not occur in July.

It appears, then, that mean temperature could be a good indicator of prevailing weather conditions. Data in Table 2 also support this conclusion. Here the analysis was expanded to include more stations and months, although only temperature and precipitation data are available for

Table 1. Correlation Matrices Showing Relationship of Pan Evaporation to Other Climatic Variables for June and July at Winnemucca and Salt Lake City.

Asterisks indicate coefficient is significant (p≥.95).

WINNEMUCCA JUNE

	Temp	Ppt	Wind	Sky	RH
Precip	-.26				
Wind	.12	-.10			
Clear Sky	.31	-.69*	.26		
RH	-.59*	.74*	-.36*	-.67*	
Pan Evap	.36*	-.69*	.08	.60*	-.73

WINNEMUCCA JULY

	Temp	Ppt	Wind	Sky	RH
Precip	.09				
Wind	.19	.05			
Clear Sky	-.30	-.21	-.07		
RH	-.10	.40*	-.18	-.28	
Pan Evap	.13	-.01	.03	.18	-.63*

SALT LAKE CITY JUNE

	Temp	Ppt	Wind	Sky	RH
Precip	-.66*				
Wind	.25	-.31*			
Clear Sky	.52*	-.76*	.42*		
RH	-.74*	.75	-.26	-.66*	
Pan Evap	.72*	-.77*	.17	.64*	-.77*

SALT LAKE CITY JULY

	Temp	Ppt	Wind	Sky	RH
Precip	-.40*				
Wind	.08	-.11			
Clear Sky	-.30	-.20	-.11		
RH	-.52*	.58*	-.02	-.23	
Pan Evap	.42*	-.57*	.08	.07	-.69*

Table 2. Correlation of Monthly Pan Evaporation (E), Average Monthly Temperature (T) and Precipitation (P) at Selected Great Basin Stations.

Asterisks indicate coefficient is significant (p≥.95).

Month	Station	No of Years	Correlation Coefficient			Partial Corr.	
			E-P	E-T	T-P	E-P/T	E-T/P
APR	Saltair	21	-.56*	.75	-.19		
	Milford	22	-.58*	.71	-.26		
MAY	Rye Patch	25	-.63*	.61*	-.47*	-.48*	-.44*
	Topaz Lake	13	-.60*	.78*	-.24		
	Saltair	20	-.77*	.84*	-.78*		
	Milford	25	-.65*	.72*	-.54*	-.38*	.53*
JUN	Rye Patch	29	-.73*	.56*	-.46*	-.64*	.35*
	Topaz Lake	16	-.45*	.91*	.04		
	Saltair	23	-.81*	.77*	-.77*	-.53*	.40
	Milford	26	-.79*	.72*	-.56*	-.68*	.54*
	Ruby Lake	20	-.72*	.60*	-.47*	-.62*	.43
	Scofield D	27	-.71*	.42*	-.50*	-.65*	.15
JUL	Rye Patch	30	-.24	.37*	.02		
	Topaz Lake	19	-.50	.28	.15		
	Saltair	21	-.19	.29	.40*	-.35	.41
	Milford	26	-.39*	.18	.08		
	Ruby Lake	24	.06	.06	.12		
	Scofield	29	-.41*	-.05	.02		
AUG	Rye Patch	29	-.65*	.32*	-.49*	-.60	.09
	Topaz Lake	19	-.41*	-.12	.31		
	Saltair	23	-.64*	.54*	-.38*	-.56*	.42
	Milford	26	-.31	-.39*	-.02		
	Ruby Lake	21	-.38	.19	.18		
	Scofield D.	30	-.74*	-.27	.23		
SEPT	Rye Patch	26	-.40*	.53*	.05		
	Topaz Lake	17	-.44*	.16	.16		
	Saltair	23	-.76*	.67*	-.46*	-.69*	.56*
	Milford	26	-.55*	.23	-.24		
	Ruby Lake	23	-.35	.30	-.25		
	Scofield D.	26	-.37	.38	.18		
OCT	Saltair	22	-.45*	.57*	-.27		
	Milford	25	-.65*	.54*	-.47*	-.53*	.34

these stations. Again, the sharp decrease in significant correlations in July is obvious, with some improvement in August. In non-summer months the linear relationship between T and PE is often good to excellent, indicating that estimating changes in PE directly from temperature variations can be done with confidence for much of the year.

Based on the above correlations between temperature, pan evaporation and other climatic parameters, we finally adopted the climatic water balance model developed initially by Budyko (1963) as described and modified by Sellers (1965). This approach is superior to that of Thornthwaite in arid regions because potential evapotranspiration from unirrigated lands in the arid west appears more closely related to precipitation (through soil moisture availability) than to temperature.

Results

Regional Effects of Climatic Change Scenarios

Within the western United States, the climatological water-balance model yielded as little as a 3 to 11% decrease in regional natural runoff for the mild scenario (temperature increase only) and as much as an 18 to 33% decrease in natural runoff for the severe scenario (temperature increase and precipitation decrease). The smaller percentage changes were found for the relatively wet Pacific Northwest. For other regions, representative percent-changes were 10% for the temperature-increase-only scenario and 30% for the warmer-drier scenario.

The corresponding percent-change in streamflow varied greatly from subregion to subregion, depending largely on the magnitude of streamflow. If the flow out of a subregion is already nearly depleted by use, a small decrease in rainfall can of course lead to a 100% decrease in streamflow.

The key question here on the importance of climatic change is whether the resulting streamflow decrease makes a difference in placing a subregion in the "inadequate streamflow" category.

Subregions with projected streamflow by year 2000 are shown in Figure 2. A distinction is made between subregions where streamflow would be inadequate without climatic change, and there where climatic change would make the crucial difference. The assumption was made in this analysis that ground-water mining[4] would proceed at the current rate and thus continue acting as a buffer against water shortages in some regions.

Inadequate streamflow is projected for eleven subregions by the year 2000 under existing climatic conditions. The average annual runoff in these subregions is generally less than 5 inches. These subregions are in the arid Southwest and the western Great Plains, and are areas with intensive irrigation or urban development -- for example, the San Joaquin Valley of California and the subregion containing metropolitan Los Angeles.

No additional subregions were placed into the "inadequate" category by the temperature change scenario, but many were should the change to a warmer and drier climate occur. The largest effect was in the Missouri Basin, where the number of subregions with inadequate streamflow increased from 2 to 9. The wettest subregion to be adversely affected was the Sacramento-Lahontan in northern California. That subregion currently has runoff greater than 15 inches, but also has large export commitments.

The picture presented by Figure 2 is over optimistic because some subregions which depend heavily on groundwater mining are rapidly depleting

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[4]Mined groundwater is that portion of the average annual groundwater withdrawal that exceeds the average annual groundwater recharge.

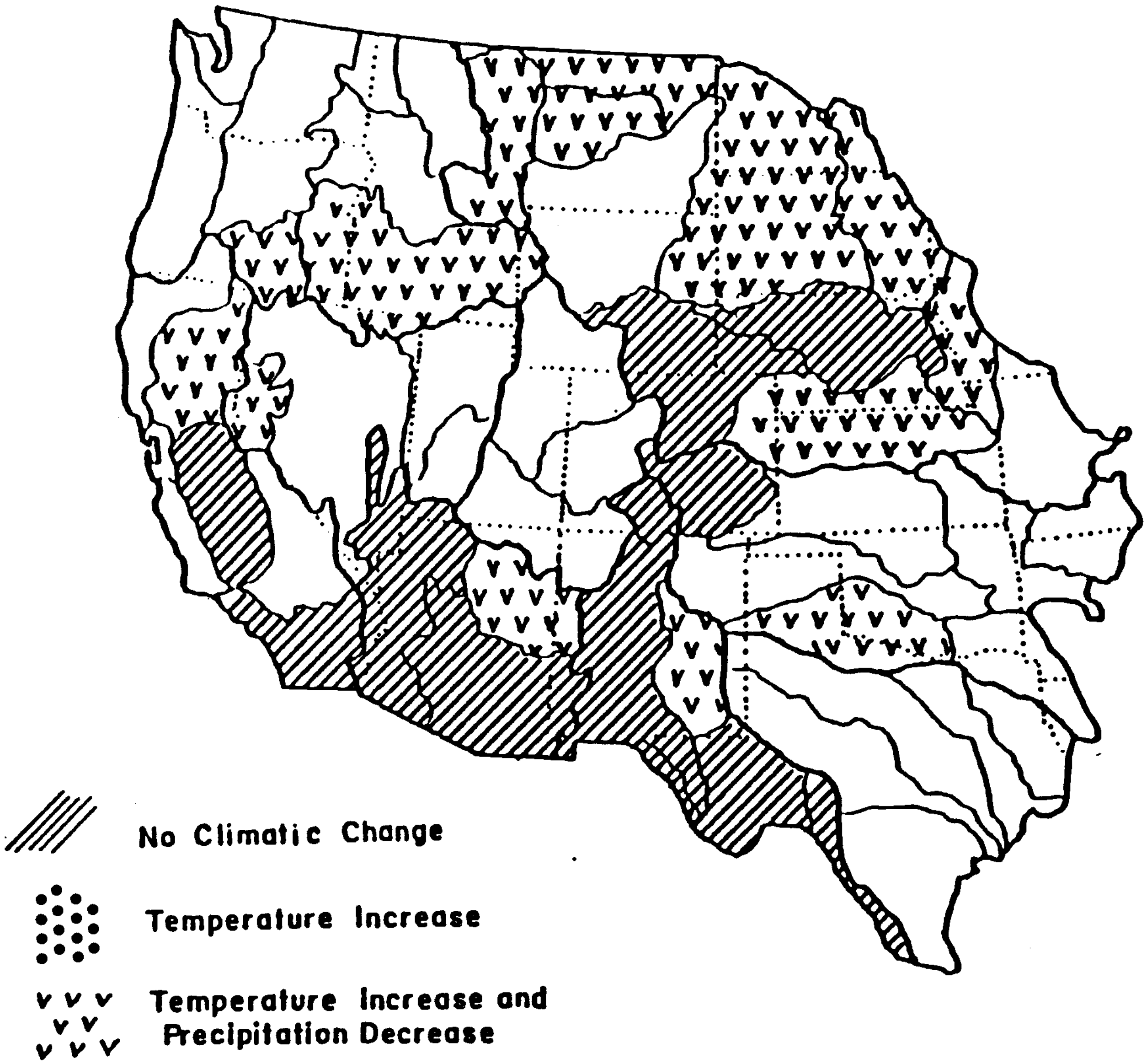


FIGURE 2. Subregions projected to have inadequate streamflow in year 2000 assuming current rate of groundwater mining. Three scenarios are shown: 1) unchanged climate; 2) 2°C increase in mean annual temperature; and 3) same temperature increase combined with 10% decrease in annual precipitation. Streamflow is defined as flow out of subregion in an average year.

their groundwater reserves. The importance of this problem can be appreciated from year-2000 projections similar to those in Figure 2, but assuming no groundwater mining in year 2000 (Figure 3). Under this assumption the mild climatic-change scenario leads to inadequate streamflow in four subregions in the central and southern Great Plains. The assumption on groundwater mining is obviously pivotal in producing the differences between Figure 2 and 3. The reason is clear from the numbers inset in Figure 3: groundwater mining supplies water amounting to 33-81 percent of total depletions[5] in subregions entering the inadequate category because of mild climatic change. Note also that in several of these subregions more than 20% of available groundwater reserves will be exhausted by the year 2000 at the present rate of groundwater mining. Increased pumping costs and possible deterioration of water quality are likely to make groundwater mining less attractive in the future. Consequently the assumption of no groundwater overdraft by year 2000 may be more realistic than the assumption of mining at the present rate.

Upper Rio Grande Region

Results obtained in the pilot study of the Upper Rio Grande are reasonably typical of the effects that the projected climatic change had on other river basins. The Rio Grande was selected for detailed analysis because it represents an "extreme case" due to its critical supply/requirements ratio. Also, problems encountered in the basin such as modeling

[5]Depletions equals water lost to consumption plus net evaporation from ponds and reservoirs exceeding 1.63 billion gallons capacity. Consumption is water withdrawn for offstream uses and not returned to a surface or ground-water source

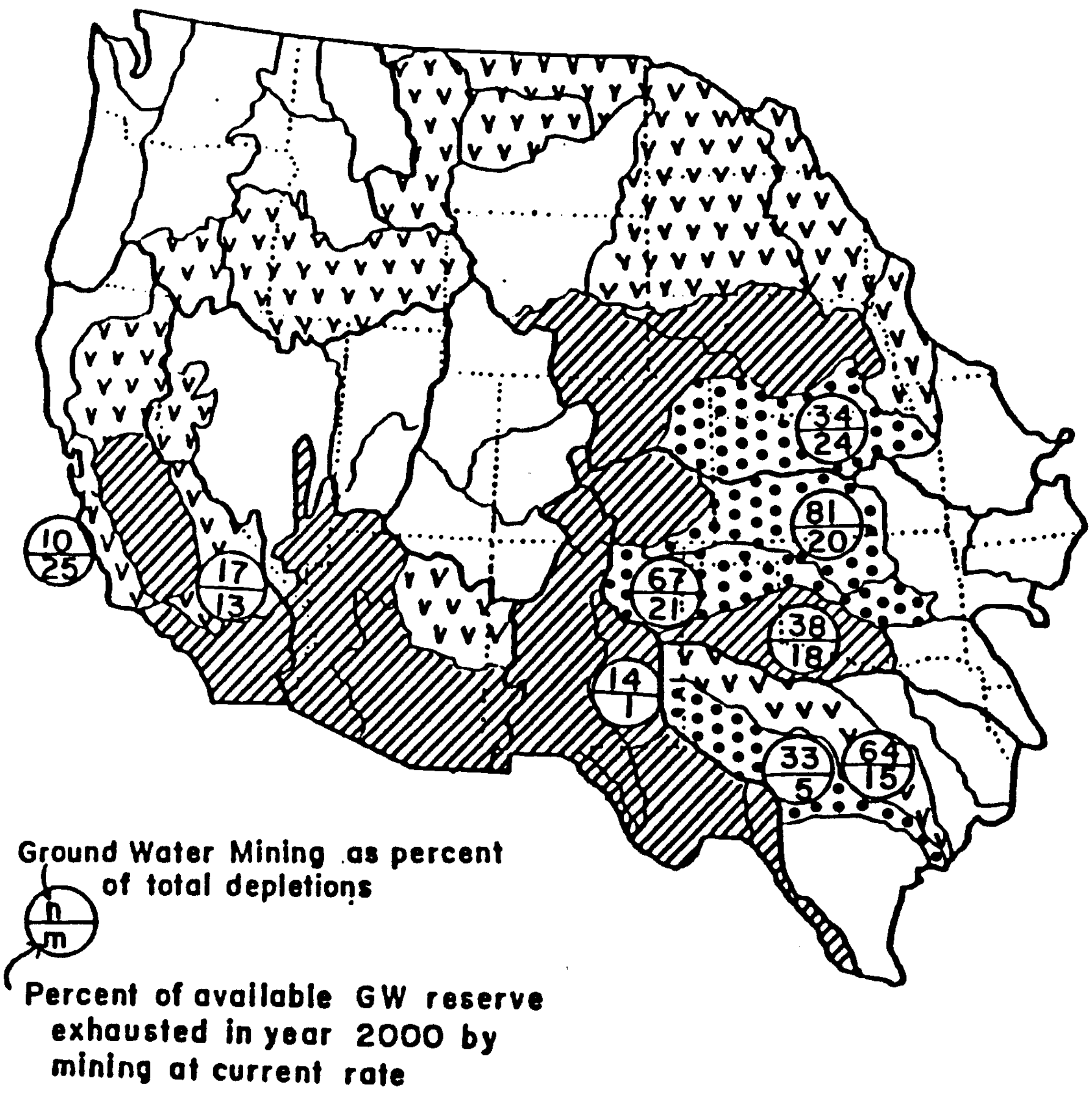


FIGURE 3. Subregions projected to have inadequate streamflow in year 2000 assuming no groundwater mining. Remainder of legend as in Figure 2. Inset numbers on groundwater mining are shown only for subregions whose "inadequate streamflow" designation differs from Figure 2.

snowmelt runoff, unrecorded diversions and scarcity of climatic and runoff data would likely be present in basins included in the overall study.

The selection of sub-basins suitable for inclusion in the model development was complicated by the fact that the Rio Grande has long been subject to extensive, and only partially recorded diversions and regulation. To illustrate this point, the estimated natural flow of the river at the Colorado-New Mexico state line is three times greater than the observed flow. This discrepancy increases to 8 times at the New Mexico-Texas border. Three sub-basins were finally selected which met, in varying degrees, criteria for data reliability and record length. These include the drainage areas above the following locations where suitable gaged runoff data were available:

1. Del Norte, Colorado on the Rio Grande with a drainage area of 1320 sq.mi. Elevation of the Del Norte Gage is 7,980 feet and the mean annual discharge is about 660,000 maf.
2. Conejos River at Magote, Colorado. Drainage area is 282 sq.mi.; gage elevelation, 8272 feet; and mean annual discharge 246,000 maf.
3. Rio Chama below El Vado dam, New Mexico. Drainage area is 777 sq.mi.; Gage elevation 6692 feet; and mean annual discharge 277,300 maf.

These three sub-basins, comprising about 7% of the total drainage area, contribute about 50% of the estimated natural flow of the Rio Grande at El Paso.

The precipitation-runoff pattern shown for Del Norte, Colorado (Figure 4) is similar to that of the other basins. Although a large part of the precipitation occurs from July - October, most of the runoff occurs in May and June from melting snow at the higher elevations of the watersheds. Summer rainfall, largely from convective thunderstorms, falls on extremely dry ground and thus makes minimal contributions to runoff.

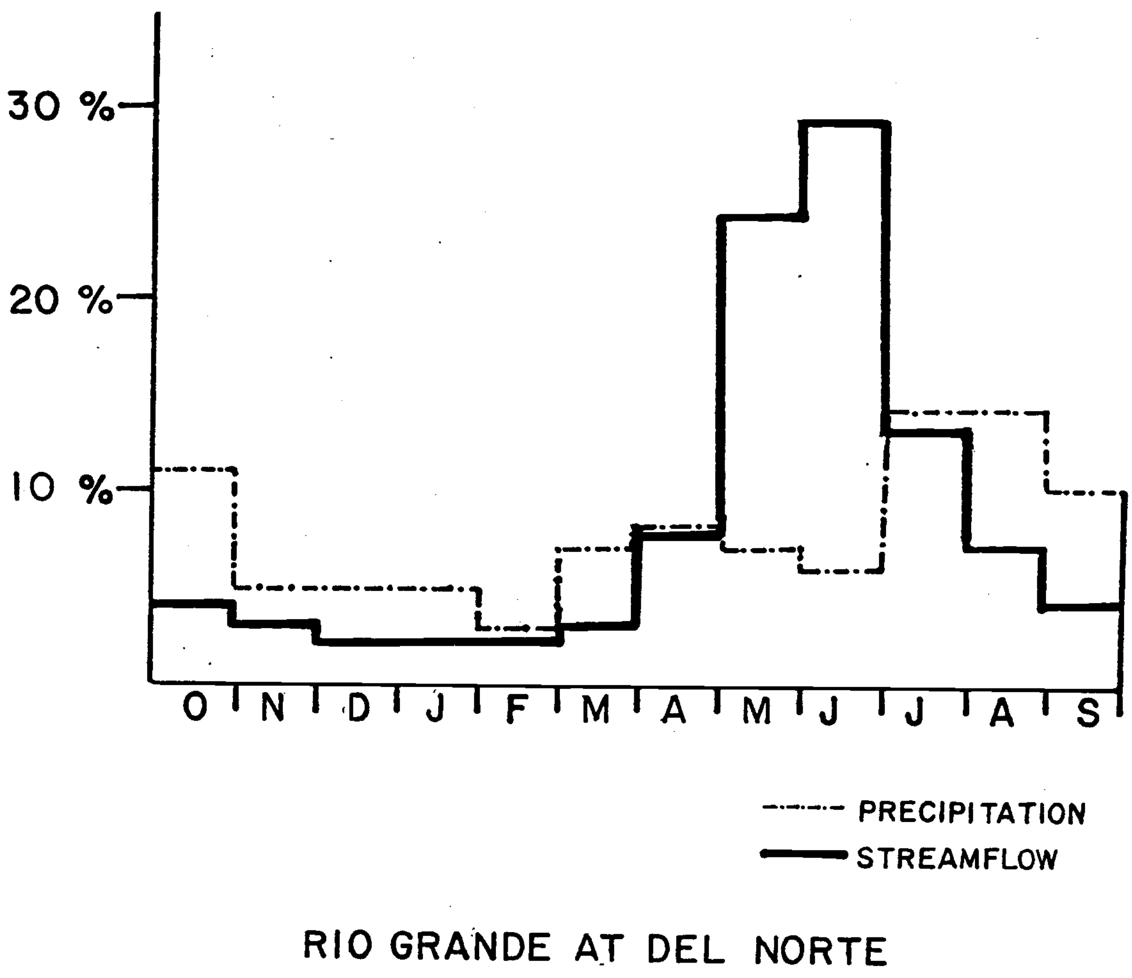


FIGURE 4. Precipitation and streamflow at Del Norte, Colorado.

The climatic water balance model was developed as described earlier. Predicted runoff agrees favorably with gaged values (Figure 5). Comparison statistics for all three series are shown in Table 3.

The postulated changes in temperature and precipitation (+2^{o}C temperature and -10% precipitation) were used as model inputs and the resulting effectson streamflow for each of the three sub-basins are shown inTable 4.

Influence of Drought

The variability of precipitation, resulting in periods of relative abundance and scarcity of water, profoundly affected prehistoric developments in the Upper Rio Grande. This point is illustrated by the archaeological history of Arroyo Hondo, a 14th century pueblo located 4 1/2 miles south of present-day Santa Fe, New Mexico at an elevation of 7,100 feet.

Table 3. Comparative Statistics for Observed Streamflow Records from Study Watersheds and Models.

	RIO CHAMA	RIO GRANDE	CONEJOS RIVER
MEAN DISCHARGE (ACRE-FEET)			
Observed Record	266,648	640,160	239,582
Model	262,108	664,013	239,061
STANDARD DEVIATION			
Observed Record	132,015	219,503	81,599
Model	169,572	283,360	91,473
SKEW			
Observed Record	0.867	0.001	0.153
Model	0.953	0.333	0.291
CORRELATION COEFFICIENT			
Precipitation w/ Observed Record	0.75	0.71	0.77
Model Discharge w/ Observed Record	0.91	0.83	0.84
SAMPLE SIZE	35	65	65

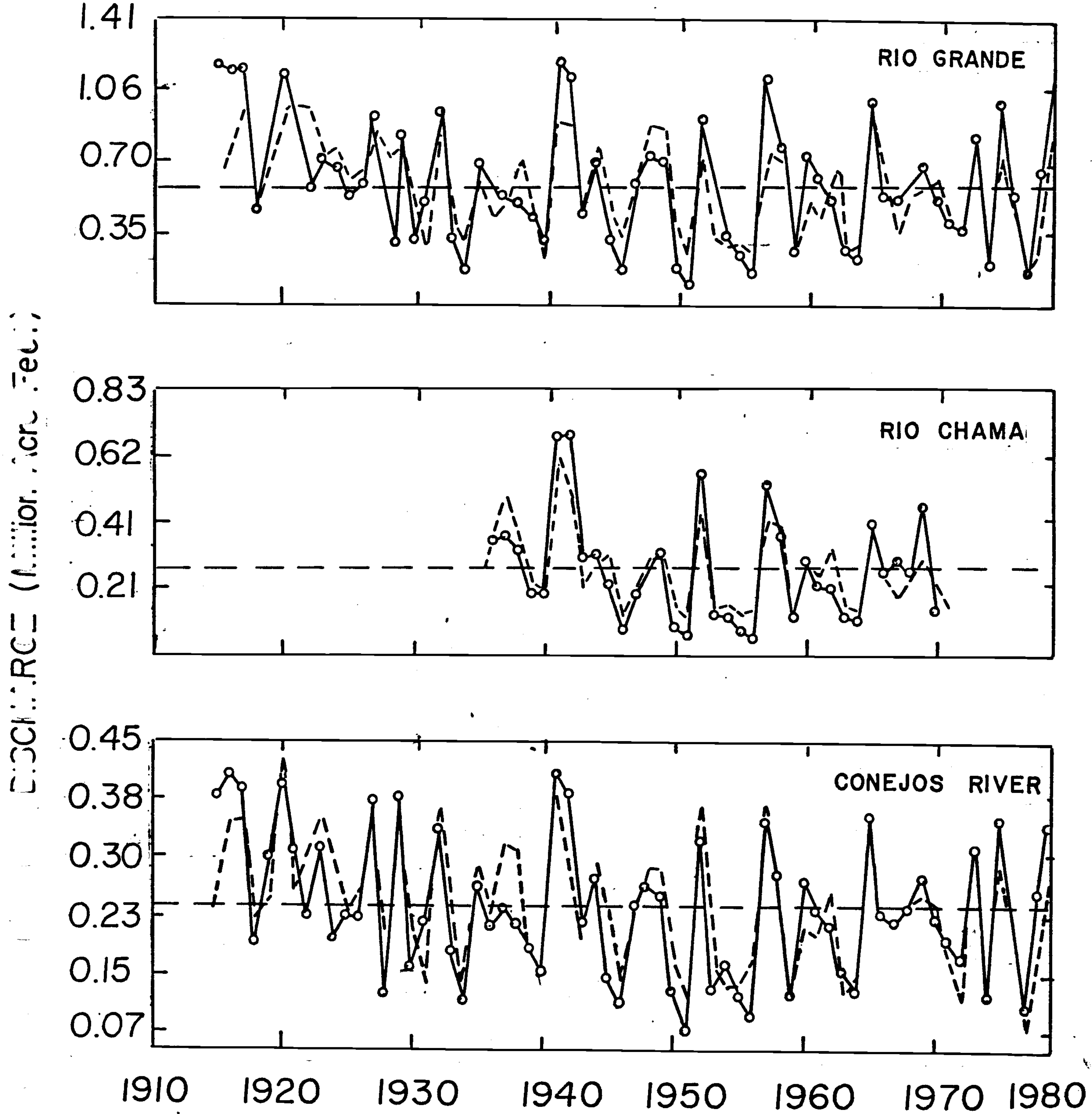


FIGURE 5. Gaged and predicted runoff for the Rio Grande at Del Norte, Colorado, Rio Chama below El Vado Dam, New Mexico and Conejos River at Magote, Colorado. Predicted values indicated by solid line with circles.

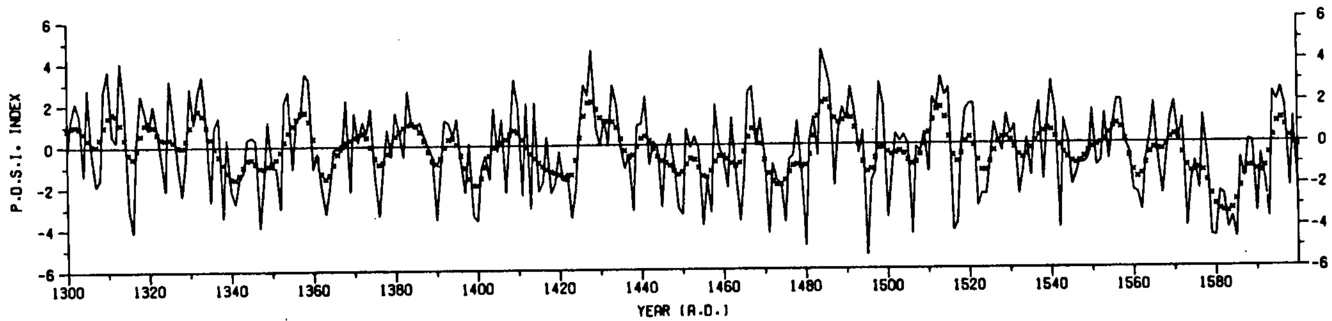
Table 4.

MEAN ANNUAL DISCHARGE (ACRE-FEET)

BASIN	Model Present	Model Projected	Change	% Change
Rio Chama	262,108	183,579	78,259	-30
Conejos River	239,582	175,366	64,216	-27
Rio Grande	644,013	451,264	212,749	-32

As part of a multidisciplinary study conducted by the School of American Research at Santa Fe, Rose, Dean and Robinson (1981) reconstructed the climate of the area using tree-ring chronologies developed from living trees and archaeological materials. Their work, along with other investigations, have made it possible to relate the development of Arroyo Hondo to climatic variations.

Arroyo Hondo was established around A.D. 1300 when precipitation was increasing after a 50-year period of below average values. Precipitation remained above the long-term mean for most of the first 35 years of settlement. The pueblo reached its greatest size during this period and was one of the largest communities in the area. Precipitation became quite variable around 1335 (Figure 6), population began to decline and the village was virtually abandoned by 1345. After about 40 years of near-abandonment, and coincident with another period of favorable precipitation, a second phase of settlement began. A new town was built upon the ruins of the old and it reached maximum expansion in the early 1400's. Again, precipitation



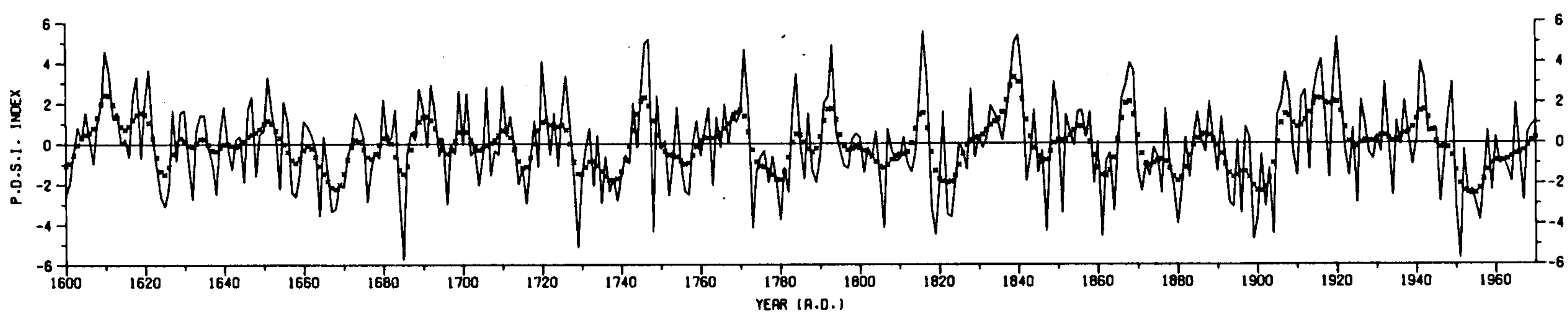


FIGURE 6. July Palmer Drought Severity Index reconstructed by tree rings for the Northern Rio Grande climate division. Low pass filtered series is indicated by the symbols. (Figure and data by Martin Rose)

declined and reached a low point in the 1,000 year tree-ring record about 1420 (Figure 6). Following a disastrous fire the final occupation came to an end.

For his doctoral research Rose (Martin Rose, Laboratory of Tree-Ring Research, University of Arizona, Personal Communication) has greatly expanded the Arroyo Hondo work with reconstructions of climatic variables based on a network of tree-ring chronologies and climatic stations in Colorado and New Mexico. Eighteen chronologies were used for reconstructions extending from 1970 to A.D. 1650 and seven chronologies for the A.D. 1649-900 intervals.

Figure 6, developed by Rose, shows variations in the Palmer Drought Severity Index from A.D. 1300-1960 as reconstructed from tree-ring data. The high frequency with which periods of moderate to severe drought have occurred during the past 660 years is of interest and importance to both archaeologists and water resource planners. Note, especially, that droughts recorded during the present century are not climatic anomalies but have been essentially equalled or exceeded on several occasions during the 1300-1960 period.

Should the past variability of climate, especially precipitation, extend into the predicted period of warming, and many believe that even greater variability can be expected, then water shortages will become even more acute. For instance, a drought equal to that of the 1950's, acting in concert with a warmer and drier climate, would likely be a major disaster. During the 1950-1957 period, actual streamflow was only 69 percent of the mean annual discharge and under the combined effects mentioned above would be further reduced to 39 percent. Allocation changes that might be required to meet such diminishing supplies would be difficult to implement because of the existing complex web of international treaties, interstate compacts and both federal and local laws.

Great Basin Region

The Great Basin Region consists of WRC subregions 1601, 1602, 1603 and 1604 and includes a large number of closed basins with drainages terminating in Utah and Nevada (Figure 7). The region is quite large (139,345 sq. mi.) which contributes to its highly variable climate. It is one of the most arid basins in the country. Precipitation averages 11 inches over the entire region and varies from a little as 3 inches at lower elevations to 60 inches in some of the higher mountains.

Occurrence of surface water is uneven as the varied topography produces many smaller drainages rather than the larger tributary systems common elsewhere. Total streamflow is about 6.7 maf per year; only the Rio Grande is lower. Most of the streamflow is currently committed. Actual withdrawals often exceed the available streamflow since return flows are frequently used. Substantial runoff occurs only from higher elevations of the large mountain systems on the eastern and western borders of the region.

Groundwater reserves, in contrast, are substantial although aquifer recharge is limited. At present there is very little overdraft of groundwater in the region, although many aquifers have not been developed because they are in relatively remote areas.

The closed basin characteristics of the Region provided limited choice of gaged watersheds that can be used in developing the water balance model. Four drainages were selected which best met the standards of data accuracy and runoff length. These include the following:

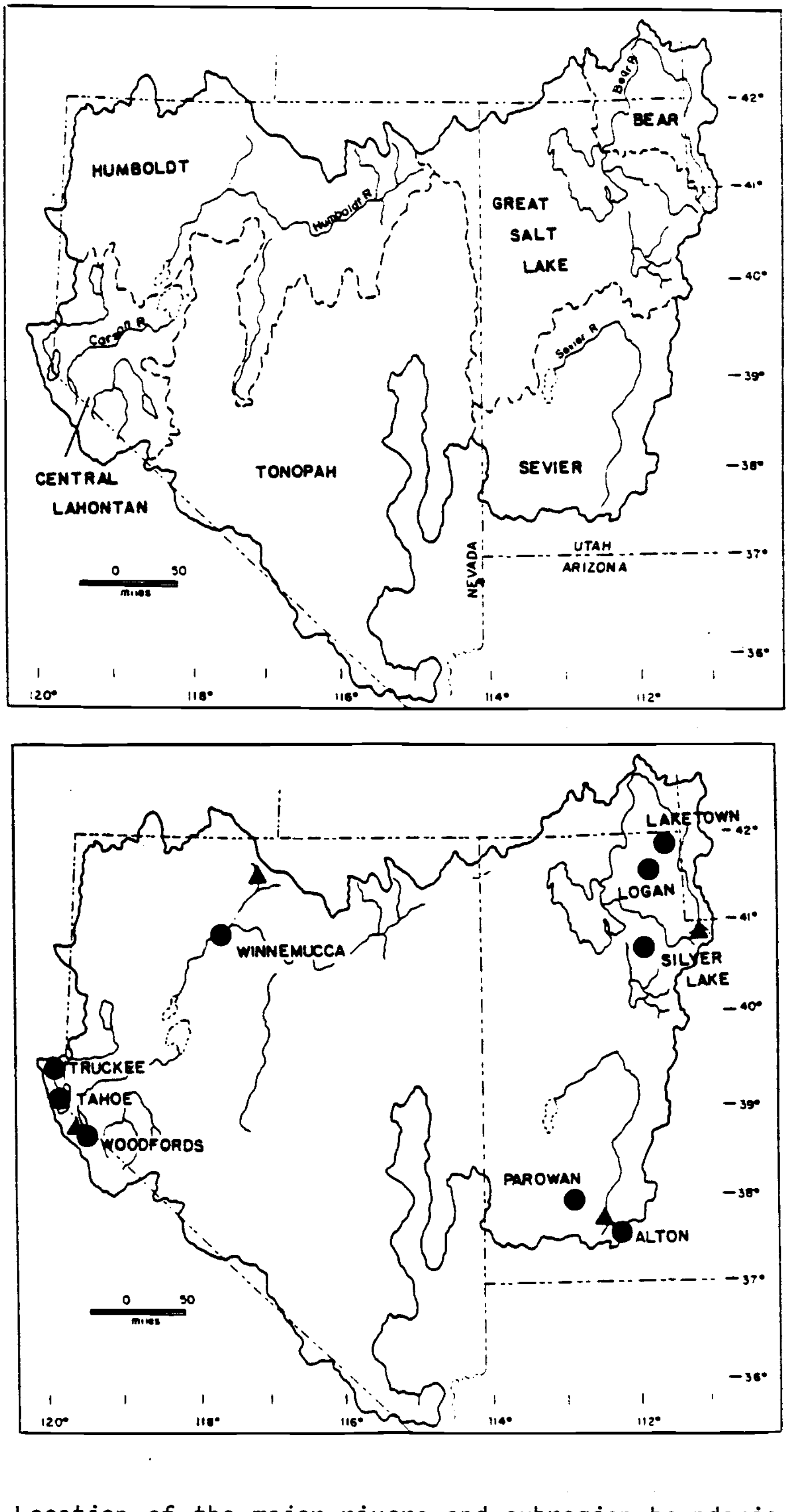


FIGURE 7. Location of the major rivers and subregion boundaries (top map) and the streamflow gages (▲) and climate stations (●) (bottom map) in the Great Basin region.

1. West fork of the Carson River at Woodfords, California (Subregion 1604, Central Lahontan).
2. Martin Creek near Paradise Valley, Nevada (Subregion 1603, Humbolt-Tonopah).
3. Bear River near the Utah-Wyoming State Line (Subregion 1601, Bear-Great Salt Lake).
4. Sevier River at Hatch (Subregion 1602, Sevier Lake).

Gaging station characteristics are listed in Table 5 and their location shown on Figure 7.

Climatic stations were located as near the stream gaging stations as possible. Stations used and the relationship between climatic data and streamflow are shown in Table 6; locations are shown on Figure 7. Because most climatic stations are located at lower elevations and do not adequately represent runoff-producing areas, both temperature and precipitation had to be adjusted for different elevational zones before they could be used in the model. Inputs to the water balance model were varied, always within reason, until a good agreement was obtained between the model output and gaged streamflow. Comparative statistics for observed streamflow and model runoff are listed in Table 7 and time-series plots for each watershed are shown on Figure 8. The most notable discrepancies occurred during peak flow years. Other variations can usually be explained by areal variations in precipitation that were not reflected by climatic station records.

Once verified, the model was run again with various climatic change scenarios superimposed on the input data. The following were considered:

1. Warm and dry (+2^{o}C; -10% precipitation)
2. Warm and very dry (+2^{o}C; -25% precipitation)
3. Cool and wet (-2^{o}C; +10% precipitation)
4. Cool and very wet (-2^{o}C; +25% precipitation)

Although the warm-dry scenario is deemed most likely to occur, the two more extreme changes (warm and very dry; cool and very wet) may reflect conditions that have occurred either in very wet years or periods of

Table 5. Characteristics of Gaging Stations Used to Verify Model Results.

Basin Reference	Gage Name	Drainage Area (sq mi)	Mean Flow (af/yr)	Gage Elev (ft)	Remarks
CARSON	W. Fork Carson R. at Woodfords, CA	66	79,024	5,760	1 small diversion 1 reservoir (cap. 1500 af)
MARTIN	Martin Creek near Paradise Vly, NV	172	22,796	4,700	div. for irrigation of 40 acres
BEAR	Bear R. near Utah-Wyoming State Line	176	135,465	7,965	div. for irrigation of 2,800 acres
SEVIER	Sevier R. at Hatch	340	88,836	6,870	2 small diversions

Table 6. Characteristics of Climate Stations used as Model Input.

Station Name	Elev	Mean Annual Ppt (in)	Mean Annual Temp	Correlation Gage with: Ppt	Correlation Gage with: MRO	Gage	Period of Common Record
Tahoe	6230	31.52	42.9	.94	.93		
Truckee	5995	31.09	42.5	.93	.93	Carson	1943-81
Woodfords	5670	20.73	49.3	.90	.87		
Winnemucca	4297	7.87	48.7	.60	.64	Martin	1921-81
Logan	4780	17.35	48.0	.47	.60		
Laketown	5980	11.63	38.2	.55	.54	Bear	1943-81
Silver Lake Brighton	8740	42.21	36.4	.75	.78		
Alton	7040	16.56	45.7	.57	.58	Sevier	1941-81
Parowan	5930	12.16	49.3	.53	.51		

Table 7. Comparative Statistics for Observed Streamflow and Model Runoff Under Current Climatic Conditions.

Record	Mean (acre-feet)	St Dev (acre-feet)	Skew	N	Correlation (Mod with Obs)
CARSON					
Observed	72,131	27,581	.29	40	.96
Model	72,099	33,375	.53		
MARTIN					
Observed	23,109	11,622	1.06	58	.64
Model	23,070	11,987	.57		
BEAR					
Observed	135,459	32,358	-.10	39	.80
Model	138,518	31,453	-.50		
SEVIER					
Observed	77,566	34,450	.91	41	.83
Model	79,745	49,873	1.41		

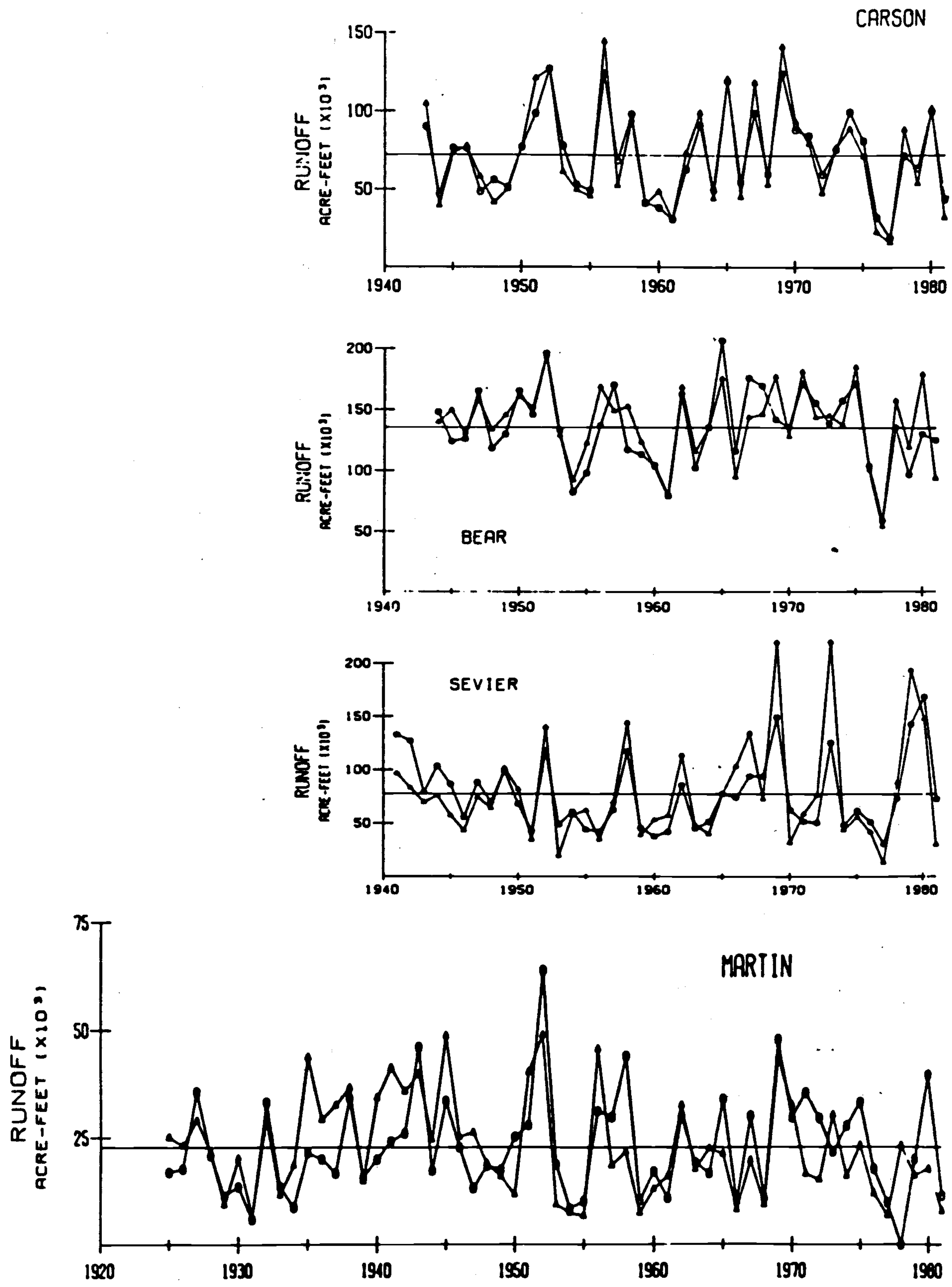


FIGURE 8. Observed discharge and model predictions for West Fork Carson River, Upper Bear River, Sevier River and Martin Creek of the Great Basin region.

Table 8. Summary of Changes in Model Outputs for Climatic Change Scenarios.

Basin	Scenario	Model Inputs		Model Outputs		Change in RO
		PPT	PE	ET	RO	
CARSON	Cool, Very Wet	44.2	30.3	15.3	29.0	+ 40%
	Cool, Wet	38.9	30.3	13.8	24.9	+ 20%
	Current	35.3	32.8	14.6	20.7	
	Warm, Dry	31.9	35.3	14.7	17.2	- 17%
	Warm, Very Dry	26.5	35.3	13.6	12.9	- 38%
MARTIN	Cool, Very Wet	16.5	32.6	12.2	4.3	+ 76%
	Cool, Wet	14.5	32.6	11.2	3.3	+ 35%
	Current	13.2	35.3	10.8	2.4	
	Warm, Dry	11.8	37.9	10.1	1.8	- 28%
	Warm, Very Dry	10.0	17.9	8.8	1.2	- 51%
BEAR	Cool, Very Wet	35.2	27.3	13.8	21.1	+ 46%
	Cool, Wet	31.0	27.3	13.2	17.7	+ 22%
	Current	28.3	29.7	13.7	14.5	
	Warm, Dry	25.6	32.2	14.1	11.3	- 22%
	Warm, Very Dry	21.3	32.2	12.9	8.3	- 42%
SEVIER	Cool, Very Wet	24.2	35.9	17.0	7.4	+ 68%
	Cool, Wet	21.5	35.9	15.7	5.8	+ 31%
	Current	19.5	38.7	15.2	4.4	
	Warm, Dry	17.6	41.5	14.4	3.3	- 25%
	Warm, Very Dry	14.6	41.5	12.5	2.2	- 50%

drought. For instance, the very heavy snowfall during the winter of 1982-83 produced serious flooding in Salt Lake City and other localities at the foot of the Wasatch Mountains in Utah. The same snowpack caused unprecedented flooding in the Lower Colorado River Valley because large releases of water had to be made from storage reservoirs to accomodate inflow from the runoff-producing regions in the Colorado Rockies. Under persistant conditions of this kind, additional flood control measures would be required to protect life and property.

Results of the scenario runs are summarized in Table 8. For the moderate changes reductions in runoff ranged from 17 to 28 percent and increases from 20 to 35 percent. When expressed as a percentage of the present mean, changes in runoff were more severe for the drier basins. This suggests that basin aridity may be a dominant factor in determining runoff response to climatic change. This does not mean, however, that the impact of climate is more severe in arid regions. In absolute terms, as opposed to percentage change, losses or gains are greater in more humid basins. In the Carson and Bear models, for instance, each inch of precipitation change produced essentially the same amount of runoff. In constrast, the response was about 0.5-inch of runoff for each inch of precipitation change in the drier Martin and Sevier basins.

The real impact of a change in water supply can best be evaluated in conjunction with water need. Should a shift toward a cooler and wetter climate occur, current water shortages would be alleviated. Seasonal shortages could still occur, as reservoir storage in many areas is not sufficient to guarantee flows throughout the irrigation season. As mentioned above storage facilities would also have to be examined from the standpoint of flood control as greater winter precipitation would produce higher flow levels during the snowmelt season.

Since the more likely change for the Great Basin Regions is toward a warmer and drier climate, the effect of this scenario was determined by superimposing it upon the WRC's Water Adequacy Analysis for the year 2000. (WRC, 1978, Vol. 3, Appendix III). This was done for each month and the results are shown on an annual basis in Table 9. The supply figure was determined by reducing the WRC's 1975 values for "Assessed Total Supply" by the appropriate percentage runoff reduction projected by the water balance model (from Table 8). Estimated future consumption was taken directly from the WRC estimates for the year 2000.

Higher use to supply ratios are evident for all regions under the warmer and drier climatic scenario. The Sevier and Humbolt-Tonopah

Table 9. Effect of warmer and drier climate on water supply and in supply/use ratios. (mgd)

	SUPPLY			DEMAND		USE AS % OF SUPPLY		
WRC Subregion:	1975	% Reduction warm/dry scenario	2000	Off-stream	In-stream	Off-stream	In-stream	Total
Bear-Great Salt Lake	2849	-22	2222	1266	1656	57	75	131
Humbolt-Tonopah	922	-28	664	1337	554	202	83	285
Sevier Lake	472	-25	354	561	278	159	79	237
Central Lahotan	1304	-17	1248	917	901	73	72	146
Basin	5547	-19	4488	4081	3389	91	76	167

Subregions show severe shortages, with offstream demand alone being up to twice the supply. The Central Lahontan and Bear-Salt Lake regions still show more than adequate water to meet offstream demands. Total use is markedly greater than supply, however, and conflicts between instream and offstream demands are likely to intensify. Such conflicts already exist. In the Truckee River area, for example, expansion of needed sewage treatment plants has been limited because the loading capacity of streams is already exceeded (Fordham, 1982). The Pyramid Lake fishery is threatened by declining lake levels and consequent water quality deterioration. The amount of inflow to the lake is currently under litigation, but the requirement for increased flow could put considerable strain on upstream users.

It should be emphasized that the WRC supply and demand projections were made for "average" conditions. If drought periods should be correspondingly drier, then the effect would be more severe than indicated. In addition, climatic change need not manifested only in the mean; it could also include changes in variance or persistence and these possibilities bring their own unique problems. Finally, even subregion-wide assessments are somewhat fictional as transfers of water are limited and each area is dependent primarily on nearby supplies. Locally, the situation could be better or worse than indicated here.

Water allocation is, even under present conditions, a pressing problem in many parts of the Great Basin. Droughts in the recent past have forced curtailment of irrigation and voluntary conservation among domestic users. Rights to existing supplies, even when adequate, are often in dispute, and the complex legal and institutional issues will take many years to settle.

Climatologists have suggested that a change to a drier climate is quite likely, and that this change might be felt within the next 20-30 years. It is imperative that governing agencies begin now to consider the implications of a reduction in water supply, and to include such a possibility in their planning.

Streamflow Variations

If global warming does occur as predicted, will climate become more or less variable? Although this is an important question, there is no clear-cut answer at this time. Much, of course, will depend upon how large-scale atmospheric circulation patterns might be altered, modified or otherwise changed. Thus in considering the possible effects of climatic variability on surface water supplies under a warmer and drier climatic regime, we can, at best, determine how past periods of drought and excessive precipitation have affected streamflow. We have investigated this by looking at long-time streamflow series in the various WRC regions of the western United States to determine a) variations in streamflow through time and b) correlations between different regions or subregions with regard to the occurrence of drought years which substantially reduce streamflow.

Streamflow was used as a measure of climatic variation since it tends to integrate the effects of both precipitation and temperature. It directly measures a precipitation-minus-evapotranspiration residual and represents an areal sum. As a consequence much of the noise inherent in local climatic stations is smoothed out.

Precipitation in the mountainous west reflects precipitation at higher elevations and thus overcomes the lowland bias of most weather records. Unfortunately a high percentage of streamflow records are distorted by diversion or regulations, leaving only a small subset of gages suitable for study. The 26-gage network selected for use (Figure 9, Table 10) represents six of the WRC Regions and 21 Subregions with varying degrees of coverage.

Table 10. Streamflow gages by number and location with drainage areas and mean annual flow.

MAP NO.	I.D. NUMBER[1]	REGION & SUBREGION[2]		DRAINAGE AREA (km^2)	MEAN ANNUAL FLOW[3] ($10^6 x m^3$)
1	06099550	Missouri	1002	8397	841
2	06207550		1004	2989	841
3	06441500		1005	8047	133
4	06452000		1005	26418	470
5	06478500		1006	55814	344
6	06707000		1007	1241	147[4]
7	06810000		1009	7267	947
8	06902000		1010	17819	3313
9	06933500		1010	7356	2142
10	08033500	Texas Gulf	1201	9420	2044
11	08095000		1203	2517	184
12	08167500		1205	3320	290
13	09306500	Upper Colorado	1401	10412	593
14	09085000		1402	3758	1076[4]
15	09166500		1402	1440	370
16	09498500	Lower Colorado	1503	11152	730
17	12354500	Pacific N.W.	1701	27736	6729
18	12134500		1706	1386	3604
19	12401500		1702	5750	1391
20	14113000		1702	3359	1454
21	13185000		1703	2150	1092
22	13302500		1704	9738	1784
23	13342500		1704	24786	13900
24	14243000		1705	5796	8344
25	14321000		1705	9539	6806
26	11213500	California	1803	2719	1295

[1]as in U.S. Geological Survey Water-Supply Papers.
[2]numbers follow U.S. Water Resources Council (1978)
[3]for period 1932-80.
[4]adjusted for intermountain diversions.

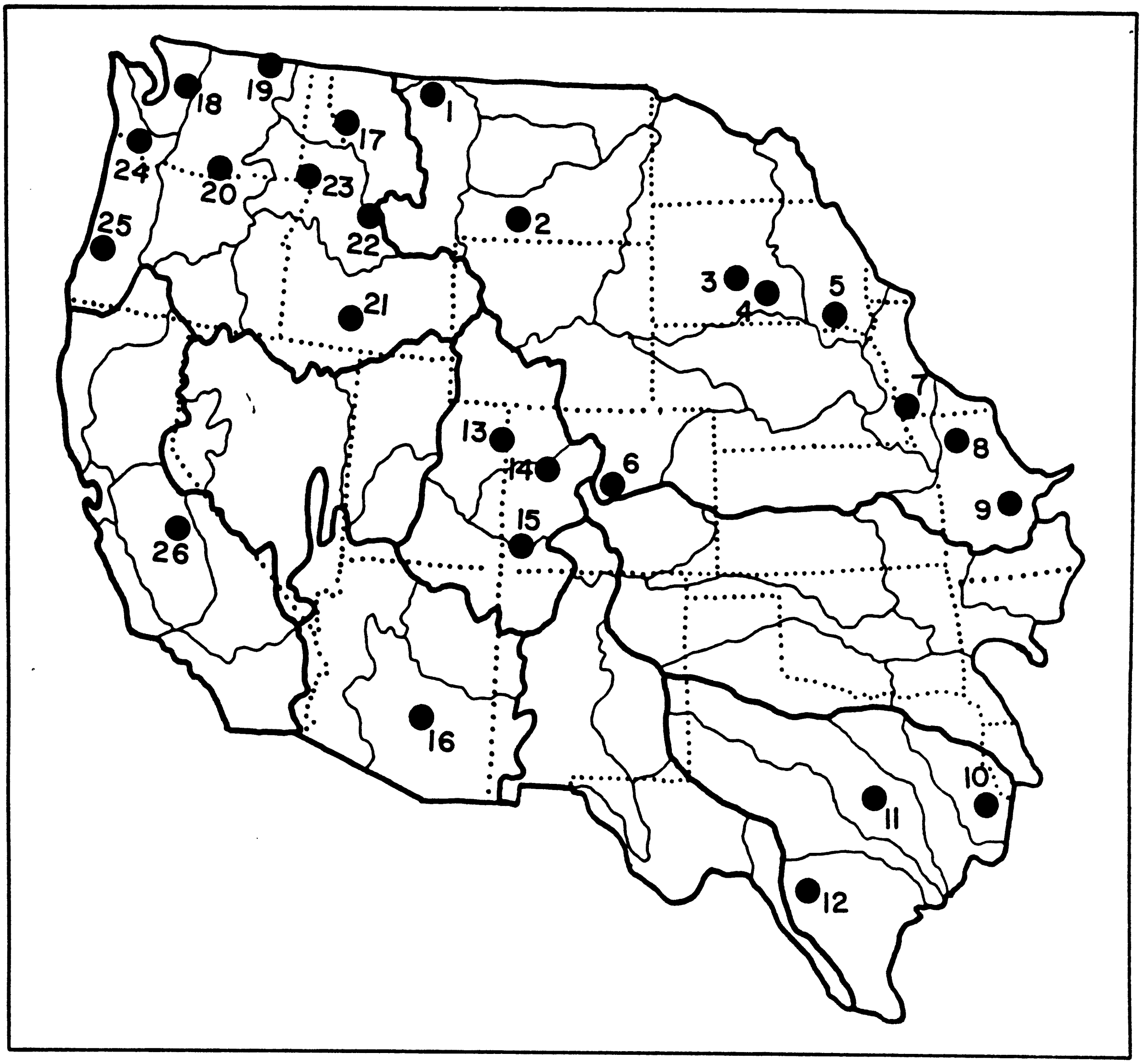


FIGURE 9. Locations of selected streamflow gages and boundaries of Water Resources Regions (thick line) and Subregions (thin line). Numbering follows Table 10.

Inter-regional Correlations

Correlation coefficients between the Upper Colorado regional series and subregional series from other regions 1932-80 are mapped in Figure 10. The wide band of positive values oriented SW-NE probably reflects the preferred orientation of winter storm tracks. Correlation drops off rapidly to the northwest, such that coefficients with all except the nearest of the subregions to the Pacific Northwest are essentially zero or negative. The correlation between regional series for the Upper Colorado and Pacific Northwest is -0.02. The pattern of correlation indicates that distances involved are great enough compared to the size of weather systems, so that shifts in the storm tracks produced compensating anomalies in the extreme reaches of the two regions. Northwest-southeast contrast is more obvious when the Pacific Northwest is used as the key region (Figure 11). A broad band of zero correlations is flanked on the south by significant (.05 level) negative correlations in Texas and Arizona. The only subregions positively correlated with the Pacific Northwest are those in the upper reaches of the Missouri Region, draining the adjacent eastern side of the continental divide.

The spatial variation in seasonal distribution of precipitation and runoff is another factor contributing to decrease of correlation of annual streamflow with distance is spatial variation in seasonal distribution of precipitation and runoff. The season of primary maximum in precipitation varies from late fall in the Pacific Northwest, to winter in California, to late spring over much of the Missouri and Upper Colorado, to summer in the Lower Colorado and Texas Gulf (Pike 1972). Cool-season precipitation and snowmelt are dominant components of annual streamflow in the mountainous West, but not in the Texas Gulf and lower reaches of the Missouri Region.

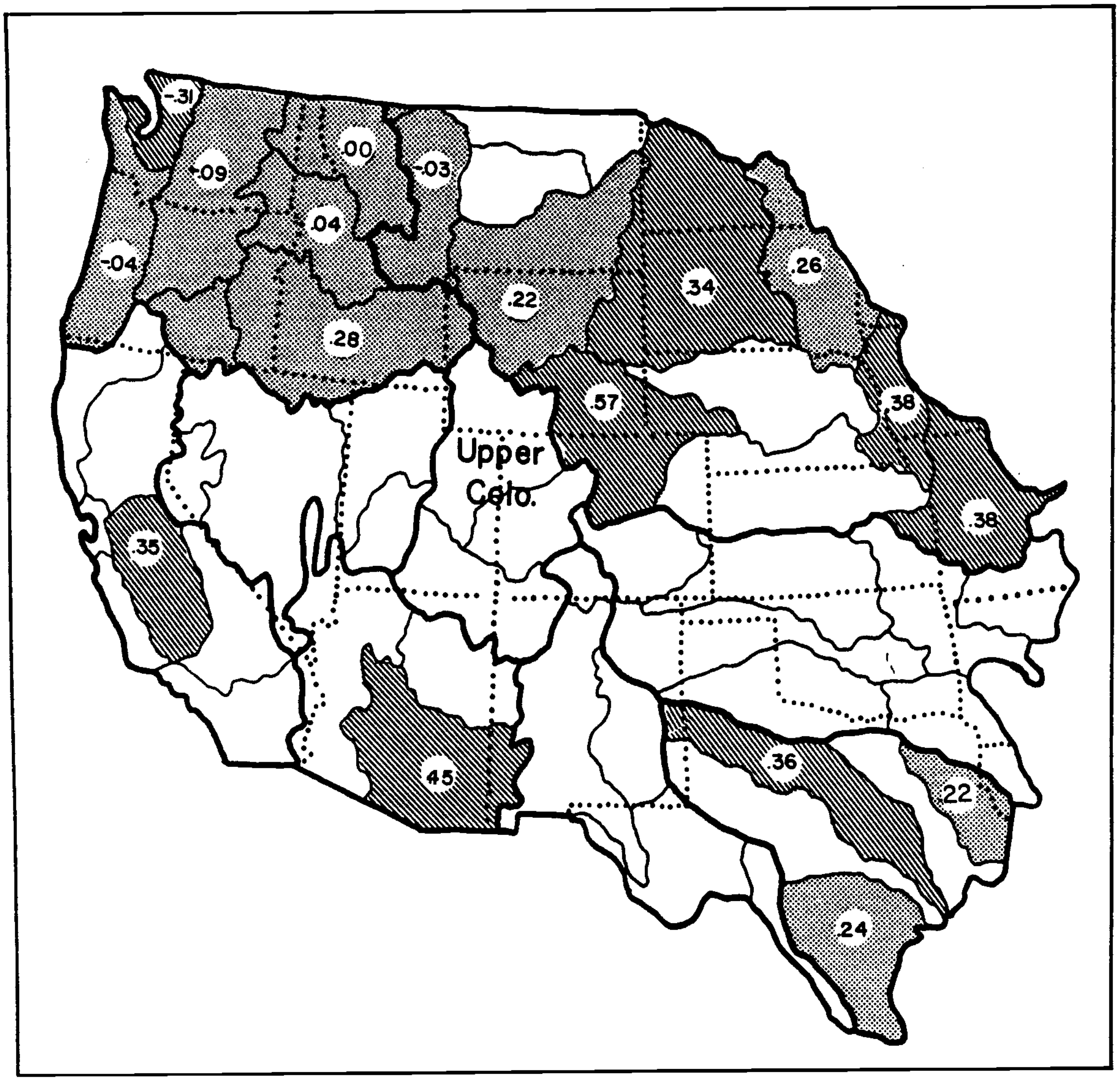


FIGURE 10. Correlation coefficients 1932-80 of various subregional streamflow series with the regional series for the Upper Colorado. Hatching represents significance at .05 level, and stippling non-significance at .05 level. Subregions outside the key region for which no data were analyzed are blank.

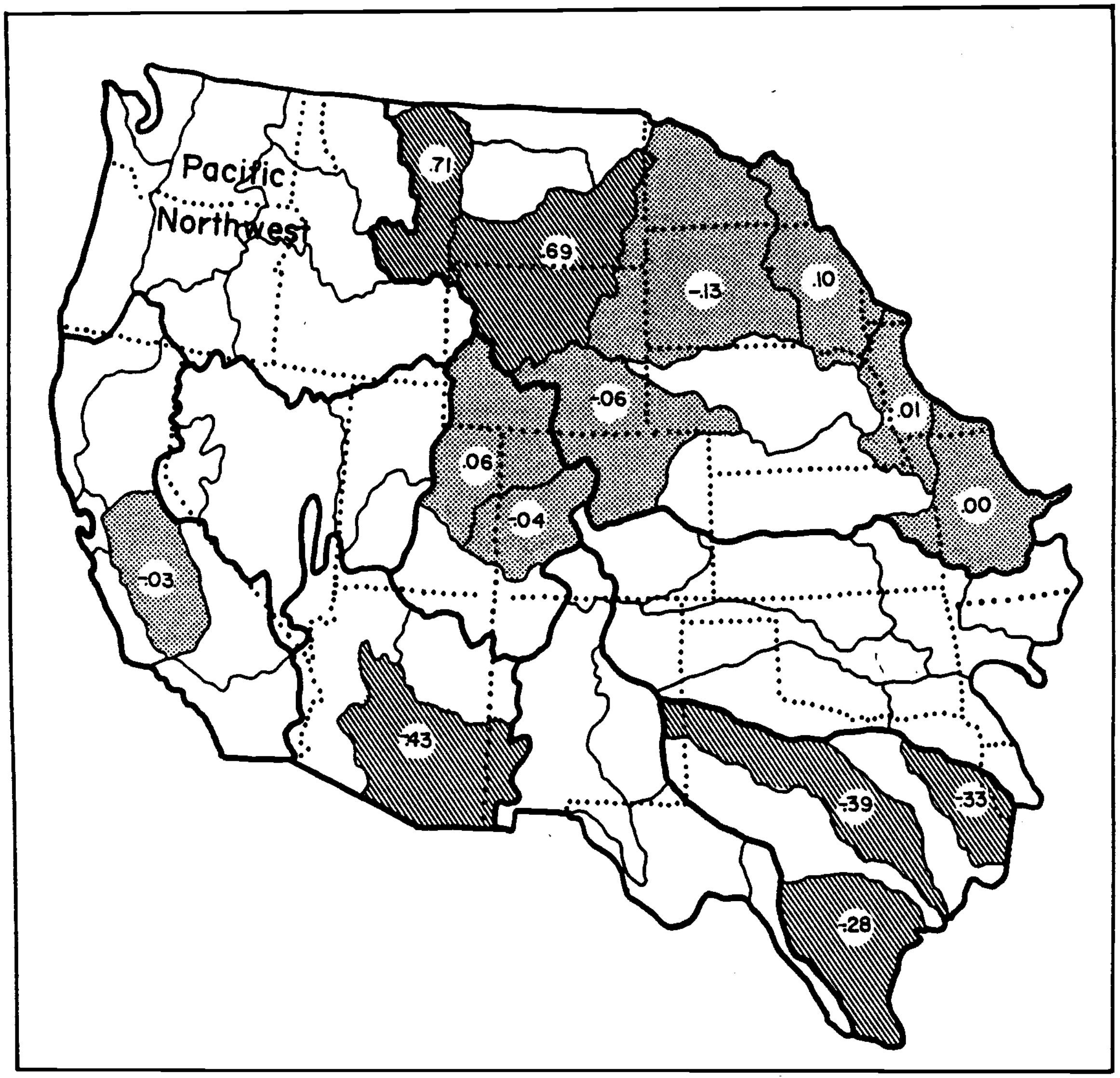


FIGURE 11. Correlation coefficients 1932-80 of various subregional streamflow series with regional series for the Pacific Northwest. Remainder of legend as in Figure 10.

Large-Scale Drought

The very low streamflows recorded in the Pacific Northwest, California, and the Central Rockies during the 1977 drought (Buchanan and Gilbert, 1977), suggests that the statistical picture given by the foregoing spatial correlations can be misleading. To study the simultaneous occurrence of drought in various regions in detail, an empirical definition of drought was adopted: a drought year was defined as any year among the driest 10 years (driest 20%) in a given regional series from 1932-1980. The analysis was restricted to regions whose streamflow was determined mainly by cool-season precipitation. A time series plot of regions in drought is shown in Figure 12. Regional streamflow as a percentage of the 1932-80 normal corresponding to the 10th-ranking dry year was as follows:

Upper Colorado	80
Lower Colorado	41
Pacific Northwest	79
California	59

In only one year, 1977, were all four regions simultaneously in drought. The meteorological conditions of the 1977 drought have been well-documented and reported by Namias (1978). A strong ridge dominated the upper level winter circulation over the western U.S. The mean position of the ridge line at the northwest coast and the exceptional strength of the ridge as measured by height anomaly at 700 mb were favorable for maximum effect on water basins throughout the West. Examination of upper air maps (Namias 1979) revealed that the 700 mb height patterns for other severe drought years over the western basins were moderated versions of the 1977 pattern. For example, during the winter of 1961 an anomalous (but weaker) ridge dominated the West and the position of the ridge line was inland from the Pacific Northwest coast at about 120^{o}; streamflow in 1961 was extremely

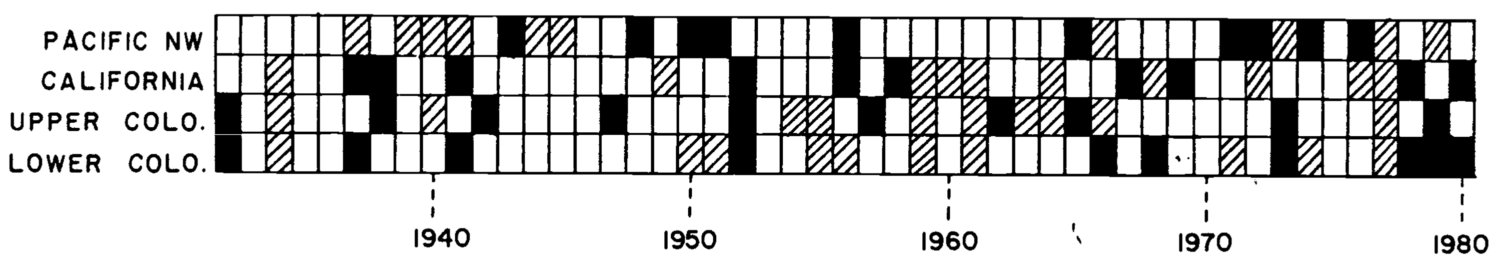


FIGURE 12. Drought years (hatched) and wet years (solid) in four regions, 1932-80. Drought (wet) years are defined as those with 10 lowest (highest) mean annual flows out of 49 years in the regional series.

low in the Upper and Lower Colorado Region but normal in the Pacific Northwest.

The winter and spring of 1977 was apparently an extreme outlier in producing low streamflow from the Pacific Northwest to the mountains of central Arizona. In fact, in agreement with correlation analyses discussed previously, large anomalies in the Pacific Northwest and the Southwest were often of opposite sign. Of the 10 driest years in the Lower Colorado Region, 5 were among the 10 wettest in the Pacific Northwest; conversely, 10 driest in the Pacific Northwest, 5 were among the 10 wettest in the Lower Colorado. Based on tests with a simple binomial model, the probability of this occurring by chance was $< .05$.

Similar analyses keyed on each of the four westernmost regions indicate that drought in the Pacific Northwest is generally not associated with simultaneous drought over any other region, including the California Region. This result is based on analysis of regional streamflow sums, and does not necessarily imply lack of correlation for adjacent subregions across regional boundaries. Note in particular that the California "region" is represented here by the Kings River, which drains only the central part of the Sierra Nevadas. Closer linkage with Pacific Northwest drought might be expected from watersheds in the northern Sierras. As for the Upper Colorado Region, severe droughts there were positively linked (.05 significance level) with droughts in both the Lower Colorado and California Regions.

Secular Trends

Identification of climatically-induced trends in streamflow series is complicated by the interdependence of surface water and ground water.

Although the surface-flow component of streamflow may reflect annual fluctuations in net precipitation (precipitation minus evapotranspiration), the base-flow component, that due to ground water, may require years to respond in some basins (McDonald and Langbein, 1948). An additional distortion is introduced in some basins by ground-water pumpage for irrigation and other uses. The following four gages were selected to minimize nonclimatic influences in evaluating long-term climatic trends.

RIVER	MAP NO.	PERIOD OF RECORD
Umpqua, Ore.	25	1906-80
Clark Fork, Mont.	17	1911-80
Roaring Fork, Colo.	14	1911-80
Salt, Ariz.	16	1914-80

The Umpqua drains from the Pacific slopes of the Cascade Mountains; the Clark Fork, a tributary of the Columbia River, drains from the central part of the northern Rockies; the Roaring Fork, a tributary of the Colorado, drains from the Front Range of the Colorado Rockies; and the Salt, a tributary of the Colorado, drains from the central mountains of Arizona. These series, though certainly insufficient for fine detail of geographic variations in runoff, serve to sample runoff in widely spaced mountainous areas where cool-season precipitation and snow melt are dominant components of streamflow. In view of the possible distortion of annual fluctuations by ground-water storage, a low-pass filter was applied to emphasize low-frequency variation. Filter specifications and filtered plots are shown in Figure 13.

A prominent feature in the plots of low-pass-filtered series is the divergence in trends between the northernmost rivers and the Salt River in the 1940's and 1950's. This behavior is in contrast to the parallel decrease for all four rivers in earlier segments, especially from the wetness

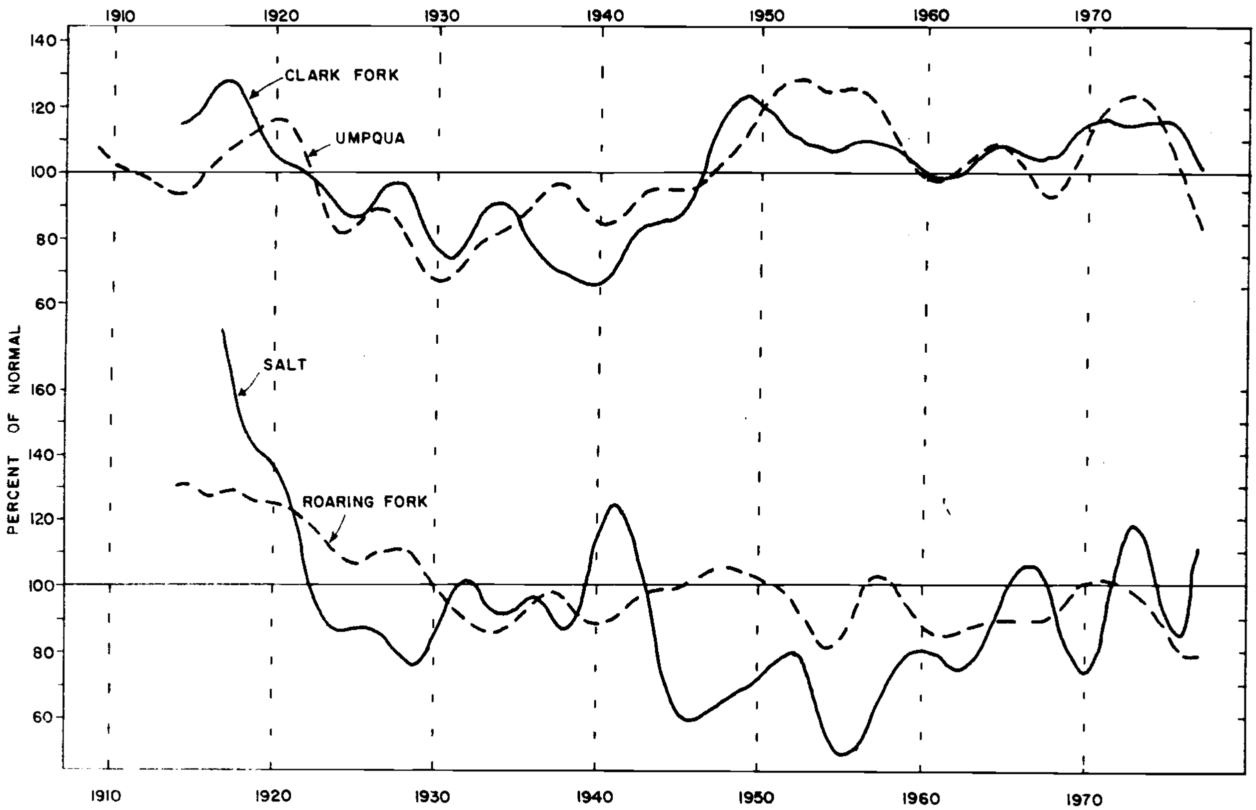


FIGURE 13. Low-pass filtered plots of mean annual flow of four long streamflow series. Y-axis is percent of 1915-80 normal. A raised-cosine filter (Hamming, 1983) with weights .2646, .2187, .1158, .0332 on lags 0 through ± 3 was used. Frequency response falls below .01 at wavelength 4.6 years.

of the 1910's to drought in the 1930's. The 1930's were drier than normal (1915-80 mean) in all four series. The early 1950's showed a spatial contrast, with extremely dry in the Southwest and extremely wet in the Northwest coast as reflected in the Umpqua series. After a widespread drought centered about 1961, flow in all four rivers gradually increased through the early 1970's.

The time series trends evident in Figure 13 can be explained in terms of trends in precipitation and temperature. The streamflow trends for the Clark Fork and Roaring Fork Rivers, which drain from the Rockies at latitudes 47^{o}N and 39^{o}N respectively, parallel secular trends in Rocky Mountain precipitation and temperature (Bradley et al. 1982). The low-frequency variation in precipitation reaches peaks (wet) in the 1910's, 1940's and 1970's; and troughs (dry) in the 1930's, and late 1950's to early 1960's. The time series plots for Montana and Colorado (Bradley et al. 1982) also show that, particularly for spring and summer, major wet anomalies tended to be cool, and dry anomalies warm. Variations in evapotranspiration therefore likely acted in concert with those of precipitation in producing the observed low-frequency streamflow anomalies.

The strong opposition of streamflow anomalies between the two Pacific Northwest rivers and the Salt River (Arizona) from the mid-1940's to late 1950's (Figure 13) appears to reflect climatic influences in different seasons. Summer rainfall contribution to the annual flow on the Salt River probably cannot be ignored, and summer rainfall in Arizona declined steadily from the 1910's to the mid-1940's (Bradley et al. 1982). Over the same period, Blasing and Lofgren (1980) show a marked decrease in frequency of a summer surface pressure pattern associated with northward and westward displacement of the Bermuda High. Winter precipitation also declined steadily in Arizona from the 1910's to the mid 1950's, with steepest, decline after 1940 (Bradley et al. 1982; Sellers, 1960). Interestingly, streamflow in the northern Rockies and Cascades increased dramatically at this time.

Results of eigenvector analysis of monthly precipitation (Sellers, 1968) and winter cyclone frequency (Diaz and Fulbright, 1981) indicate a pronounced northward shift in winter storm track in the late 1940's and 1950's. The observed low-frequency contrast from above normal streamflow in the Montana Rockies and Oregon Cascades to slightly below normal in the Colorado Rockies to much below normal in the mountains of central Arizona (Figure 13) is compatible with such a shift.

Comparison of low-frequency streamflow variations on the Clark Fork River (Montana) and Salt River (Arizona) (Figure 13) suggest two types of epochs: one with anomalies of the same sign in the northern and southern parts of the western U.S. (1910's to early 20's) and another with anomalies of opposite sign (late 40's to early 50's). These epochs may be associated with preferred modes of variation in atmospheric circulation. Sellers (1968), in a study of monthly precipitation patterns in the West 1931-66, concluded that two of the most important eigenvectors probably represented 1) east-west shifts in the mid-latitudes pressure systems and 2) north-south shifts in the storm track. The observed streamflow epochs may represent periods when one of these features dominated over the other. Some association with larger-scale atmospheric circulation characteristics is suggested by Dzerdzeevskii's (1962) plots of departure from normal of zonal and meridional components of the general circulation in the Northern Hemisphere. The plots for seasons most important to streamflow (those other than summer and autumn) indicate that meridional flow dominated in the 1910's and zonal in the late 40's and early 50's.

Magnitudes of Anomalies

The large magnitude of low-frequency streamflow variations (Figure 13) points to an uncertainty in ascertaining mean annual supply from available record lengths. This difficulty is illustrated by a test of difference of means 1914-46 versus 1947-80 for the seven records extending back to 1914 (Table 11). Gages in the northern Rockies and Pacific Northwest showed a 20% increase in mean between the two periods; gages to the south showed a 15-20% decrease. A "t" test (Panofsky and Brier, 1968) revealed that the means of the four northernmost gages increased significantly (.05 level) while the mean of the Roaring Fork River in the Upper Colorado decreased significantly. The decreases in mean in the remaining southern series, although even larger as a percentage of normal than on the Roaring Fork,

Table 11. Mean annual streamflow for sub-periods.

Gages[1]	Region	Mean Flow[2]		Ratio[3]
		1914-46	1947-80	
1	Missouri	763	926	1.21
10	Texas Gulf	2311	1845	.80
14	Upper Colorado	1273	1125	.88
16	Lower Colorado	856	719	.84
18	Pacific Northwest	6023	7344	1.22
22		986	1150	1.17
25		6053	7131	1.18

[1] as numbered in Table 10.
[2] $10^6 \times m^3$
[3] ratio of 1947-80 mean to 1914-46 mean.

were not significant at the .05 level due to the relatively large standard deviations of the flows.

Streamflow variations on the Colorado River are of particular importance because of the Upper Colorado Basin's strategic importance to water supply in the West. The flow of the Colorado River at Lee Ferry, Arizona, is a measure of outflow from the entire basin. The dominant component of that flow is snowmelt runoff from mountainous areas: 85% of the streamflow comes from 15% of the area of the basin (Stockton and Jacoby, 1976). Magnitudes of streamflow anomalies 1924-78 were examined for the flow at Lee Ferry and for two subseries -- the Regional Upper Colorado series and the series for the Roaring Fork River (gage no. 14 in Figure 9). Some statistics (1924-78) of these series are as follows:

RIVER	AREA(km^2)	MEAN-ANNUAL FLOW($10^6 m^3$)	AVERAGE RUNOFF(cm)
Roaring Fork, Colorado	3758	1131	30.0
Upper Colorado Regional	15600	2128	13.6
Colorado River	279460	17219	6.2

The Roaring Fork is clearly a very small sample of entire water supply of the Upper Colorado Basin, but it is from the central part of the important runoff-producing higher elevations.

To facilitate comparison with frequently-used 30-year climatic normals, series were first converted to percent of 1924-78 normal, which differs only slightly (0.1%) from the 1941-70 normal for the Lee Ferry record. Time series variations in decadal-average anomalies on the relatively small Roaring Fork River closely track variations in the total flow of the Colorado River (Figure 14). This observation testifies to the representativeness of the Roaring Fork of the key runoff-producing areas of the Colorado watershed. Expressed as percent of 1924-78 normal, extreme anomalies of various length were consistently more severe for the total flow of the Colorado River than for the relatively small tributary, the Roaring Fork (Figure 15). Possible reasons for this unexpected result are that the flow at Lee Ferry includes contributions from many arid and semi-arid watersheds whose flows are extremely sensitive to changes in precipitation, and that the precipitation anomalies associated with very low annual flows are large enough in spatial extent to simultaneously affect widely separate watersheds within the Colorado Basin.

Although the projected effects of increasing CO_2 on temperature and precipitation over the Colorado Basin are uncertain, some perspective on a reasonable scenario can be gained by comparing the anomalies shown in Figure 15 with the 29% reduction that Revelle and Waggoner (1983) estimate would take place in the flow of the Colorado River if climate over the basin were to warm by 2^oC. The 29% value corresponds approximately to the level of the driest 3-year period since 1906 on the Colorado River. In the driest single year (1977), flow was 64% below normal. The critical distinction between an anomaly and a CO_2-induced reduction is that a CO_2 effect would likely be a lowering of the mean rather than a flucuation. The large surface-storage capacity of the Colorado system (U.S. Geological Survey, 1970), while mitigating the effects of transient anomalies in flow, would only delay inevitable water shortage under a reduced mean flow. Note, however, that changes in 30-or-40-year "means" on the order of 20% have been characteristic of series of annual streamflow over much of the western United States in this century (Table 11).

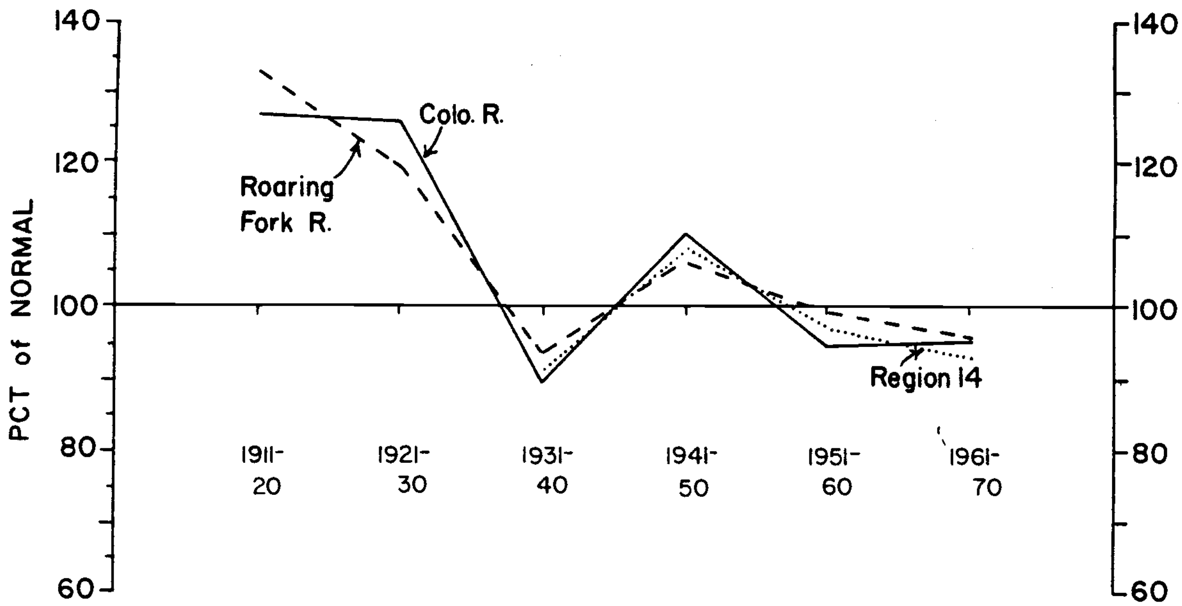


FIGURE 14. Decadal-average anomalies (as percent of 1924-78 mean) for three streamflow series from Upper Colorado Region. The Colorado River at Lee Ferry, Arizona, is the outflow series for the entire Upper Colorado Basin. The Roaring Fork drains from the Front Range of the Colorado Rockies. The Region-14 series includes flow of the Roaring Fork plus the White River, Utah, plus the Dolores River, Colorado.

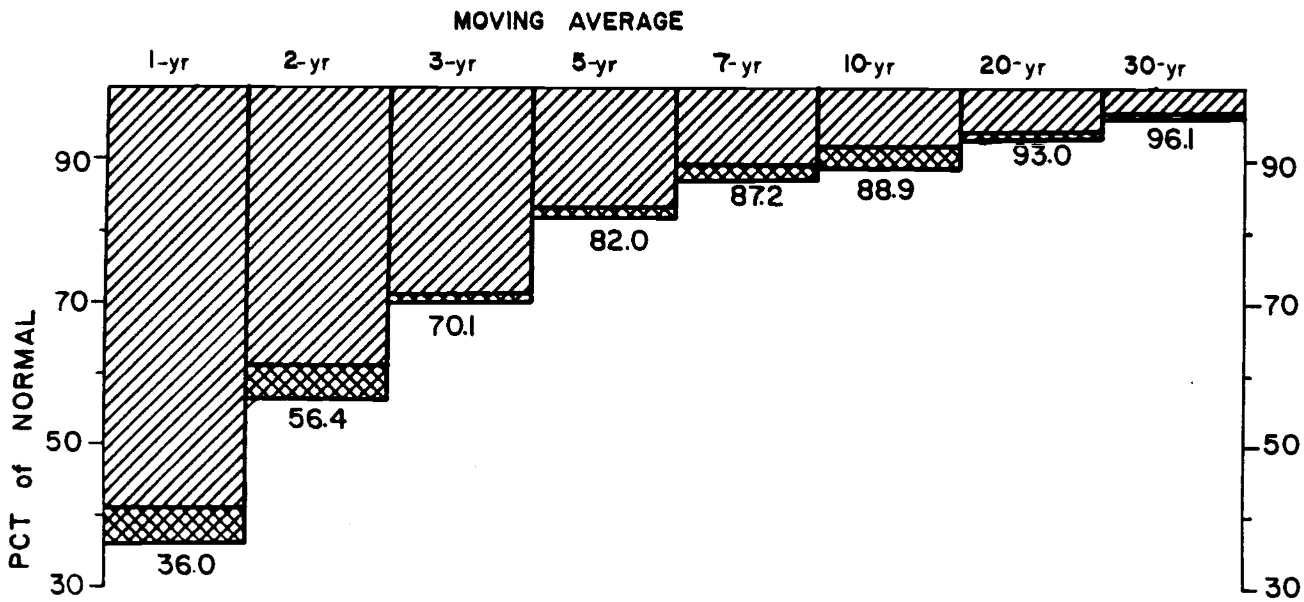


FIGURE 15. Extreme anomalies (as percent of 1924-78 mean) of streamflow for moving averages of various lengths on Roaring Fork River (hatched) and Colorado River at Lee Ferry, Arizona (cross-hatched). The period for analysis was 1914-78, but the same values apply for the longer 1906-78 period in the Lee Ferry flow.

Great Plains Droughts

The Great Plains extends from the Canadian to the Mexican border and is generally considered to include the area between the Front Range of the Rocky Mountains eastward to about the 98th meridian of longitude. The latter essentially represents the 20-inch isohyet of precipitation which, in turn, marked the transition between the tall-grass prairies and forest to the east and short-grass prairies characteristic of the Great Plains at the time of settlement. The area includes several of the WRC regions and subregions used elsewhere in this report. The work reported here represents an extension and refinement of our research reported in previous NSF-sponsored projects. It was made possible by a greatly expanded tree-ring data base from collections made by ourselves and others. (See Appendix I for data on new sites collected from 1980-1983).

The Great Plains might well be more severely affected by a change to a more arid climate than any other area in the United States. Much of the region's economy depends on irrigated agriculture which in 1977 included about 26.5 million acres. Approximately half of the irrigation water came from groundwater with the Ogallala aquifer as the main source. The Ogallala is being rapidly depleted and the overdraft is considered serious in many areas. (Borrelli, 1981).

During historic times the Great Plains have been the victim of repeated droughts which, occurring about every other decade, have disrupted agriculture and caused economic hardship. The miseries caused by the "dust bowl" drought of the 1930's, although well-documented, are but a part of history except for those who actually experienced or witnessed the consequences. The dust-bowl producing mechanisms are still in place and could be triggered by another severe drought or a trend toward aridity. Hence both of these factors are important parameters for long-range planning for agriculture and water resources. Unfortunately weather records rarely extend beyond late 1800's and are too short to establish secular trends.

Our earlier use of tree rings as a proxy data source to reconstruct the occurrence of large scale drought in the western United States (Stockton and Meko, 1975) was seriously limited by a lack of sites near the eastern and western borders of the Great Plains. New sites collected in 1982 from the eastern sections of Wyoming and Montana, together with chronologies provided by other workers in Iowa, Oklahoma and Arkansas have greatly enhanced the tree-ring data base from the mid-section of the country. We have utilized these new data to reconstruct the occurrence of drought back to A.D. 1700 for four areas centered around Iowa, Oklahoma, eastern Montana and eastern Wyoming (Figure 16). The objective was to place two major droughts of this century (1930's and 1950's) in long-term perspective and to seek evidence of the 22-year periodicity reported in our earlier work (Mitchell et al. 1979). Results of the present study have been reported in detail by Stockton and Meko (1983).

Considering intensity, duration and areal extent, the droughts of the 1930's and 1950's were at least equaled in magnitude by drought periods in the mid-to-late 1750's; early-to-mid 1820's; mid-1850's to late 1860's; and the 1890's. Although the 1930's drought included three closely spaced dry years (1934, 1936, 1939) this period was not as severe as droughts centered around 1757 and 1830 when conditions were averaged over 3 to 10 years. Given the margin for error in the reconstructions, 1936 might well be the most severe single drought year experienced by the regions as a group during the 278 years of tree-ring records.

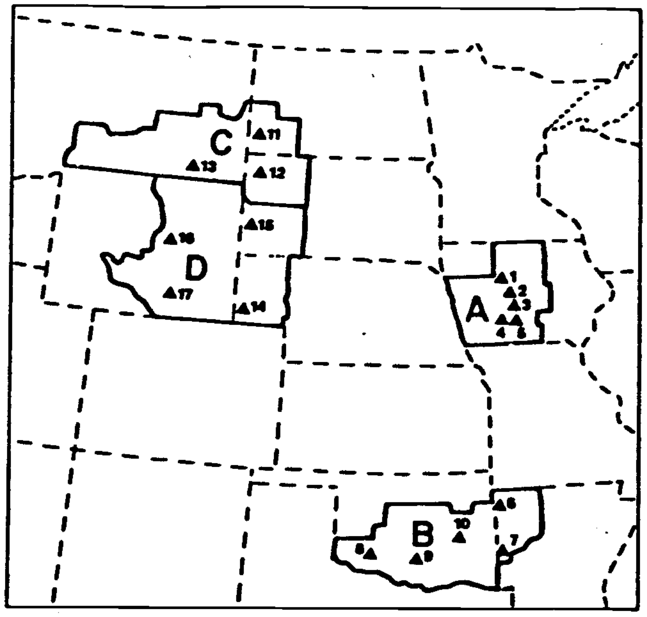


FIGURE 16. Map showing regions and tree-ring sites used for the reconstruction of the occurrence of drought back to A.D. 1700 for the four areas centered around Iowa, Oklahoma, eastern Montana and eastern Wyoming.

Drought and non-drought years tended to cluster in all of the regional reconstructions (Figure 17). Drought years clustered most noticeably in the late 1750's and 1860's. The persistent recurrence of dry years in those periods was unmatched even in the 1930's. Stretches of 10 or more drought free years in any of the regions occurred only once or twice per century. The most striking such period was from 1825-1838, immediately following the extreme drought of the early 1820's.

Empirical probability calculations suggest that the most severe drought year of the 1930's had only a 2% chance of being exceeded in a given year; the corresponding probability for the worst year of the 1950's was 5%. In terms of 10-year moving averages the 1930's were exceeded 5% of the time, the 1950's, 12% of the time. The clustering of dry years makes extrapolation into the future rather risky. Once a drought regime begins,

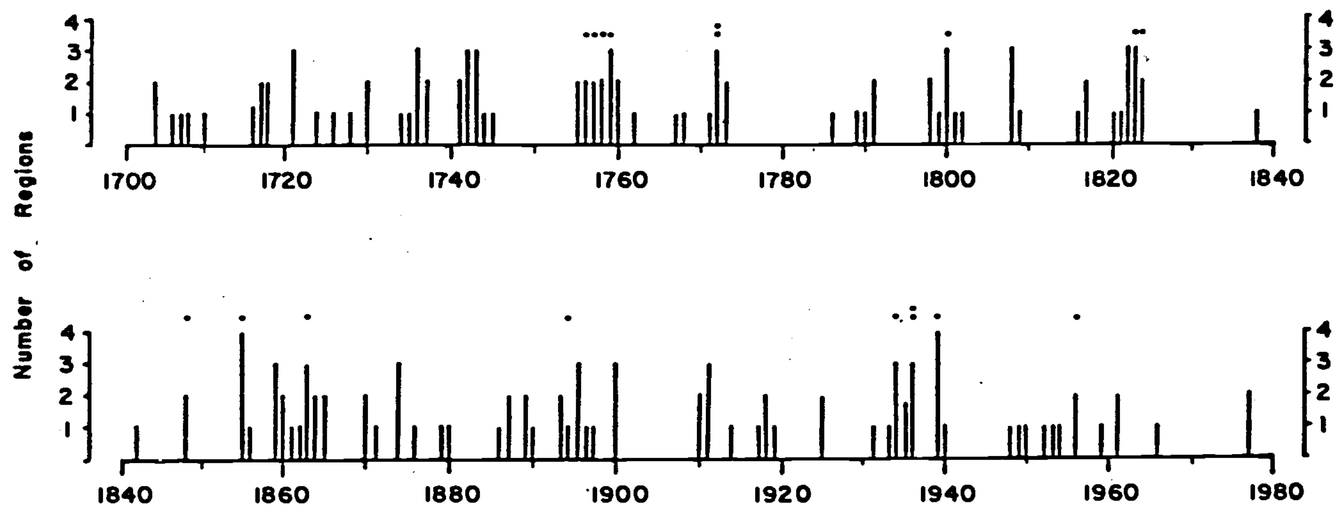


FIGURE 17. Number of regions reconstructed in drought for years 1700-1977. Bars indicate number of regions with reconstructed precipitation at least one standard deviation below 1933-77 normal. Dots mark year in which precipitation was at least two standard deviations below normal in one or more regions. Standard deviations were computed from 1933-77 reconstructed regional series.

drought probability for a given year may be higher than indicated by straightforward empirical probabilities.

When averaged over the four regions (Figure 18) the recurrence of drought was rhythmic, with an average period of about 19 years. The periodicity, however, was not characteristic of all regions nor of all segments of the drought record in any region. The Iowa and Oklahoma regions contributed most to the 19-year periodicity in the mean series. Even in those regions, the 22-year and 17-year periodicities were not stable over time. A near 22-year rhythm was most clearly defined in the latest 88 years (1890-1978), less clearly in 1801-1889 and not at all from 1714-1801. The results emphasize the point that drought rhythm in one location cannot be generalized to all locations within the Great Plains.

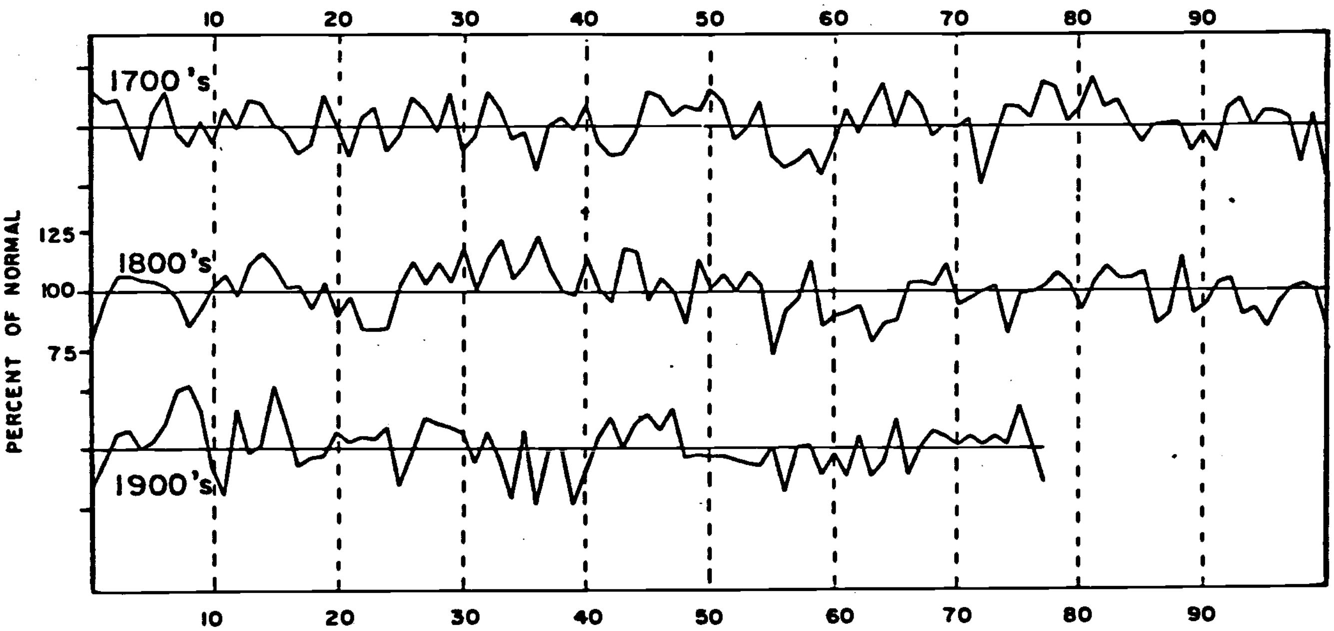


FIGURE 18. Time series plot of average of four regional reconstructions. Regional reconstructions were converted to percent of 1933-77 normal before averaging.

Inferences on Water-Supply Variation from Tree Rings

The well-known correlation of tree-ring variations with drought established by previous NSF supported studies, raises the possibility of extending our knowledge of spatial patterns of streamflow variations back several hundred years. We have shown (section entitled "Streamflow Variations") that streamflow in the western United States has been characterized by:

- large low-frequency variations that make 30-year means quite unrepresentative of long-term conditions.
- epochs of high-flow or low-flow years where the sign of the streamflow anomaly is the same along a north/ south transect of the Rocky Mountains throughout the U.S.
- epochs of opposite anomalies in the north and south.

Tree-ring data collected between the years 1962 and 1981 in the interior western United States were used to infer the long-term history of these spatial features so clear in historical, streamflow data.

The area of study and locations of sites or groups of sites are shown on Figure 19. The area is roughly bounded by longitudes 102°W and 111°W and by the northern and southern boundaries of the United States. This area was divided into northern, central and southern regions, which were further divided into subregions. Regional and subregional boundaries are shown in Figure 19. The southern region was the most intensively sample (74 tree-ring sites); the central region was of special importance because of its coverage of the Upper Colorado River Basin (37 sites); the northern region was most sparsely sampled (25 sites), but of great interest because much of the region had been unsampled prior to the present collections which were supported by the current NSF grant. The network shown in Figure 19 allows us to examine regional tree-growth variations along a longitudinal transect which passes through the central Rocky Mountains of Colorado, a major runoff producing area for several major streams.

Regionalization of Tree-ring Data

Analyses were restrictd to the 1700-1962 period common to all tree-ring sites. Subregional series (e.g. 1a, 1b, 1c, 2a, . . .) were computed by averaging chronology indices from all sites in a subregion and converting the average sites to Z scores by subtracting the 1700-1962 mean and dividing by the standard deviation. Regional series were computed by averaging subregional Z-score series together. The resulting series were then converted to regional scores corresponding to regions 1, 2 and 3 (northern, central and southern) in Figure 19.

Time series plots of the low-pass filtered regional tree-ring series (Fig. 20) show remarkable region-to-region similarities, but with periods of marked regional contrast. The 1905-1920 period is unique for intensity

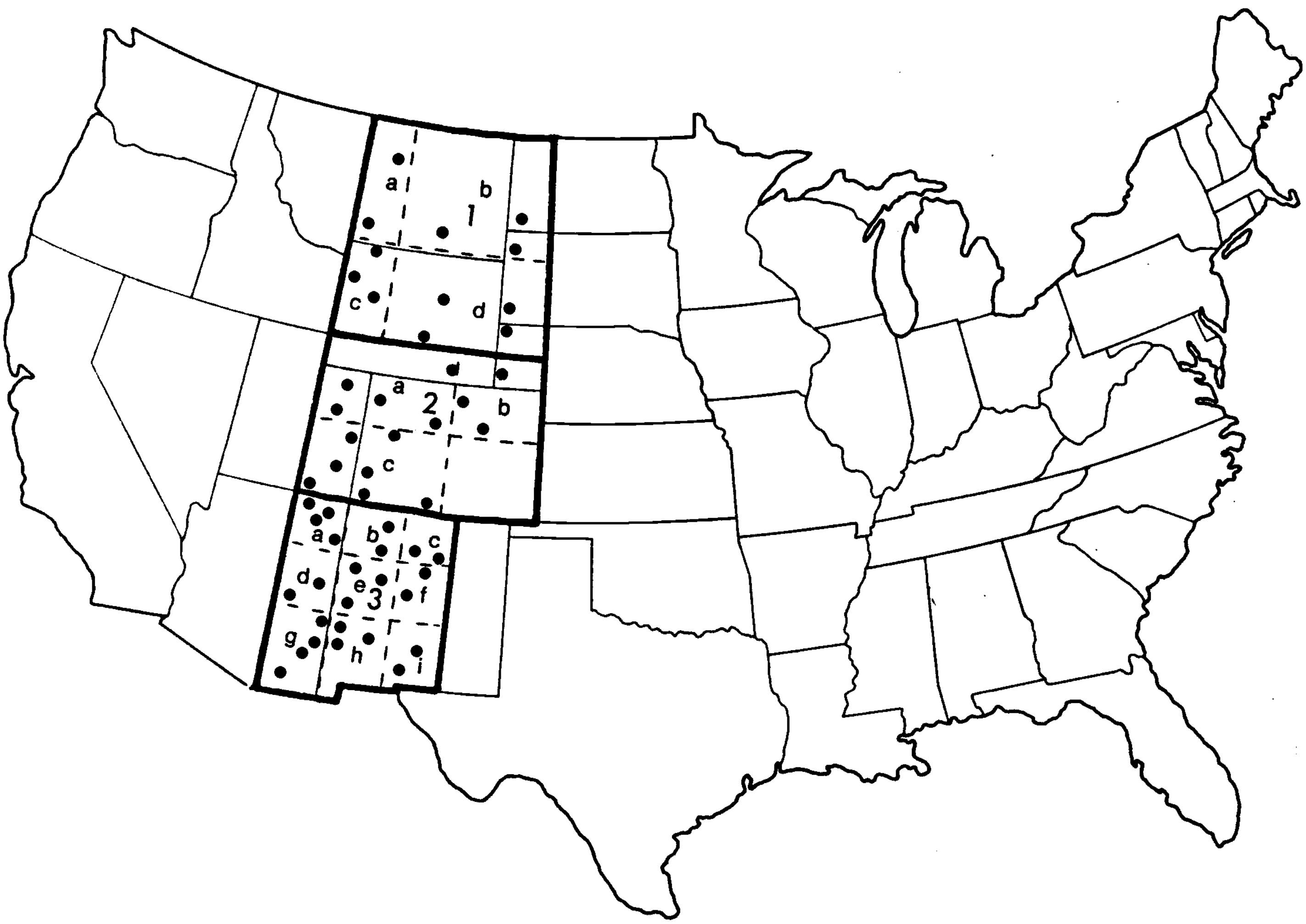


FIGURE 19. Map showing tree-ring regions (thick solid line), subregions (dashed line), and general locations of sites or groups of sites (dots). Subregions are referenced in text as 1a, 1b, etc.

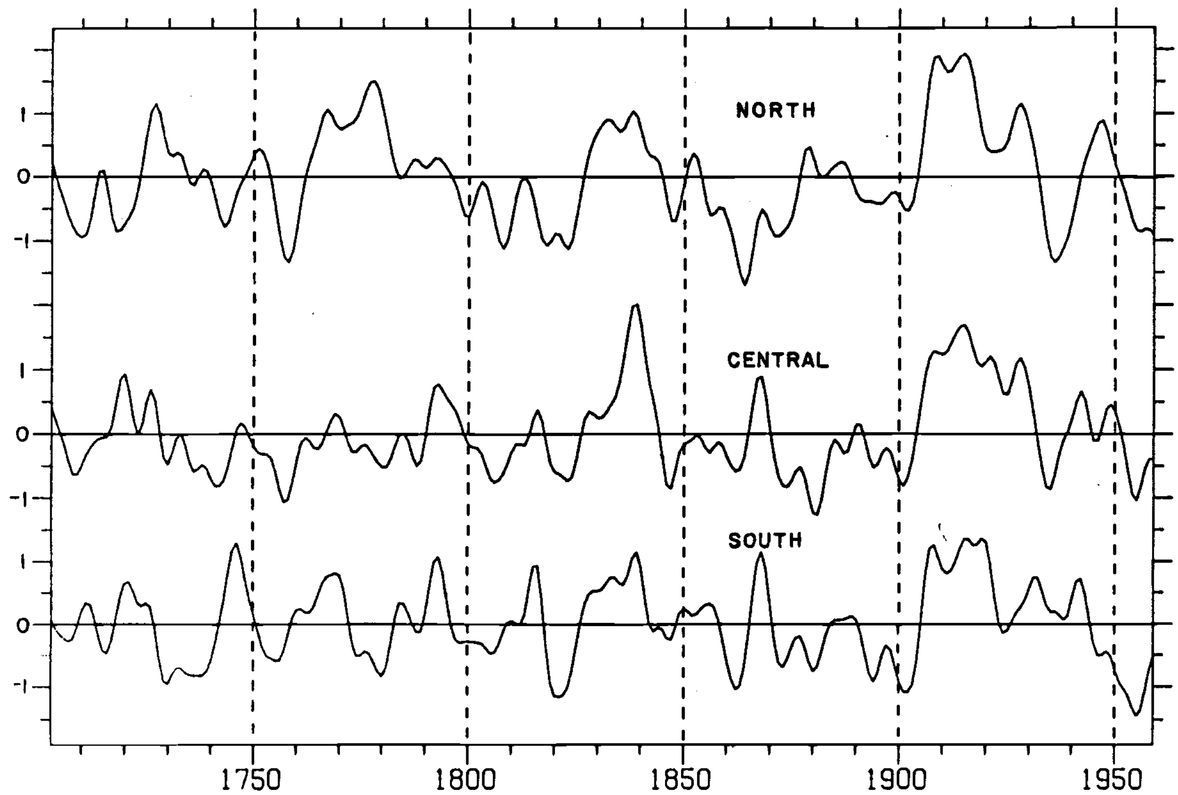


FIGURE 20. Time series plots of regionally averaged tree-ring series. Series were converted to Z scores and then filtered with a bell shaped (raised cosine) filter with frequency response of 0.5 at a wavelength of about 8 years. "North, central and south" refer to regions 1, 2, and 3, respectively on the map in Figure 19.

and duration of high growth in all three regions. The only period even remotely similar was centered in the late 1830's, though growth anomalies were not nearly as great then as in the 1910's. Some low-growth periods were apparently centered to the north and some to the south. In the present century the 1930's was a "northern" drought, the 1950's a "southern". Other droughts that can clearly be distinguished as "northern" and "southern" were centered at the following times:

Southern	Northern
1730	1757
1778	1863
1902	

The distinction here often lies in a gradation of extreme drought to mild drought along a latitudinal transect, rather than from drought to wetness. A drought which occurred about 1820 was equally dry in the north and south.

Earlier in the "Streamflow Variations" section north to south contrast in streamflow was interpreted as evidence of a zonal mode of circulation with the storm track passing either farther north or south than normal. One of the primary spatial modes of tree-growth variations as indicated by the second eigenvector of the 16 subregional tree-ring series (Figure 21b) also is a north/south contrast. The most important tree-growth eigenvector (Figure 21a), on the other hand, represents anomalies of the same sign in all subregions. Eigenvector #1 would be expected to dominate in periods of meridional atmospheric flow, and eigenvector #2 in periods of zonal flow. In years with a large positive amplitude for eigenvector #2 the storm track was most likely displaced northward; in years with a large negative score on eigenvector #2 the track was probably displaced southward.

Several observations can be made from time-series plots (smoothed) of amplitudes of eigenvectors #1 and #2 (Figure 22). First is the striking

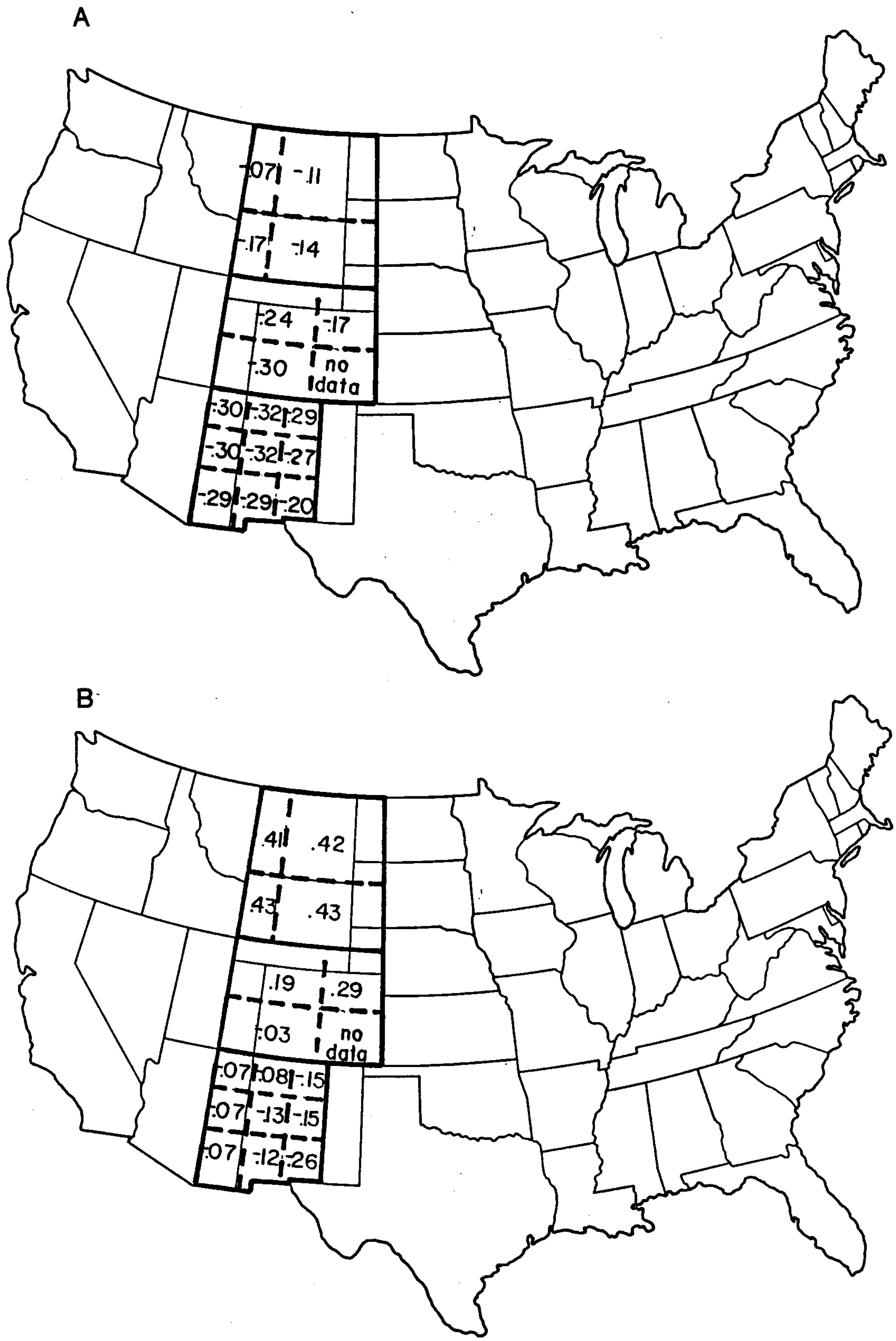


FIGURE 21. Eigenvector weights on subregional tree-ring series. (A) First eigenvector, (B) second eigenvector. Eigenvector computed on period using 16 subregionally averaged tree-ring series for 1700-1962.

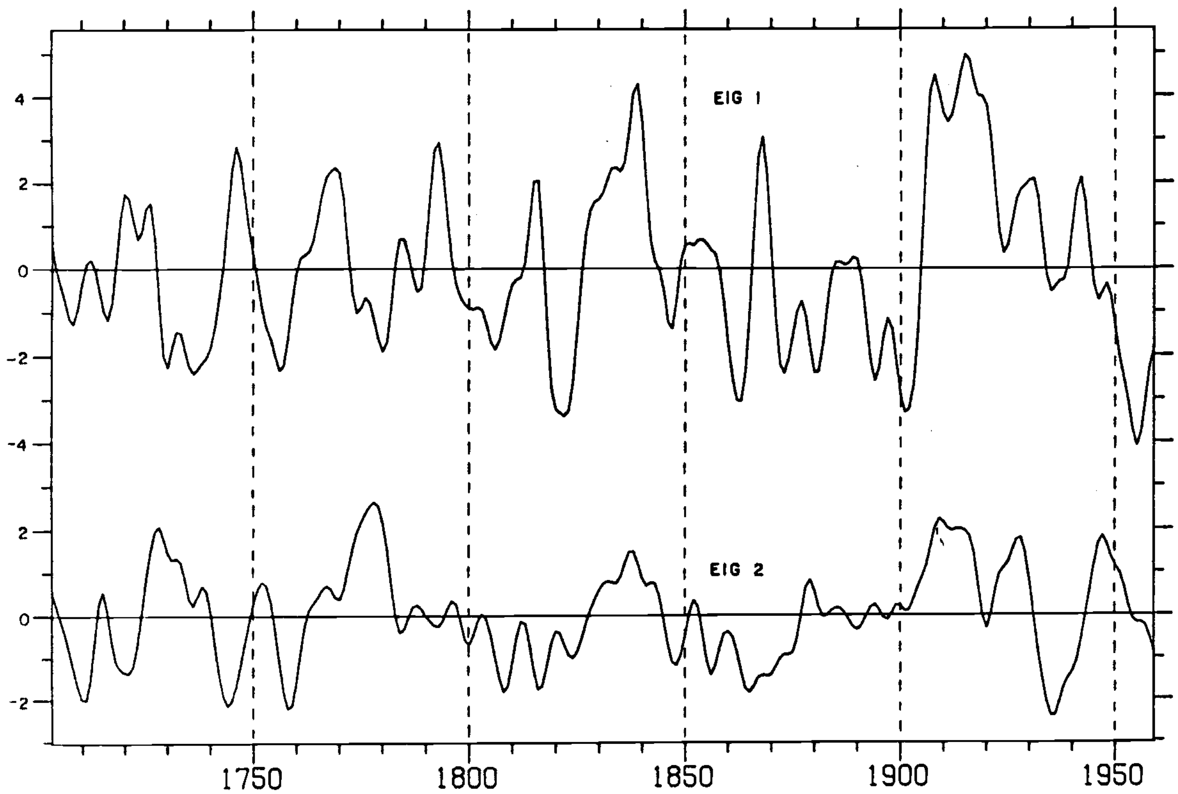


FIGURE 22. Time-series plots of eigenvector amplitudes for first two eigenvectors whose weights, are shown in Figure 21. The sign for eigenvector #1 has been reversed so that positive values correspond to wet conditions. Series were filtered with the low-pass filter described in legend for Figure 20.

dominance of eigenvector #1 from 1905-20, implying unsurpassed general wetness at that time; eigenvector #1 again dominated toward the end of the 1950's; except with the sign of the amplitude reversed -- dry conditions everywhere. In contrast, periods centered on 1935 and 1947 were dominated by eigenvector #2 : dry north centered on 1935, dry south on 1947. For no other time back to A.D. 1700 does tree-growth imply such a rapid (within 10 years) swing of storm tracks from north to south or vice versa. The general conclusion from the eigenvector amplitude plots in Figure 22 is that the current century's climate at the longitude and latitude of this study has been notable for both extremes of wetness and drought, and for extremely rapid shifting of the storm track within a generally zonal regime of atmospheric flow.

A picture very similar to that given by the eigenvector amplitude plots is shown by the time series of the average of tree-growth anomalies for the far north and the far south, and the difference between the two. Far north was defined as the averages of subregional series 1a and 1b and far south as the average for subregions 3g, 3h and 3i in Figure 19.. The time series plots of these "average" and "difference" series (Figure 23) again clearly show the dominant wetness of 1905-1920, and the north/south contrast in the 1930's and 1940's. Unlike the plot of eigenvector #2, however, the difference series in Figure 23 suggest that northward shifts in the storm track similar to that near 1942 also occurred in the 1720's and 1870's. The eigenvector plots in Figure 22 are probably the more reliable of the two indicators because they are based on a much larger data set -- tree-growth data from 16 subregions as opposed to 5 subregions for Figure 23.

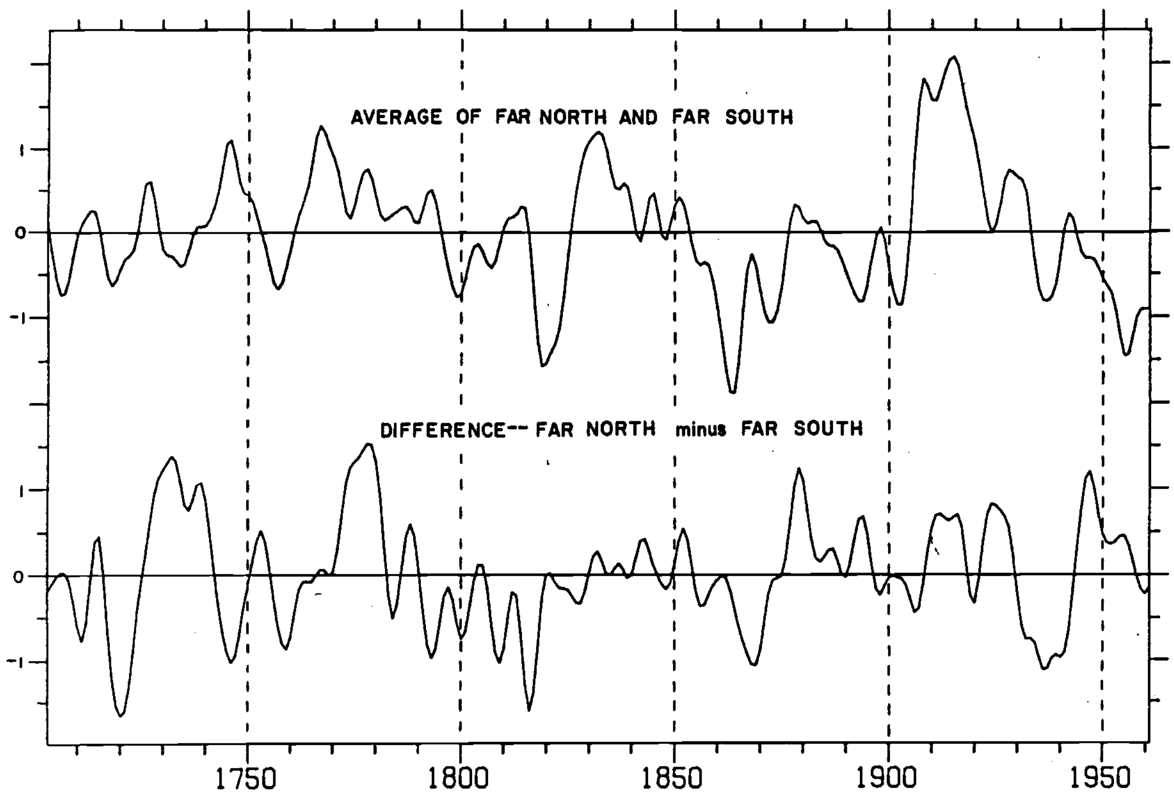


FIGURE 23. Average (top) and difference (bottom) series for tree growth in the far north (subregions 1a, 1b) and for south (subregions 3g, 3h, 3i). All tree-ring indices within the above groupings were averaged to form a "far north", "far south" series. The average of these two series is the top plot above. The difference "far north" minus "far south" is the bottom plot. Series were converted to Z-scores and filtered (see legend for Figure 20) before plotting.

Discussion

It is evident from the data presented here that surface water supplies in much of the western United States would reach critical stages should the warmer and drier climatic scenario become a reality. This is especially true when instream demands, considered necessary by some for recreation, preservation of scenic reaches and maintenance of habitat for fish and wildlife are added to the more conventional offstream uses. As Anderson (1982) points out, very few western streams can meet both the instream and offstream demands under present conditions.

Any diminution of present supplies is bound to cause increasing conflicts between users in regions where demand and supply are nearly equal. The present "crisis" in California might well typify conditions that are likely to occur throughout the west. The dilemma arises because water-rich northern California receives more than two-thirds of the rainfall while 60 percent of the population lives in the much more arid south. Southern California presently imports about 4.7 million acre feet of water from the Colorado River but will lose 650,000 acre feet of this amount when the Central Arizona Project is completed during the latter part of the present decade. Thus southern California argues that it needs more water from the north to meet present and projected demands. The Peripheral Canal Proposal, designed to partially meet this need by diverting water from the Sacramento-San Joaquin Delta, was defeated by voters in 1982 (Engelbert and Scheuring, 1982).

Conflicts over water are not confined to California, as illustrated by the present dispute between the City of El Paso. Texas, and the State of New Mexico. El Paso with a population approaching one-half million and still growing rapidly, is largely dependent on groundwater which is rapidly being depleted. In an effort to meet demands the city obtained groundwater rights in southern New Mexico. The State of New Mexico, one of the driest in the country, promptly passed legislation to ban the export of water. This law was declared unconstitutional by the federal courts and New Mexico passed additional legislation to circumvent the court decision. El Paso is currently suing to have the latest law declared unconstitutional - and so ad infinitum.

Another conflict between states involves suits by Iowa, Missouri and Nebraska to prevent South Dakota from the annual selling of 20,000 acre feet of water from the Missouri River to the Energy Transportation Company. The water was to be used in a coal-slurry pipeline from the Powder River Basin of Wyoming to electric power plants in Arkansas and Louisiana. The original proposal would have used groundwater from the Madison aquifer and drawn from wells located in Wyoming. South Dakota contended that the main recharge for the aquifer was from the Black Hills area (South Dakota) and proposed the use of Missouri River water as an alternative. The conflict between the various States is of particular interest because the diversion involved a miniscule portion (about one-tenth of one percent) of the river's average annual flow and was considered a part of South Dakota's allocation from reservoirs on the Missouri.

The above examples are a likely preview of the conflicts that might well occur should surface water supplies be reduced by 20 to 30 percent, as suggested by our determinations under a warmer and drier climate. Greatest conflicts would likely be in regions where demand approaches or exceeds supplies as shown in Table 12. (Data in the table are based on the WRC (1978) report). The regional supply figures given by WRC for 1975 (column

2) were reduced by the amount determined in the water balance analyses for the warmer and drier climatic change scenario (column 3).

Based strictly on offstream demands, the most critical regions are the Rio Grande, Lower Colorado and Great Basin. The Rio Grande figure may be misleading for the lower part of the region as the WRC data do not include inflow across international borders. The Rio Conchos flows into the Rio Grande from Mexico at Persidio, Texas, about 200 miles southest of El Paso. For most of the time it provides permanent flow below the junction of the two rivers. The predicted supply/demand ratio (column 9) is probably accurate for the Rio Grande above Persidio.

Table 12. Comparison of regional annual water supply versus demand for year 2000 under existing 1975 and warmer and drier climate. Values are 1000 acre-feet

REGION	SUPPLY		DEMAND YEAR 2000[a]			USE AS % OF SUPPLY		
	Year 1975	Warmer-drier Climate	Off-strm[a]	In-strm	Total	Off-strm	In-strm	Total
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
10 Missouri	61,525	43,683	25,508	33,958	59,466	58	78	136
11 Ark-Wht-Rd	67,694	49,417	11,998	46,169	58,167	26	93	118
12 Texas Gulf	35,626	25,651	12,521	22,917	35,438	49	89	138
13 Rio Grande	5,309	3,663	4,801	2,287	7,088	131	62	193
14 Upper Colo.	13,956	9,630	3,960	7,947	11,907	41	82	124
15 Lower Colo.	8,296[b]	5,890	5,944	6,864	12,808	101	116	217
16 Great Basin	5,547	4,488	4,369	3,389	7,758	98	75	173
17 Pacific NW	268,523	220,189	17,279	214,004	231,283	08	97	105
18 California	68,050	54,440	30,385	32,607	62,992	56	60	116

[a]Includes evaporation from reservoir, etc.

[b]Amount given is inflow from the Upper Colorado. Regional input is negative due to excess of evapotranspiration over precipitation. Supply column has been adjusted by this amount.

The situation in the Great Basin would not be as severe as indicated because of the large amount of undeveloped groundwater reserves. Likewise, the large amount of reservoir storage on the Lower Colorado would cushion the effect of reduced inflows over a period of several years.

The addition of instream demands places all regions, even the water-rich Pacific Northwest, in a deficit position. It should be emphasized that the instream values are estimates by the U.S. Fish and Wildlife Service for optimal fish and wildlife conditions. The validity of these estimates may be subject to question.

Another point of emphasis is that all values used here are for average conditions and do not take variance into consideration. As pointed out in the Great Basin and Rio Grande studies, the occurrence of droughts would greatly heighten the impact of a warmer and drier climate. Even water-rich regions can be seriously affected by reduced streamflow during droughts. For example, the severe drought during the 1976-1977 water year reduced runoff of the Columbia River at The Dalles, Oregon, from a mean annual discharge of 131 MAF to 78.9 MAF. This exceeded the previous low-flow record of 84.9 set in 1925-26. The water shortage resulted in considerable reduction in electric energy production throughout the northwest where 80 percent of the electric energy is hydro-generated (Gordon et al. 1980). Had the drought lasted another year, as it did in California, severe shortages of electric energy would have occurred and anadromous fish population would have been threatened.

In California, where the drought lasted two years, the 1977 water year was the driest since records were started a century ago; the preceding water year, 1976. was the fourth driest. During 1976, precipitation was 65 percent of the average and dropped to 45 percent in 1977. Streamflow during the same water years was reduced to 47 and 22 percent respectively (Freeman, 1980). The impact was greatest in northern and central California, especially in municipal supplies where extreme conservation and curtailment measures had to be taken. The impact in southern California was relatively minor due to the importation of water from the Colorado River. Agriculture fared better than expected because of conservation measures and 20 percent increase in the use of groundwater. An estimated 7,500 new wells were drilled, existing old wells reactivated and others deepened during 1977 (Rischard and Tsao, 1980).

Should droughts, such as those discussed above, occur on top of reduced streamflow, the results would have been much more severe. Also, reduced streamflow, acting in concert with increasing demands, would mean that the effects of less severe drought periods would be amplified. As shown by tree-ring studies, longer and more severe drought periods have occurred in the past and that there is little reason to think that history will not be repeated in the future.

The obvious and all-important question is whether western regions can meet future demands for surface water if streamflow is reduced by an increasingly warmer and drier climate. The answer undoubtedly lies in whether water resource planners at local, state and federal levels will take the impending climatic changes seriously enough to incorporate the threat to surface water supplies into the planning process. Such a move would be a considerable departure from current procedures which essentially ignore the idea of climatic change as a planning parameter.

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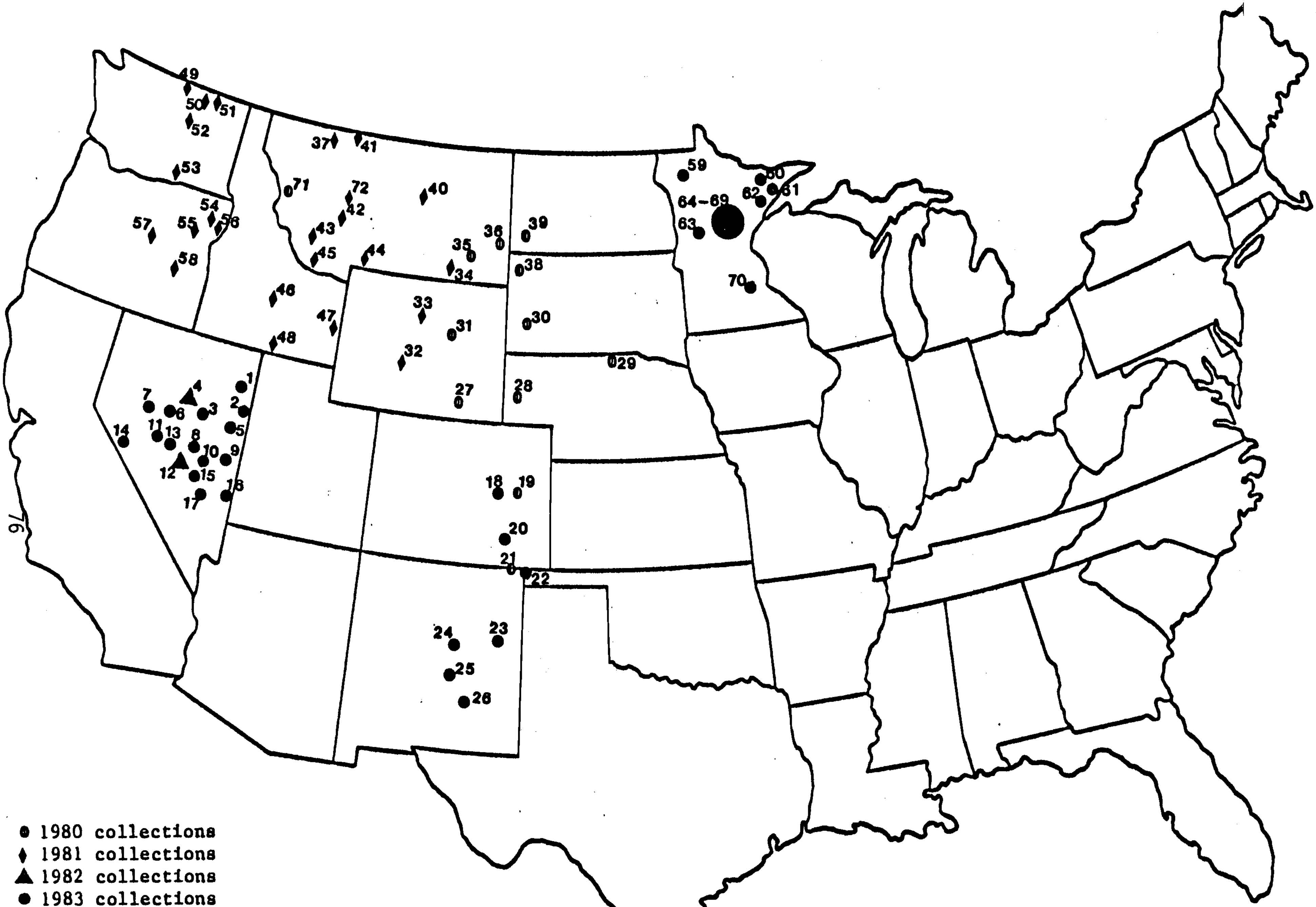
APPENDIX I

Map and listing of tree-ring sites collected by the Hydroclimatology Section of The Laboratory of Tree-Ring Research during 1980-84 as part of this grant.



Tree-ring data collections by Hydrology section.

Hydrology Section Collections 1980-1984

1. Pequap Summit,Nevada
2. White Horse Summit,Nevada
3. Diamond Mtns.,Nevada
4. Roberts Mtn.,Nevada
5. Pony Express,Nevada
6. Pete's Summit,Nevada
7. Carroll Summit,Nevada
8. Moody Mtn.,Nevada
9. Connor Pass,Nevada
10. Currant Pass,Nevada
11. Wall Canyon,Nevada
12. Morey Peak,Nevada
13. McCann Canyon,Nevada
14. Lucky Boy Pass,Nevada
15. Cherry Creek Summit,Nevada
16. Panaca,Nevada
17. Groom Mtns.,Nevada
18. Bijou,Colorado
19. Limon,Colorado
20. Smith Canyon,Colorado
21. Cimarron River,New Mexico
22. Kenton,Oklahoma
23. Tumacacori,New Mexico
24. Clines Corner,New Mexico
25. Gallinas Peak,New Mexico
26. Capitan Mtns.,New Mexico
27. Rock River,Wyoming
28. Scott's Bluff,Nebraska
29. Norden,Nebraska
30. Custer,South Dakota
31. Teapot Ranch,Wyoming
32. Atlantic City,Wyoming
33. Tensleep,Wyoming
34. Tongue River Reservoir,Montana
35. Otter Creek,Montana
36. Knowlton,Montana
37. Kiowa,Montana
38. Slim Butte,South Dakota
39. Burning Coal Vein,North Dakota
40. James Kip,Montana
41. Sweet Grass Hills,Montana
42. Helena,Montana
43. Divide,Montana
44. Gardiner,Montana
45. Dell,Montana
46. Ketchum,Idaho
47. Wayan,Idaho
48. City of Rocks,Idaho
49. Bonaparte,Washington
50. Quartz Mtn. Jct.,Washington
51. Sherman Creek Campground,Washington
52. Grand Coulee Dam,Washington
53. Griffin Peak,Washington
54. Joseph,Oregon
55. Westfork Lake Creek,Oregon
56. Lakefork Campground,Oregon
57. Table Mtn.,Oregon
58. Malheur,Oregon
59. Mud River,Minnesota
60. Ed Shave Lake,Minnesota
61. Old Pine Trail,Minnesota
62. White Pine Campground,Minnesota
63. Lake Itasca,Minnesota
64. Cass Lake,Minnesota
65. Pine Point,Minnesota
66. Coddington Lake,Minnesota
67. Clubhouse Lake,Minnesota
68. East Lake,Minnesota
69. Burns Lake,Minnesota
70. Wolsfeld Woods,Minnesota
71. Missoula,Montana
72. Raynesford,Montana