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Article Information

Journal Title: Changing Climate

Volume: **Issue:**
Month/Year: 1983**Pages:** 419-432

Article Author: Revelle and Waggoner

Article Title: Revelle, R. R., and P. E. Waggoner, Effects of a carbon dioxideinduced climatic change on water supplies in the western United States, in Changing Climate, pp. 419–432, Nat. Acad., Washington, D. C., 1983.

Loan Information

Loan Title:

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8/13/2006 7:16:12 PM (bradu) Publisher is National Academies Press
8/14/2006 11:55:10 AM (llj) Branch has Call Number: QC981.8.C5 C5 1983

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7 Effects of a Carbon Dioxide-Induced Climatic Change on Water Supplies in the Western United States

Roger R. Revelle and Paul E. Waggoner

In this chapter we show that warmer air temperatures and a slight decrease in precipitation would probably severely reduce both the quantity and the quality of water resources in the western United States. Similar effects can be expected in many water-short regions elsewhere in the world. We have not attempted to estimate these, primarily because we do not know enough to be able to do so. But we hope that hydrologists of other countries will be stimulated by our calculations to investigate the probable consequences of a CO_2-induced climate change on water resources in their own countries. In all countries, planning and construction of large-scale water-resource systems takes many decades. The time involved is of the same order of magnitude as the time over which a significant change in climate from increase of carbon dioxide and other greenhouse gases can be expected. Thus, we believe that planners and managers of water systems throughout the world should be able to make good use of forecasts of the hydrologic consequences of a warmer climate and of possible changes in precipitation.

7.1 EMPIRICAL RELATIONSHIPS AMONG PRECIPITATION, TEMPERATURE, AND STREAM RUNOFF

To assess the effects on the United States' water resources of probable climatic change we used the empirical relationship found by Langbein et al. (1949) among mean annual precipitation, temperature, and runoff. This was based on representative data from 22 drainage basins in the conterminous United States. Their relation in Table 7.1 gives the estimated annual runoff for different values of mean annual precipitations and weighted mean annual temperatures. The latter were computed for each catchment basin by dividing the sum of the products of average monthly temperature and precipitation by the mean annual precipitation. In this way, the average temperature during each month is weighted by the precipitation during that month.

The catchments studied by Langbein and his colleagues were distributed over climates from warm to cold and from humid to arid, but in Table 7.1 we have shown the relations among runoff, temperature, and precipitation only for relatively arid areas. In these arid areas, the value of actual evapotranspiration is less than the potential evapo-

TABLE 7.1 Runoff (mm yr^{-1}) as a Function of Precipitation and Temperature[a]

Weighted Average Temperature (°C)	Precipitation (mm yr-1) 200	300	400	500	600	700
- 2	54	92	154	230	330	440
0	40	74	124	190	275	380
2	28	57	95	154	225	320
4	17	40	78	125	190	265
6	9	25	60	100	155	220
8	0	17	42	82	128	185
10		8	29	64	103	155
12		0	19	47	80	130
14			10	32	65	105
16			0	20	50	85

[a] Source: W. B. Langbein et al. (1949).

transpiration that would occur if sufficient water were present and evapotranspiration was controlled mainly by temperature. For example, at a temperature of 4°C, potential evapotranspiration is about 450 mm yr^{-1}. Yet Langbein's data show that even when annual precipitation is only 300 mm, there is still significant runoff, about 13% of the precipitation. Correspondingly, average actual evapotranspiration must be only 260 mm yr^{-1}.

From Table 7.1 we observe that for any given annual precipitation, runoff diminishes rapidly with increasing temperature. Similarly, for any given temperature, the proportion of runoff to precipitation increases rapidly with increasing precipitation. For example, at a weighted mean annual temperature of 4°C and annual precipitation of 200 mm, runoff is only 8.5% of precipitation, whereas for the same temperature and an annual precipitation of 700 mm, runoff is 38% of precipitation. At an annual temperature of 8°C, runoff is zero when precipitation is 200 mm or less and is 185 mm--or 26.4% of precipitation--when the average annual precipitation is 700 mm.

For any particular region, the relations shown in Table 7.1 are rather crude approximations because many physical factors, including geology, topography, size of drainage basin, and vegetation, may alter the effect of climate on runoff. We believe, nevertheless, that these relationships can be used without serious error to describe the effects of relatively small changes in average temperature and precipitation on mean annual runoff.

In Table 7.2, we have used the data in Table 7.1 to compute the approximate percentage decrease in runoff for a 2°C increase in temperature. Climate models (e.g., Manabe and Wetherald, 1980) indicate that a temperature change of this magnitude or greater is likely as a result of the doubling of carbon dioxide and increased concentration of "greenhouse gases" expected during the next century. We see that for a

TABLE 7.2 Approximate Percent Decrease in Runoff for a 2°C Increase in Temperature[a]

Initial Temperature (°C)	Precipitation (mm yr-1) 200	300	400	500	600	700
- 2	26	20	19	17	17	14
0	30	23	23	19	17	16
2	39	30	24	19	17	16
4	47	35	25	20	17	16
6	100	35	30	21	17	16
8		53	31	22	20	16
10		100	34	22	22	16
12			47	32	22	19
14			100	38	23	19

[a] Computed from Table 7.1.

present weighted mean annual temperature of 4°C and annual precipitation of 300 mm, a 35% diminution in runoff would follow a 2°C warming. The percentage decrease in runoff from a warming diminishes with increasing precipitation and becomes greater for successively higher values of the initial temperature.

Table 7.3 shows the approximate percentage decreases in runoff for a 10% decrease in precipitation. According to the results of climate models (see Chapter 4), such a diminution in precipitation is likely, at least in certain regions of the United States, with a doubling of atmospheric CO_2. Again we see that the effect becomes larger with higher average annual temperatures. There is a relatively small difference in the percentage decrease in runoff at a given temperature over the range of initial precipitation values shown in the table. Comparison of Tables 7.2 and 7.3 shows that below an initial mean annual precipitation of 500 mm, the effects of a 2°C warming are larger than those caused by a 10% decrease in precipitation. The reverse is true when mean annual precipitation is 500 mm or more.

7.2 EFFECTS OF CLIMATE CHANGE IN SEVEN WESTERN U.S. WATER REGIONS

Stockton and Boggess (1979) have used Langbein's empirical relation to estimate the effects of a climatic change on water in the 1[illegible] water regions of the conterminous United States defined by the U.S. Water Resources Council (1978). They find that a 2°C warming and a 10% reduction in precipitation would not have serious effects in the humid regions east of the 100th meridian. In the West, however, the impact would be severe on seven water regions: the drainage basins of the Missouri, Arkansas-White-Red, Rio Grande, and Colorado rivers; the river basins draining into the Gulf of Mexico from the northern two thirds of Texas; and the rivers of California. The only western water

TABLE 7.3 Approximate Percentage Decrease in Runoff for a 10% Decrease in Precipitation[a]

Temperature (°C)	Initial Precipitation (mm yr-1)				
	300	400	500	600	700
- 2	12	16	17	18	18
0	14	16	17	19	19
2	15	16	19	19	20
4	17	19	19	21	21
6	23	23	21	21	21
8	30	24	24	22	22
10		24	27	23	23
12		40	30	25	25
14			34	30	27
16			50	36	29

[a] Computed from Table 7.1.

regions that would not be severely affected are the water-rich Pacific Northwest and the Great Basin (parts of Nevada, Utah, and Idaho), where demand is relatively small and groundwater reserves are large.

In estimating the impact of climate change, Stockton and Boggess assumed:

1. The region-by-region variation in annual runoff is predominantly influenced by climate, although other factors such as geology, topography, vegetation, and many other variables may be important, especially in smaller drainages.
2. The empirical curves associating total annual precipitation and total annual runoff with weighted mean annual temperature are appropriate for all 18 regions although derived from a relatively small (22 drainage basin) sample.
3. Changes in land use have relatively small influences on regionwide annual runoff.
4. Annual runoff is not greatly affected by large-scale groundwater overdraft.
5. Evapotranspiration is controlled solely by temperature.
6. The postulated climatic change does not modify the present monthly distribution of temperature and precipitation; only the amplitude of the present distribution is increased or decreased.
7. Selection of a few meteorological stations for each region adequately establishes the relation of the weighted mean temperature and annual precipitation to annual runoff.

In Table 7.4 we have summarized the estimates by Stockton and Boggess of the effects of a 2°C increase in temperature and a 10% reduction in precipitation in the seven water regions of the western United States in which climate change would have the most serious

TABLE 7.4 Comparison of Water Requirements and Supplies for Present Climatic State and for a 2°C Increase in Temperature and 10% Reduction in Precipitation in Seven Western U.S. Water Regions[a]

	Present Climate						Warmer and Drier Climate		
Water Region[b]	Area ($10^{10}/m^2$)	Mean Annual Runoff (10^{10} m^3 yr^{-1})	Mean Annual Runoff (mm)	Mean Annual Supply (10^{10} m^3 yr^{-1})	Mean Annual Requirements[c] (10^{10} m^3 yr^{-1})	Ratio of Requirement to Supply	Mean Annual Supply (10^{10} m^3 yr^{-1})	Percent Change in Supply	Ratio of Requirement[d] to Supply
Missouri	132.4	8.50	64	8.50	3.63	0.43	3.07	-63.9	1.18
Arkansas-White-Red	63.2	9.35	148	9.35	1.67	0.18	4.32	-53.8	0.39
Texas Gulf	44.9	4.92	110	4.92	1.74	0.35	2.47	-49.8	0.70
Rio Grande	35.2	0.74	21	0.74	0.67	0.91	0.18	-75.7	3.72
Upper Colorado	29.6	1.64[e]	55	1.64	1.63[f]	0.99	0.99	-39.6	1.65
Lower Colorado	40.1	0.38	10	1.15[g]	1.37	1.19	0.50[g]	-56.5	2.68
California	42.9	9.56	222	10.18[g]	4.22	0.41	5.71[g]	-43.9	0.74
For the 7 regions together	388.3	35.09	90.4	35.09[h]	14.93	0.43	16.53[h]	-53	0.90

[a] Source: Stockton and Boggess (1979) and calculations in this paper for Upper Colorado Basin.

[b] As defined by the U.S. Water Resources Council (1978).

[c] Projected through year 2000 A.D.

[d] Assuming no increase in requirement because of increased evapotranspiration from irrigated farms or reservoirs.

[e] Average "virgin flow" of the Colorado River at Lee Ferry from 1931 to 1976.

[f] Includes allocation to Lower Basin States, California included, of 0.93 x 10^{10} m^3 yr^{-1}.

[g] Includes water received from Upper Colorado Basin, but not mined groundwater.

[h] Total is less than sum of the column because of flow of Lower Colorado derived from Upper Colorado (g).

impact. These regions cover about half the area of the conterminous United States, but they produce only about 15% of the mean annual stream runoff. The table shows the present mean annual water supply for each region, not including mined groundwater, in millions of hectare meters (10^{10} m^3 yr^{-1}) and the estimated mean annual requirement in the year 2000. The mean annual requirements listed in Table 7.4 represent "consumptive" use of water plus evaporation from reservoirs, that is, the total quantity of water that is evapotranspired in the course of beneficial human use. Although actual withdrawals from streams and underground aquifers are considerably larger, portions of these withdrawals are returned to the streams or back into the ground where the water may be reused. In the present climate the ratio of estimated requirements to supplies is less than one for all regions except the Lower Colorado River. In this region today, the deficit of supply is presently made up by extensive mining of groundwater.

For the postulated climatic change, supplies would greatly diminish in all regions, ranging from almost a 76% reduction in the Rio Grande region to nearly 40% in the Upper Colorado, with the result that estimated requirements would exceed supplies in the Missouri, Rio Grande, and Upper and Lower Colorado regions. Mean annual requirements would still be less than future mean annual supplies in the Arkansas-White-Red, Texas Gulf, and California regions. But requirements would almost certainly exceed supplies in the Texas Gulf and California regions during future prolonged droughts. Conditions are highly variable in different parts of the Arkansas-White-Red region, with the western part tending to be deficient in water supplies and the eastern part having a surplus. To maintain the present pattern of water use, large-scale transfers between basins might be necessary here even under average conditions, let alone to meet water requirements during prolonged droughts. A serious deterioration in water quality would follow from climatic change in all seven regions.

The ratio of future requirements to supply would probably be even less favorable than indicated in Table 7.4 because evapotranspiration from irrigated farms and reservoirs would undoubtedly increase with a rise in temperature. On a global basis this would be compensated for by an increase in precipitation, but this might or might not occur in the regions we are considering.

At present, California depends for about 15% of its water on imports from the Colorado River. These imports might be eliminated entirely with the postulated climatic change, in which case the ratio of mean annual requirements to mean annual runoff would increase to 0.83, more than double the present ratio.

In all seven regions, irrigation is by far the largest user. Its share of water withdrawals ranges from 68% in the Texas Gulf region to 95% in the Rio Grande region. Total water withdrawals for agriculture are now 13.2 million hectare meters, and in the seven regions the irrigated area is (very approximately) 13 million hectares (Rogers, 1983) so that, on the average, the annual depth of irrigation is about 1 m. Consumptive water use in irrigation is much smaller; a large share of the water that is not consumed reappears as return flows that can be used downstream. Reduction in the irrigated area and an increase in the efficiency of water use in irrigation would significantly lower the overall water requirements in the seven western regions. A 15% increase in water-use efficiency is probably feasible (Jensen, 1982). Reduction in the irrigated area might come about automatically if an interstate economic market for water were to develop, because economic returns to irrigation are relatively low in large parts of the seven western regions. On the other hand, potentially very large Indian claims for irrigation water for their reserved lands must eventually be settled, and this could result in a major reallocation of water rights (Back and Taylor, 1980).

The effects of future droughts in the Arkansas-White-Red, Texas Gulf, and California regions from the assumed climatic change could be significantly mitigated by construction of additional reservoirs for water storage, but increases in storage would help little in the Missouri, Rio Grande, or Upper and Lower Colorado regions because their storage reservoirs are already so large compared to the annual runoff. In these regions strict water conservation would be essential.

The mean annual requirements listed in Table 7.4 represent "consumptive use of water plus evaporation from reservoirs, that is, the total quantity of water that is evapotranspired in the course of beneficial human use. Although actual withdrawals from streams and underground aquifers are considerably larger, portions of these withdrawals are returned to the streams or back into the ground where the water may be reused.

As Stockton and Boggess show, the one western region where a large surplus would still exist after their postulated climatic change would be the Pacific Northwest. Their estimated ratio of requirements to supplies following a 2°C warming and a 10% reduction in precipitation would be 0.10. The annual supply would then be 23.7 million hectare meters. Transfer of 20% of this total supply to water-short regions through large, long-distance conveyance could increase future supplies in the seven western regions shown in Table 7.4 by nearly 30%, thereby compensating for much of the estimated shortages from climatic change. The ratio of requirements to supplies in the Pacific Northwest region would still be a comfortable 0.18.

From an economic standpoint, however, such a transfer would probably not be desirable. The value of the hydroelectric energy that could be generated from a hectare meter of water in the Pacific Northwest, assuming a total head of 500 m and a price of 5¢ per kilowatt-hour, would be over $600, considerably in excess of the value of a hectare meter of water for irrigating the fodder and cereal crops grown in most of the western regions (Rogers, 1983).

7.3 THE COLORADO RIVER

Except for the Rio Grande, the waters of the Colorado River are more intensively used than those of any other major stream in the United States. Half the estimated "normal" flow of 18,500 million cubic meters per year at Lee Ferry in Arizona has been allocated by interstate compact, confirmed by federal law, to the lower basin states of California and Arizona, with minor amounts going to Nevada. Nearly all of the runoff originates from snow in the high-mountain area of western Colorado, southwestern Wyoming, and eastern Utah.* (As defined, the Upper Basin also includes northwestern New Mexico.)

To check the probable effect of a climatic change on the flow of the Colorado River, we calculated a multiple regression of the relation between annual averages of precipitation and temperature and the "virgin flow" of the Colorado at Lee Ferry, Arizona, which is the southernmost point on the river in the Upper Colorado Basin.

The "virgin flow" is the measured flow at Lee Ferry plus estimated depletions within the upper basin, evaporation from reservoirs, and changes in reservoir storage. Estimates for the annual virgin flows were furnished to us by Myron B. Holbert, chief engineer of the Colorado River Board of California. The flow for each water year--October 1 to September 30--from 1931 to 1976 is tabulated in Table 7.5. It ranges from 9,450 to 25,490 million cubic meters. The average for the 46-year period is 16,430 million cubic meters (13.5 million acre feet). This average value is 2065 million cubic meters, or 11% less than the assumed "normal flow" on which the Colorado River Compact is based, but it agrees well with Langbein's relationship, shown in Table 7.1, among temperature, precipitation, and runoff. Interpolating between the values given in the table for temperatures of 4 and 6°C and precipitation of 300 and 400 mm yr^{-1}, we arrive at a runoff of 53 mm, corresponding to an annual river flow for the 296,000 km^2 in the Upper Colorado drainage of 15,700 million m^3.

The flow of the Colorado is mainly collected in five catchments corresponding to the five climatic divisions in the Upper Colorado Basin outlined in Figure 7.1. Mean annual precipitation and temperature for each drainage area and water-year from 1931 to 1976 were provided to us by Daniel Cayan of the Scripps Institution of Oceanography, who obtained the original data from the National Climate Center, Asheville, North Carolina. The annual data for each division are the areally weighted averages of the records of individual weather stations. As Cayan has pointed out, the number of weather stations was not constant but gradually increased from 1931 to 1976. Between 1951 and 1980, continuous records were obtained from 45 stations in the western Colorado division, 10 stations in the Green and Bear drainages in Wyoming, and 10 in the three drainage basins of eastern Utah (North Mountains, Uinta Basin, and Southeast Utah). By 1980, there were 65 stations in western Colorado, 26 in the three Utah divisions, and 16 in southwestern Wyoming.

We weighted the data from these five drainage basins in proportion to their areas: Colorado drainage in western Colorado, 0.430; Green and Bear drainages in Wyoming, 0.184; North Mountains in Utah, 0.110;

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*See Dracup (1977) and Howe and Murphy (1981) for useful discussions of the economic, social, political, and international problems of the Colorado River compact.

FIGURE 7.1 Basins or drainages of the western United States.

Uinta Basin, 0.053; and southeast Utah, 0.223. The weighted sum of the precipitation in millimeters for the five drainages is called PRECIP in the following equation. It varies from 262 to 439 mm yr^{-1}, with an average for the 46 years of 332 mm yr^{-1}. Weighted annual average temperatures obtained in the same manner are called CELSIUS. They range from 2.52 to 6.75°C and average 4.18°C. The weighted annual averages for 1931 to 1976 are tabulated in Table 7.5.

The relation of the virgin flow to PRECIP and CELSIUS is assumed to fit the equation:

$$\text{FLOW} = b_0 + (b_1 \times \text{PRECIP}) + (b_2 \times \text{CELSIUS}).$$

The regression coefficients, b_i, and their standard errors relating the virgin flow at Lee Ferry to the mean annual precipitation and the mean annual temperature in the watershed from 1931 to 1976 are as follows:

b_0 in millions of cubic meters = 9274 ± 3838,
b_1 in millions of cubic meters/mm = 52 ± 7,
b_2 in millions of cubic meters/°C = -2400 ± 507.

The fit of the equations to the data is represented by the square of the correlation coefficient, R^2, which is 0.73. About 75% of the variation of the flow about the mean is explained by the equations.

We see that a 2°C rise in temperature would decrease the virgin flow by 4800 ± 1015 million cubic meters yr^{-1}, or about 29% ± 6%. A 10% decrease in precipitation would reduce the flow by 1730 ± 230 cubic meters, or an additional 11% ± 1.4%. The combined effect would be a reduction in flow by 40% ± 7.4%, very close to the estimate of 44% given by Stockton and Boggess.

Estimates of the virgin flow between 1900 and 1930 were also provided by Holbert, and we attempted a similar analysis for these years, using data published in the Weather Bureau publication, The Climates of the States. Unfortunately, the data for these earlier years are sparse. Only 10 stations recorded precipitation more or less continuously during this period in western Colorado and even fewer in Utah and Wyoming. Temperature data were available from only Garnett, Colorado; Lander, Wyoming; and Modena, Utah, and none of these is in the high-mountain regions of heavy snowpack that contribute most of the runoff to the Colorado River.

The data for 1900 to 1930, Table 7.6, indicate that the average runoff was about 20% greater than between 1931 and 1976, while the average precipitation was about 7% less and the average temperatures for the three available stations were about 2°C higher. The low estimate of average precipitation may reflect a deficiency in estimating the quantities of water precipitated as snow. These estimates were very uncertain before the advent of the "snow courses" initiated by the U.S. Soil Conservation Service in the 1930s. The extreme variations in average annual temperature for the three stations were only 2.45°C, in contrast to the range of 4.23°C for the average of the much larger number of stations in 1931-1976.

TABLE 7.5 Annual Averages of Precipitation, Temperature, and Virgin Flow of the Colorado River at Lee Ferry, Upper Colorado Region, 1931-1976

Year	Precipitation (mm yr^{-1})	Temperature (°C)	Flow (10^6 m^3 yr^{-1})
1931	268	4.95	9583
1932	355	3.23	21270
1933	283	3.51	14009
1934	228	6.75	6958
1935	316	5.14	14247
1936	349	4.62	17023
1937	378	3.80	16948
1938	392	5.04	21643
1939	301	4.22	13666
1940	323	5.71	10609
1941	451	4.11	22386
1942	357	3.51	23592
1943	362	4.68	16164
1944	334	3.99	18693
1945	355	3.97	16542
1946	305	4.08	12860
1947	418	4.39	19083
1948	346	4.13	19258
1949	385	3.32	20199
1950	320	3.68	15904
1951	298	4.60	14366
1952	424	3.20	25490
1953	273	4.63	13119
1954	308	5.64	9450
1955	291	3.57	11333
1956	255	4.31	13259
1957	429	4.25	24787
1958	323	4.28	20339
1959	294	4.75	10619
1960	262	4.49	13893
1961	340	4.82	10432
1962	300	3.38	21338
1963	305	5.44	10423
1964	286	3.61	12527
1965	439	3.30	23329
1966	282	4.06	13825
1967	350	4.20	14687
1968	326	3.45	16854
1969	361	3.84	17745
1970	352	4.05	19002
1971	302	3.78	18645
1972	303	3.46	15021
1973	435	2.52	23893
1974	254	4.22	16355
1975	347	3.51	20447
1976	300	4.27	14064
Mean	333	4.18	16432

TABLE 7.6 Annual Averages of Precipitation, Temperature, and Virgin Flow of the Colorado River at Lee Ferry, Upper Colorado Region, 1901-1930

Year	Precipitation (mm yr^{-1})	Temperature (°C)	Annual Sum (m/sec)
1901	229	6.56	16753
1902	195	6.71	11586
1903	285	5.35	18264
1904	240	6.55	19297
1905	314	6.10	19769
1906	370	5.86	23585
1907	350	6.78	28865
1908	274	6.49	15857
1909	364	6.05	28709
1910	233	6.57	17574
1911	327	7.49	19770
1912	313	5.05	25311
1913	269	5.71	17852
1914	355	6.68	26176
1915	308	6.47	17303
1916	304	7.08	23684
1917	346	5.04	29650
1918	263	7.32	18951
1919	253	6.43	15372
1920	331	5.58	27076
1921	355	6.57	28389
1922	300	6.60	22580
1923	336	6.04	22535
1924	252	5.63	17517
1925	338	6.41	16077
1926	303	6.28	19554
1927	404	6.88	22963
1928	253	6.58	21314
1929	392	5.46	26432
1930	309	6.44	18361
Mean	306	6.29	21098

The multiple regression for the earlier period showed a smaller effect of temperature and a somewhat larger effect of precipitation than during 1931-1976. But during the earlier period the standard deviations for the effects of both temperature and precipitation were almost twice as great, and the square of the correlation coefficient was only 0.57.

We conclude tentatively that the weakness of the correlation and the relatively larger standard errors from 1901 to 1930 resulted from the paucity of precipitation and temperature data, the probable inaccuracy of estimates of the quantity of water precipitated as snow, and the probably unrepresentative character of the stations used for average temperatures. In both the earlier and the later periods, variations in precipitation were reflected almost linearly in variations in runoff without the amplification that might be expected from the results obtained on smaller watersheds (Schaake and Kaczmarek, 1979) or from Table 7.3.

After the postulated climatic change, the mean annual flows at Lee Ferry computed from our multiple regression equation for 1931 to 1976 would be only 9900 million cubic meters. This last amount is 2060 million cubic meters, or 17%, less than the historically lowest 10-year average annual flow of 11,960 million cubic meters, calculated by Stockton from tree-ring records for the decade from A.D. 1584 to A.D. 1593 (Dracup, 1977). A similar prolonged drought in the middle of the twenty-first century with the same percentage decrease in runoff as in 1584-1593 could bring the 10-year annual average flow down to 7200 million cubic meters, or about 44% of the annual average virgin flow from 1931 to 1976.

Although a 2°C warming is probably a conservative estimate of the effect over the next hundred years of increase of greenhouse gases for the northern United States, the magnitude and even the sign of possible changes in precipitation are uncertain. According to our regression equation, a 10% increase in average annual precipitation combined with a 2°C rise in average temperature would result in an 18% decrease in runoff. To counteract the effects of a 2°C warming completely, a 28% increase in precipitation would be required. Clearly, higher spatial resolution in climate models is needed for more credible forecasts of the effects of increasing atmospheric carbon dioxide and other greenhouse gases on the quantity of water supplies. Possibly, also, seasonal variations from year to year in precipitation and temperature may be more critical in determining Colorado River runoff than annual averaged variations. This possibility could be investigated by statistical analysis of monthly averages of temperature and precipitation for each year against the annual "virgin flow" at Lee Ferry.

7.4 CLIMATE CHANGE AND WATER-RESOURCE SYSTEMS

Planning and construction of major water-resource systems have a time constant of 30 to 50 years. In the past, these activities have been based on the explicit assumption of unchanging climate. The probably serious economic and social consequences of a carbon dioxide-induced climatic change within the next 50 to 100 years warrant careful consideration by planners of ways to create more robust and resilient water-resource systems that will, insofar as possible, mitigate these effects.

REFERENCES

Back, W. D., and J. S. Taylor (1980). Navajo water rights: pulling the plug on the Colorado River. Natural Resources Journal, January 1980, pp. 70-90.

Dracup, J. A. (1977). Impact on the Colorado River Basin and Southwest water supply. In Climate, Climatic Change, and Water Supply. National Academy of Sciences, National Academy Press, Washington, D.C.

Howe, C. W., and A. H. Murphy (1981). The utilization and impacts of climate information on the development and operations of the Colorado River system. In Managing Climatic Resources and Risks. Panel on the Effective Use of Climate Information in Decision Making, Climate Board, National Academy of Sciences, Washington, D.C., pp. 36-44.

Jensen, M. E. (1982). Water resources technology and management. Paper presented at Soil and Water Resources Conservation Act Symposium on Future Agricultural Technology and Resource Conservation, December 1982.

Laney, N. (1982). Does Arizona's 1980 Groundwater Management Act violate the Commerce Clause? Arizona Law Review 24:108-131.

Langbein, W. B., et al. (1949). Annual Runoff in the United States. U.S. Geological Survey Circular 5. U.S. Dept. of the Interior, Washington, D.C. (reprinted, 1959).

Manabe, S., and R. T. Wetherald (1980). On the horizontal distribution of climate change resulting from an increase of CO_2 content of the atmosphere. J. Atmos. Sci. 37:99-118.

Rogers, P. (1983). Water resource technology and management in the future of U.S. agriculture. Paper presented at the Soil and Water Resources Conservation Act Symposium on Future Agricultural Technology and Resource Conservation, December 1982.

Schaake, Jr., J. S., and Z. Kaczmarek (1979). Climate variability and the design and operation of water resource systems. In Proceedings of the World Climate Conference, pp. 290-312. World Meteorological Organization, Geneva, Switzerland.

Stockton, C. W., and W. R. Boggess (1979). Geohydrological implications of climate change on water resource development. U.S. Army Coastal Engineering Research Center, Fort Belvoir, Virginia.

U.S. Water Resources Council (1978). The Nation's Water Resources, The Second National Water Assessment. U.S. Govt. Printing Office, Washington, D.C.