Precipitation Trends and Water Consumption Related to Population in the Southwestern United States, 1930–83

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ABSTRACT

The possible effects of climatic fluctuations on renewable water supplies in the western United States was examined, especially as it is impacted by the growth of population and water consumption in recent decades.

Precipitation fluctuations in the Colorado River Basin states have differed depending upon their location, but have tended to fluctuate with a time scale of one to two decades. Longer-term regimes may also be operative. For example, the Upper Basin states (Colorado and Utah) experienced a prolonged wet interval from about the turn of this century to around 1930; from 1930 to around 1978, drier than normal years tended to outnumber wet ones; and since 1978 the Upper Basin has been exceedingly wet. Lower Basin states also experienced the early wet period and drier conditions after the mid-1940s, but they undergo somewhat different alternations of wetness and dryness. However, from the point of view of water supply, precipitation variability in the Upper Basin, particularly in Colorado, is more critical.

Reservoir capacity in the arid western states is expected to gain little in additional storage capacity during the next couple of decades; in addition, withdrawal of water from the Colorado River is approaching the legal limits. The effect of a future prolonged drought on the order of those which have occurred in recent decades, or in a worse case, those inferred to have occurred in past centuries from tree ring studies, could have far more serious consequences than any in previous experience due to the large population increases in the region. These population trends show all signs of continuing, at least in the near future. The impact of a drought, however, would depend on the level of reservoir capacity that is present at the time of drought onset as well as its intensity and longevity; reservoirs in the West are presently at or near capacity.

1. Introduction

In most areas of the southwestern United States, the ratio of present consumptive use to the renewable supply of water is high, and water available for future development is limited (USGS, 1984). This USGS report points out that over time, 1) water withdrawals increase steadily and 2) storage and distribution facilities may fail to keep pace with this gradual uptrend in water demand. The result is a decline in the reliability of water supply, or conversely an increased vulnerability to drought. The USGS paper notes that this vulnerability can be ameliorated by building storage facilities, increasing underground withdrawals, and improving water resource management. However, it also notes that in recent years the rate of reservoir construction has slowed considerably. This has been accompanied by greater use of ground water supplies. Although the report recognizes that the best reservoir sites have already been developed, additional reservoir development to increase available supplies is still possible *with the exception of the arid Southwest* (USGS, 1984, Fig. 10, p. 27).

We have focused our study on this critical area of the United States. Our purpose is to assess the broad trends and combined effects of population, water usage (offstream and instream withdrawal of surface water sources) and precipitation variability since the 1930s. Despite the significant increase in reservoir capacity throughout the Colorado River Basin in previous decades, we present evidence suggesting that the degree of vulnerability to *sustained disruptions* in water supply from climatic anomalies of the kind experienced during the past 50 years has increased substantially. Given the projections of continual population and industrial growth in the area, plans must be made for the possibility of serious water supply shortages in the next couple of decades due to a prolonged drought (see also Diaz and Holle, 1984).

Most or all of the assessments of future water needs in the United States assume a stationary climate. That is, the projections take into account changes in economic activity but not in the *mean* climate state. In a study of dry and wet periods in the contiguous United States, Diaz (1983) showed that the western United States has a generally greater propensity for being in a situation where it is either "too wet" or "too dry" compared to other areas of the country. In Colorado, for instance, between 1906 and 1930, excessively wet conditions compared to the long-term mean prevailed for 200 out of 300 months; whereas between 1932 and 1940, 80 out of 108 months were categorized by much drier than normal conditions compared to the long-term averages. Therefore, the

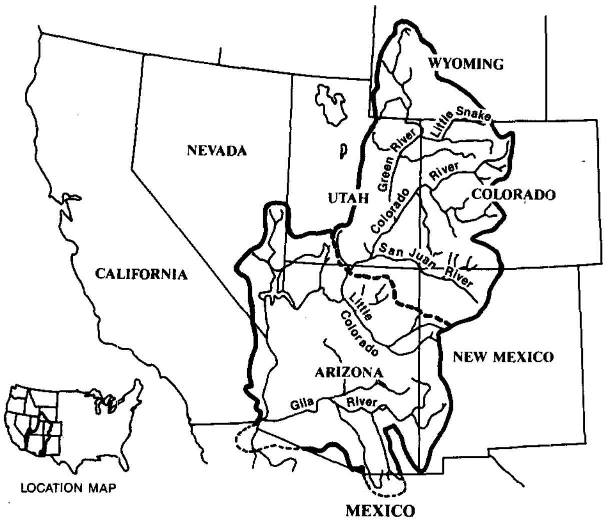


FIG. 1. Geographical region of study. Upper and Lower Basins of the Colorado River are outlined.

general course of affairs is to have alternately high or low precipitation for a period of years, sometimes decades.

We have completed this study in the midst of a major wet period in the states that encompass the Colorado River Basin (CRB). We feel that this might be a good time to think about future water shortages rather than to wait for the time, which will inevitably arrive, when just the opposite scenario is occurring.

We note, in passing, that there are other matters that bear on this issue besides water availability for civil, industrial and agricultural activities. The Mexican Water Treaty of 1944 guarantees an annual amount of 1.5 million acre-feet to Mexico, except in times of extreme shortage (Dracup, 1977). These matters also impact on areas such as water quality, preservation of fish and wildlife habitats, hydropower generation and recreational uses, to name a few.

2. Data

State average annual precipitation data were obtained from the National Climatic Data Center, Asheville, North Carolina (NOAA, 1983). These data are area-weighted averages of divisional means, which in turn are the mean values of the individual stations within each division. Water supply data were taken from U.S. Geological Survey publications (MacKichan, 1951; MacKichan and Kammerer, 1961; Murray and Reeves, 1972; and Solley *et al.,* 1983).

Annual virgin streamflow data for the Colorado River prior to 1967 were kindly supplied by C. Stockton of the Laboratory of Tree Ring Research, University of Arizona, Tucson. Values from 1967 to 1976 were taken from Revelle and Waggoner (1983); from 1977 to 1983 they were taken from Upper Colorado River Commission (1983). The reference period mean for this and the precipitation data presented in Figs. 3 and 4 is 1896–1966, since the original streamflow data encompassed this period, and later there was no need to recompute the means for the longer period of record. State population figures were taken from the *Statistical Abstract of the United States* (U.S. Department of Commerce, 1981).

3. Analysis

We first consider the broad trends and natural variability of precipitation and streamflow in the CRB. The general geographical region considered in this study is shown in Fig. 1, adapted from Dracup (1977). Figure 2 shows a cumulative departure curve

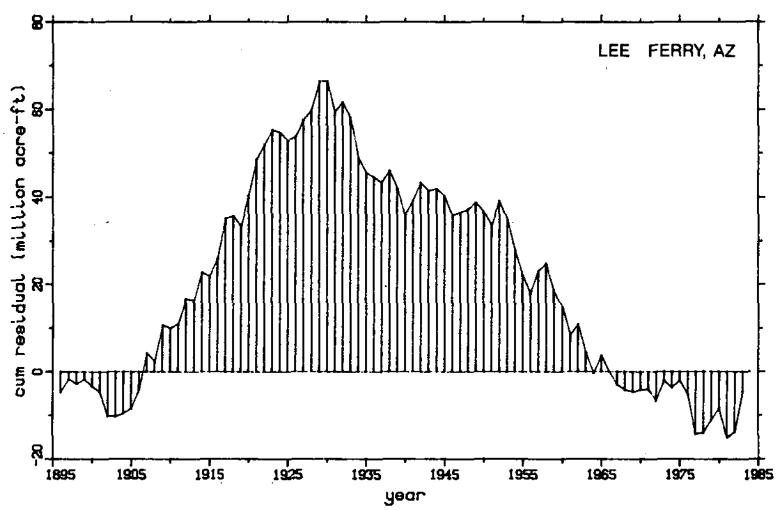
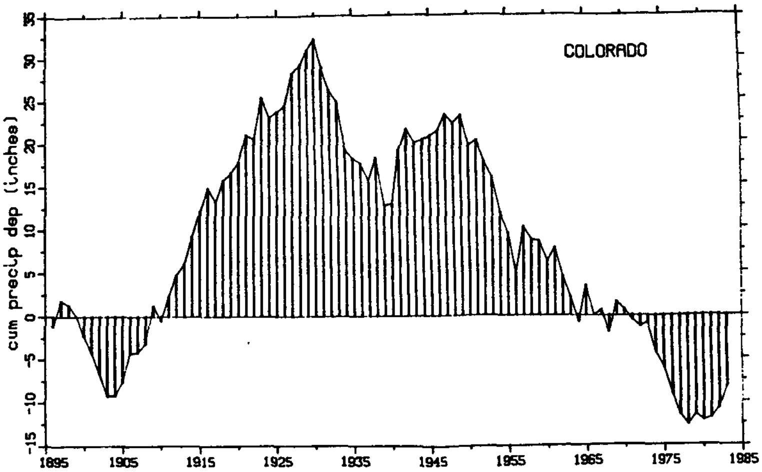


FIG. 2. Cumulative departure curve of the annual "virgin flow" of the Colorado River measured at Lee Ferry, Arizona, 1896–1983. Reference mean is period 1896–1966.



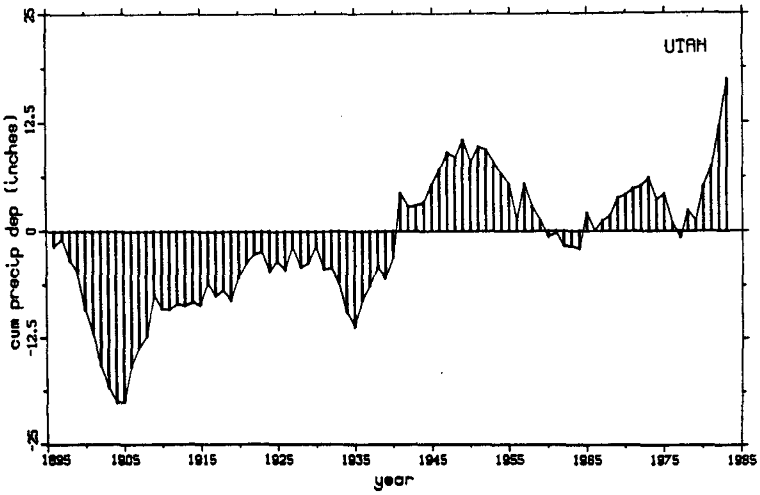


FIG. 3. Cumulative departure curves of the annual precipitation for Colorado and Utah, representative of the Upper Colorado River Basin, 1896–1983. Reference mean is period 1896–1966.

of the average annual "virgin flow" of the Colorado River measured at Lee Ferry, Arizona from 1896 through 1983. Note that the annual adjusted volume of water crossing this point has tended to undergo prolonged periods of above and below average flow. Since between 80 and 85% of the total flow of the Colorado River is contributed by the Upper Basin watershed above Lee Ferry, this figure can be regarded as representative of the whole of the Colorado River system. When comparing the cumulative residual curves in Figs. 2–4, a point below or above the zero line is not necessarily a value that is below or above normal. The curves are of value in pointing out periods of generally above or below average precipitation or streamflow and for identifying the approximate times of the changeovers in relatively abrupt regime transitions.

Dracup (1977) shows that mean flows have ranged from 11.8 million acre-feet (MAF) per year for the ten-year period 1931–40 to 18.8 MAF per year in the corresponding years between 1914 and 1923. This difference of about 6 MAF is nearly equal to a full year's supply of water for either the upper or lower basin. Furthermore, streamflow reconstructions at Lee Ferry using tree-ring indices indicate that in previous centuries, ten-year mean values as low as 9.7 MAF per year may have occurred in the late 16th century, with 15-year mean flows on the order of 10–11 MAF per year (from Dracup, 1977, using data supplied by C. W. Stockton of the University of Arizona's Laboratory of Tree Ring Research; see Stockton and Jacoby, 1976).

The streamflow variability present in the discharge record at Lee Ferry is generally reflected in the long-term annual precipitation fluctuations of the four states comprising the majority of the CRB (see Fig. 1). The cumulative departure curves for Colorado, Utah, Arizona and New Mexico are shown in Figs.

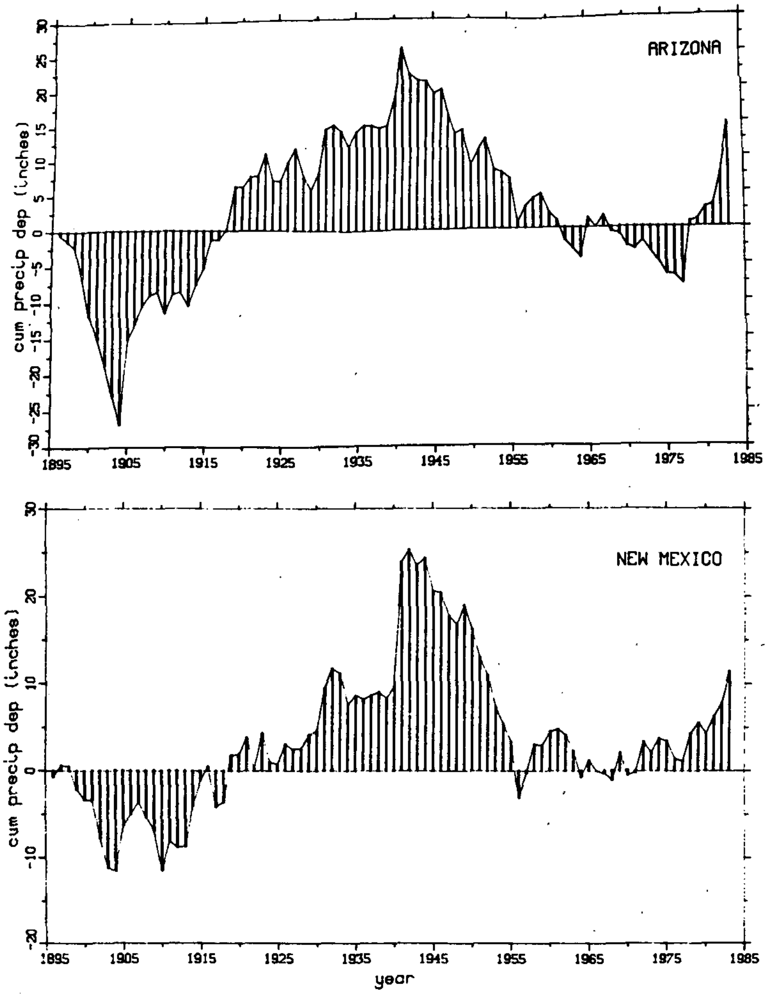


FIG. 4. As in Fig. 3 but for Arizona and New Mexico, representative of the Lower Basin.

3 and 4. The curve for Colorado is particularly important since this state provides the bulk of the runoff that eventually finds its way to the gaging site at Lee Ferry. A comparison of Figs. 2 and 3 shows a very similar time sequence, with wet conditions prevailing in the 1910s and 1920s, dryness in the 1930s, an intermediate wet regime during the 1940s, general dryness through the 1950s, average conditions in the 1960s and high variability in the 1970s. Since 1979 precipitation in Colorado has been generally at or above normal with correspondingly high flows in the Colorado River. Similar fluctuations are evident in Utah (Fig. 3, lower panel), where the Great Salt Lake has risen to record high levels for this century (Arnow, 1983).

Precipitation fluctuations in the Lower Basin (Arizona and New Mexico, Fig. 4) are characterized by a different regime. Typically, a few very wet years are interspersed among several average and below average years. For instance, some very wet years occurred in the 1930s and 1940s, followed by a string of generally dry years until about the mid-1950s. Average and below average precipitation continued until the late 1970s, since which time annual precipitation has tended to be well above average.

These data define the physical/climatological framework of natural water/precipitation fluctuations in the southwestern United States. There is another picture that needs to be considered in assessing the possible impacts of future precipitation deficits. The population of the six states that draw water from the Colorado River (we have excluded Wyoming for the purposes of this study) has nearly quadrupled over the past 50 years. Agricultural and industrial development has likewise been enormous. The development of water resources, accomplished mostly by the federal government through the Bureau of Reclamation in the Department of the Interior, has, to a very great extent, made possible these vast developments. The U.S. Geological Survey estimates that currently about 4.5 MAF per year is being used consumptively by the Upper Basin (USGS, 1984). A U.S. Department of the Interior report (1974) estimates that about 5.8 MAF per year should be used as a conservative estimate of the maximum amount of water available for consumptive use in the Upper Basin. Therefore, the present level of utilization of the available water resources in the Upper Basin is approximately 78% of the estimated maximum.

The way in which population, agricultural and industrial growth affect this region's vulnerability to precipitation variations is illustrated in Figs. 5–6. Taking Arizona, California, Colorado and Utah, which together account for the bulk of the River's water allocations, the annual Colorado River streamflow at Lee Ferry was scaled by the fraction represented by each state's allocation (see Sheridan, 1984; Rhodes *et al.,* 1984), and divided by the sum of the four states' population for each year 1930–83. The index WI_j was calculated by the following formula:

$$WI_j = (\sum_{i=1}^{4} w_i R_j)/P_j, \qquad (1)$$

where w_i is the weight given to the ith state, and is equal to the amount of its yearly allocation divided by 15 MAF; R_j is the value of the streamflow for the jth year and P_j the estimated population in the jth year. Linear interpolation between each decadal census was used to estimate each year's population. As expected, Fig. 5 shows that over the past 5 decades, there has been a very significant decrease in the population-weighted streamflow index value. In California, Colorado and Utah, the drought in the mid-1970s had a greater impact on the population and the economy of each state than similar dry spells in the mid-1950s, a consequence of the greater population. Not only are there lower index values for each subsequent precipitation minimum, but the recent maxima generally fail to reach the minima before 1960. From this point of view, there is less resiliency to precipitation variations with the current population than had been the case in past years.

A different way of measuring these relationships is presented in Fig. 6. In this case the state's area-integrated annual precipitation was divided by the consumption figures listed in Table 1, first using the total consumption, exclusive of hydropower generation (Fig. 6a) and second after including this figure (Fig. 6b). Linear interpolation between each decadal value was used to estimate annual consumption figures. Notice that the drought of the mid-1970s in California, Colorado and Utah resulted in the occurrence of minimum index values during that time, in agreement with the population-weighted index of Fig. 5. In Arizona, the hydropower-inclusive index (bottom panel) shows a more or less continuous decline throughout the period. Removing water used for hydropower (top panel) results in a much smaller, though still decreasing trend. As we noted earlier, precipitation variability in the Lower Basin states differs substantially from that of the Upper Basin states.

In Fig. 7 we combined measures of the indices given in Figs. 5 and 6. A scaling factor was used based on the proportional water allocation for Arizona, California, Colorado and Utah, using two estimates of the long-term mean flow: 13.5 and 16.5 MAF. The weighted sum of water consumption in

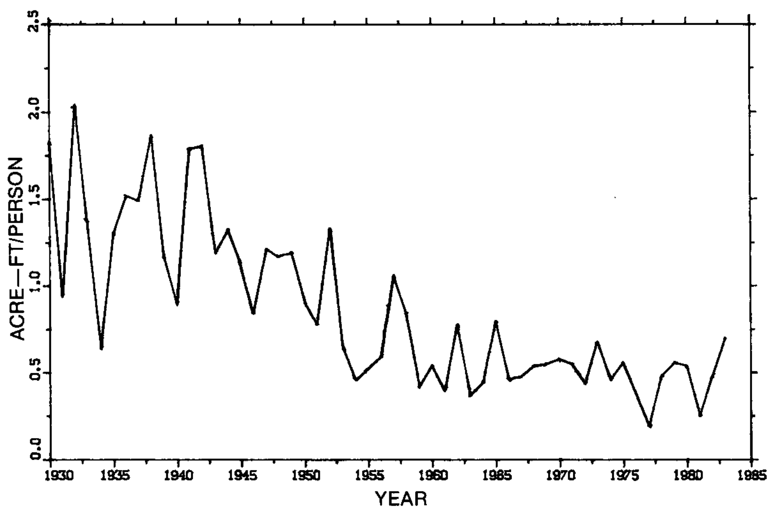


FIG. 5. Streamflow-to-population index showing the weighted ratio of annual streamflow, measured at Lee Ferry, Arizona, to the sum of the population of Arizona, California, Colorado and Utah, 1930–83 (in acre-feet per person). The weights used are the fraction of Colorado River water allocated to each of the four states; see text for details.

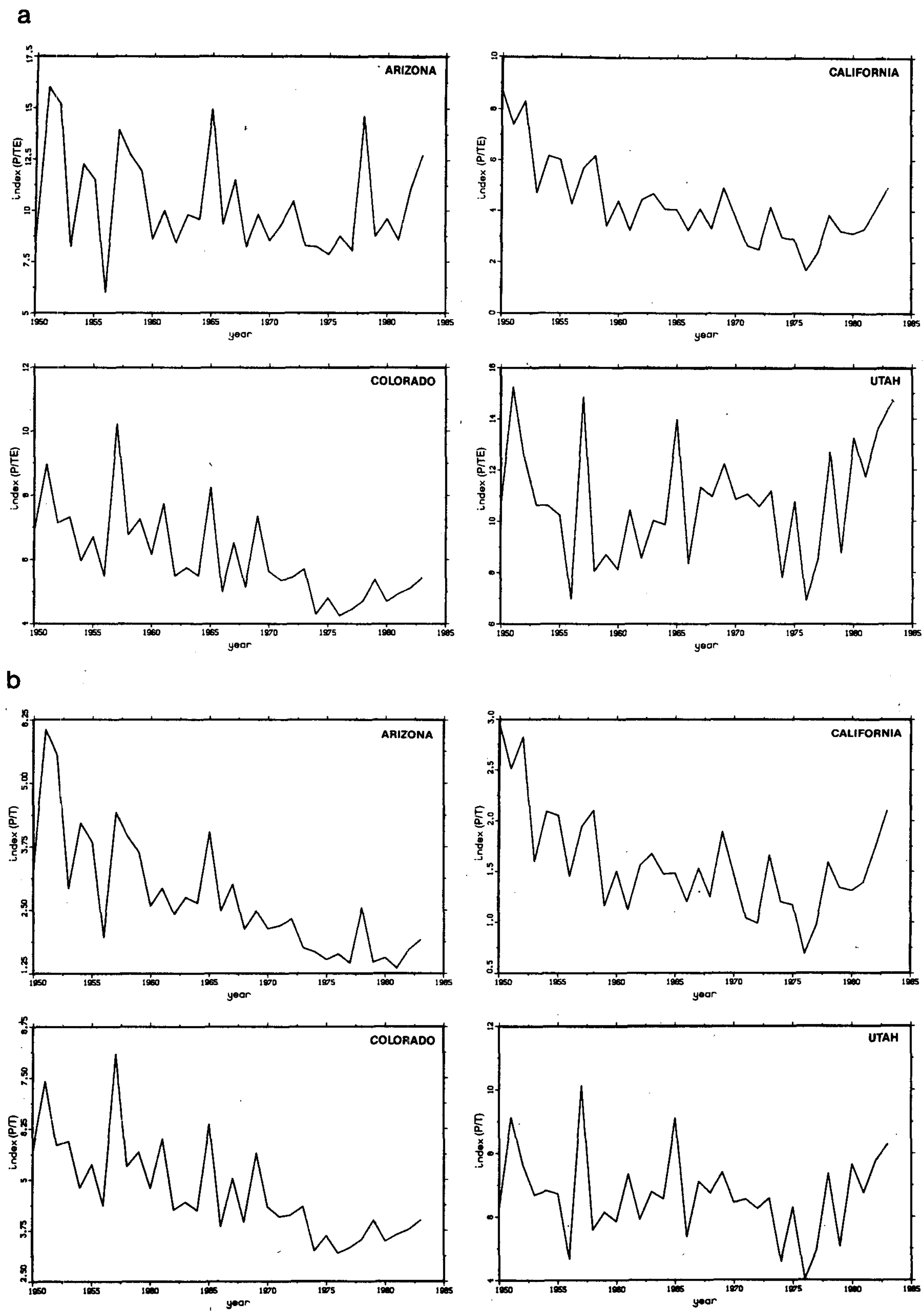


FIG. 6. Nondimensional index showing the ratio of total integrated annual precipitation to annual water consumption for Arizona, California, Colorado and Utah, 1950–83. (a) Ratio excluding water used for hydropower generation (TE in Table 1); (b) ratio including this figure (T in Table 1).

Table 1. Water Withdrawals by Type (in MAF) and Percent of Total Withdrawals Excluding Hydropower Generation

ARIZONA

	1950		1960		1970		1980	
	Vol.	%	Vol.	%	Vol.	%	Vol.	%
PR	0.12	2	0.22	3	0.40	5	0.68	8
IN	0.05	1	0.14	2	0.25	3	0.281	3
IR	5.2	97	6.44	95	7.0	92	8.0	89
TE	5.37	100	6.80	100	7.65	100	8.961	100
C	N.A.		4.61	68	5.66	74	6.07	68
H	8.3	-	16.0	-	23.0	-	46.0	-
T	13.67	-	22.80	-	30.65	-	54.96	

NEVADA

	1950		1960		1970		1980	
	Vol.	%	Vol.	%	Vol.	%	Vol.	%
PR	0.08	3	0.10	4	0.16	5	0.29	7
IN	0.02	1	0.05	2	0.15	4	0.27	7
IR	1.66	95	2.45	94	3.40	92	3.50	86
TE	1.74	100	2.6	100	3.71	100	4.06	100
C	N.A.		1.58	61	3.48	94	2.72	67
H	7.40	-	6.20	-	4.80	-	1.30	-
T	9.14		8.80	-	8.51		5.35	

CALIFORNIA

	1950		1960		1970		1980	
	Vol.	%	Vol.	%	Vol.	%	Vol.	%
PR	1.78	7	3.27	8	4.07	8	4.85	8
IN	0.33	1	11.24	29	12.14	23	13.48	22
IR	23.0	92	24.49	63	37.0	70	42.0	70
TE	25.11	100	39.0	100	53.21	100	60.33	100
C	N.A.		21.35	55	30.28	57	34.38	57
H	49.0	-	75.0	-	84.0	-	91.0	-
T	74.11	-	114.00	-	137.21	-	151.33	-

NEW MEXICO

	1950		1960		1970		1980	
	Vol.	%	Vol.	%	Vol.	%	Vol.	%
PR	0.10	3	0.15	5	0.24	7	0.29	7
IN	0.02	1	0.05	2	0.12	3	0.08	2
IR	3.70	97	2.77	93	3.20	90	4.00	92
TE	3.82	100	2.97	100	3.56	100	4.37	100
C	N.A.		2.25	76	1.87	53	2.17	50
H	0.75	-	0.58	-	0.48	-	0.48	-
T	4.57	-	3.55	-	4.04	-	4.85	-

COLORADO

	1950		1960		1970		1980	
	Vol.	%	Vol.	%	Vol.	%	Vol.	%
PR	0.25	3	0.27	2	0.49	3	0.89	5
IN	0.08	1	0.37	3	0.36	2	1.02	6
IR	9.66	97	11.57	95	14.00	95	16.00	89
TE	9.99	100	12.21	100	14.85	100	17.91	100
C	N.A.		7.19	59	9.21	62	6.29	35
H	2.00	-	3.50	-	4.50	-	6.20	-
T	11.99	-	15.71	-	19.35	-	24.11	-

UTAH

	1950		1960		1970		1980	
	Vol.	%	Vol.	%	Vol.	%	Vol.	%
PR	0.13	4	0.27	5	0.38	8	0.92	18
IN	0.08	2	0.34	7	0.33	7	0.65	13
IR	3.45	94	4.49	88	4.10	85	3.60	70
TE	3.66	100	5.1	100	4.81	100	5.17	100
C	N.A.		3.37	66	3.18	66	3.62	70
H	2.60	-	2.00	-	3.30	-	3.80	-
T	6.26	-	7.10	-	8.11	-	8.97	-

PR = public and rural supply
IN = industrial use
IR = irrigation
TE = total amount used excluding hydropower generation
C = consumptive use plus irrigation conveyance losses
H = hydropower generation
T = total amount used including hydropower generation

Percentage figures are proportions of TE

these four states, computed in a manner analogous to (1), was divided by the actual annual streamflow values. The graph shows how the rising water consumption in these states has taken an increasingly greater share of the river's flow, the actual magnitude depending upon the estimated average flow. These four states alone account for over 100% of the mean annual streamflow, regardless of its estimated long-term value. Furthermore, in times of drought the consumption far exceeds (by 200–300%) the annual streamflow (e.g., as in 1977).

The trends in water consumption by different categories over the past 30 years are summarized in Table 1. If one averages the total consumption figures ("T" in Table 1) for 1950 and 1960 and for 1970 and 1980, respectively, in California, Colorado and Utah one can see that total water usage increased by approximately 54, 55 and 27%, respectively for each state from the 1950s to the 1970s. All indications point to continued growth in water demand, more or less at the pace that has been prevalent for the past few decades.

Dracup (1977) has pointed out the potentially damaging effects of an extended period of low precipitation and streamflow in the CRB (a period of dryness similar to that experienced during the 1930s would have a very significant impact).[1] The reader is

[1] The potential impact of a protracted dry period would depend to a significant degree on the level of water storage available at the onset of the drought. Presently, most reservoirs in the Upper Basin are near capacity (see Rhodes *et al.*, 1984).

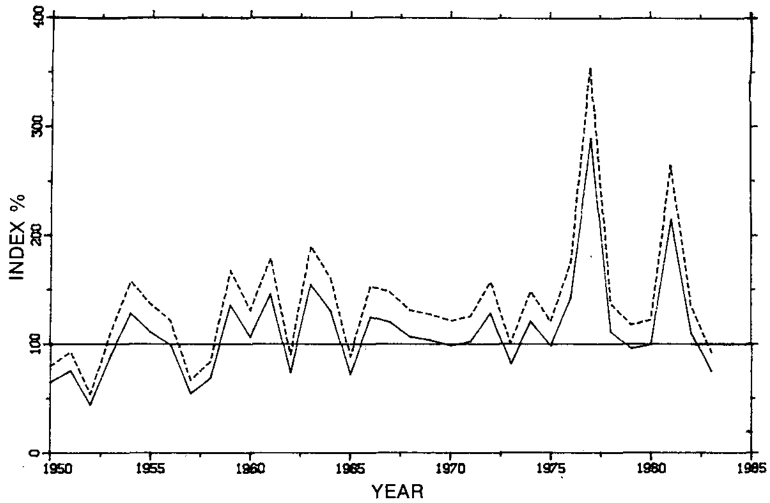


FIG. 7. Ratio of water consumption to Colorado River streamflow weighted by the proportion of water allocated to each of the states of Arizona, California, Colorado and Utah and based on two estimates of the long-term mean flow. Upper curve (dashed) assumes a mean flow of 13.5 MAF; lower curve (solid) assumes a mean flow of 16.5 MAF. Values in percent of estimated mean flow.

referred to this and a series of other articles in NAS (1977) for a discussion of the many interdependent factors associated with climate and water resources.

Synoptic studies have shown that in general, seasonal and annual precipitation are negatively correlated with temperature (Barry *et al.*, 1981). Hence, precipitation deficits are usually accompanied by above normal temperature, increased evapotranspiration, diminished runoff and low streamflow. This is supported by studies of the effects of annual temperature and precipitation on streamflow such as those of Stockton and Boggess (1979) and Revelle and Wagoner (1983). In the latter study, it was calculated that a 2°C rise in temperature together with a 10% reduction in precipitation in the UCRB (Upper Colorado River Basin) would result in approximately a 40% reduction in the long-term average virgin flow of the Colorado at Lee Ferry. This would be about 31% less flow than the historically lowest ten-year average measured flow and about 17% lower than the estimated lowest ten-year flow based on tree ring data (see Dracup, 1977).

4. Summary and conclusions

The effects of natural climatic fluctuations are often amplified by human factors. Sometimes, this results in demands exceeding a region's natural carrying capacity during times of precipitation deficits, even though the region might be able to meet those demands during times of excess.

In a region such as the southwestern United States, precipitation and streamflow undergo pronounced fluctuations with a time scale of approximately one to two decades. The strong population and economic growth that this region has experienced in the past 30 years, and which is expected to continue at a similar pace for the next couple of decades, will increase the region's sensitivity to a major drought.

In circumstances under which a prolonged drought curtails water use, conflicts may develop among categories of users such as urban versus rural, or industrial versus agricultural users. These conflicting interests, which may lie buried during times when supplies are plentiful, may be exacerbated at time of natural water scarcity. Some state legislation have begun to address the looming water shortages. For example, the Arizona legislature has approved a statute which gives the state the power, starting in the year 2006, to condemn farms and ranches in order to conserve water (*Rocky Mountain News,* 1984). The federal government has recognized these concerns and has begun to examine policy issues and technological alternatives (OTA, 1983).

Mitigating strategies to cope with potential water shortages also include the development of standby water conservation regulations, increased prices for water usage and changes in the pricing system. The Office of Technology Assessment estimates that better water resource management and improved technologies offer the best short-term payoffs. However, the longer-term problems associated with the confluence of climatic and social factors will become increasingly important issues in the future.

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