

Climate and the Colorado River: The Limits of Management

Steven L. Rhodes,¹ Daniel Ely,¹
and John A. Dracup²

"The variety of problems that the future holds in store is full-spectrum. Imminent flood danger will have to be balanced against future water shortages."

Gordon B. Freeny (1981)

Abstract

The flooding in the lower basin of the Colorado River during the spring and summer of 1983 led to discussion of the management of the heavy spring runoff from the upper basin. This analysis stresses that the reasons for the flooding go beyond the climatic events of the year and the U.S. Bureau of Reclamation's response to them. It is argued that the flooding is the result of the convergence of three factors: 1) the 17-year period of filling Lake Powell (Glen Canyon Dam) has ended and the system of water storage reservoirs on the river now considered full; 2) during the filling period, physical encroachment into the lower basin flood plain accelerated; and 3) the climatic variability experienced in the Colorado River Basin.

1. Introduction

During the late spring of 1983, unusually heavy snowmelt runoff in the Upper Colorado River Basin (Fig. 1) resulted in flooding, primarily below Parker Dam, and economic losses in the river's lower basin in Arizona, California, and Mexico. For example, residents and businesses in the communities of Needles and Blythe, Calif., and the Parker Strip and Yuma, Ariz., were affected adversely by the floodwaters.

Public awareness of flooding in the American Southwest and Mexico peaked over the July Fourth weekend as news-

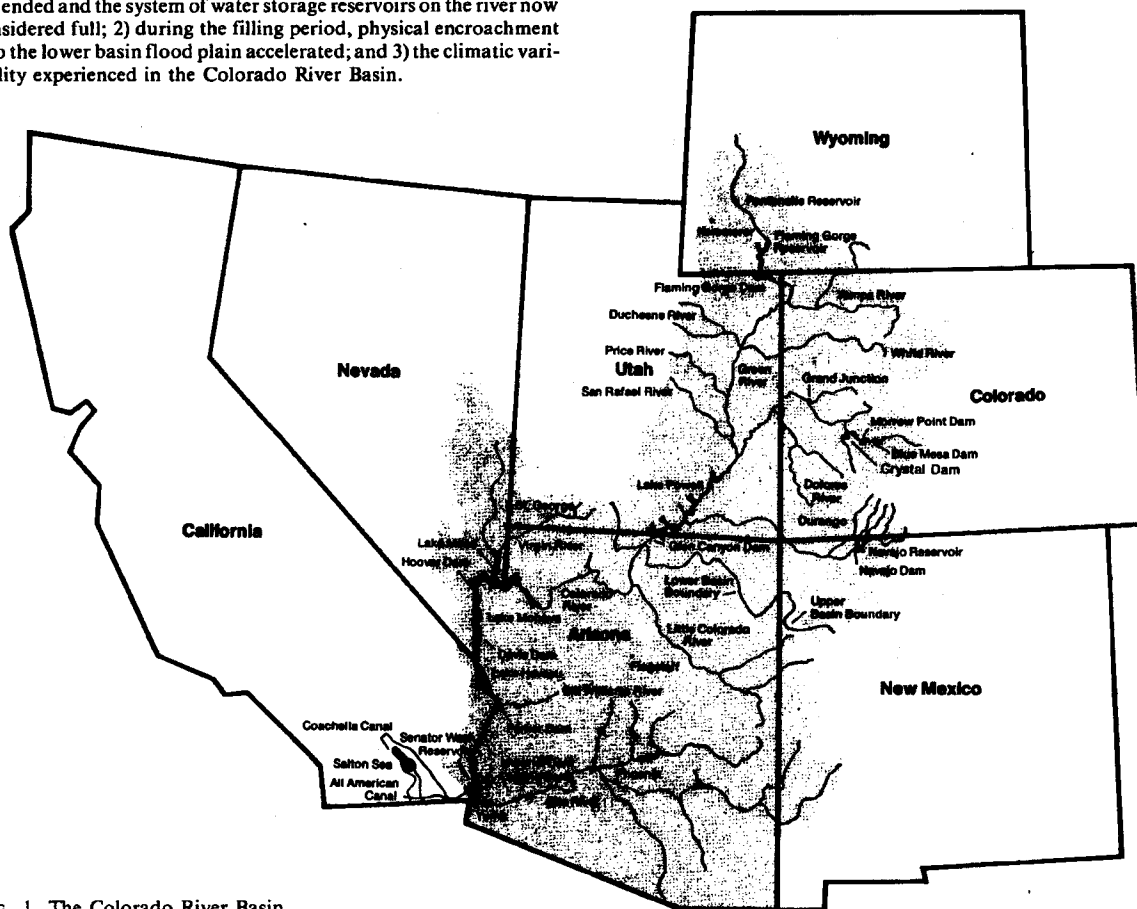


FIG. 1. The Colorado River Basin.

¹ Environmental and Societal Impacts Group, National Center for Atmospheric Research, Boulder, CO 80307. (The National Center for Atmospheric Research is sponsored by the National Science Foundation.)

² Department of Civil Engineering, School of Engineering and Applied Science, University of California, Los Angeles, CA 90024.

papers across the country featured photographs of water pouring over the spillways of Hoover Dam for the first time since 1941, when they were originally (and intentionally) tested. Having heard of the flooding and heavy spring runoff, tourists stayed away during the commercially important Independence Day weekend, further punishing the local economies. Damages have been estimated at nearly \$80 million

(*Arizona Republic*, 1983c). Those affected by the flooding were unequivocal in their condemnation of the U.S. Bureau of Reclamation, the federal agency responsible for managing the river, as homes, trailer parks, recreation facilities, and farm lands were flooded.

Those flooded in the lower basin contend that the bureau should (and could) have anticipated the heavy runoff and prepared for it by releasing water earlier in the year. This would have increased the available flood control space in Lakes Mead (Hoover Dam) and Powell (Glen Canyon Dam). Bureau of Reclamation officials have stated that under similar circumstances, river managers would not do anything differently, and that faced with such rare circumstances, the system did a great job of preventing serious loss of life and property (Dozier and Brown, 1983). Indeed, bureau personnel succeeded in holding streamflow below Hoover Dam to very near the targeted maximum rate of 40 000 cubic feet per second (cfs) ($1132 \text{ m}^3 \cdot \text{s}^{-1}$).

Media coverage (e.g., the MacNeil-Lehrer News Hour, 1983) of the flooding, and associated damage, and revenue loss from decreased tourism prompted a search for the causes of the flooding and possible improvements that might be made in flood control operations. Hearings were held in early September in Yuma, Ariz., and Needles, Calif., by the House Interior Committee because, as Rep. Harry Reid (D-Nev.) stated, "We want to make sure something like this doesn't happen again" (*Rocky Mountain News*, 1983). Hearings also were held in Las Vegas in mid-October.

Though flood victims and Bureau of Reclamation officials disagree as to whether or not the flooding could have been predicted long in advance, there is more to the origin of the 1983 flooding than a question of a short-term climate forecast. This study reveals that the 1983 flooding was the result of the convergence of three factors: the reservoir system along the Colorado generally has been full since the summer of 1980; there has been a gradual physical encroachment into the lower basin flood plain over the last 20 years; and the natural climatic variability of the basin happened to produce a large amount of runoff during the late spring of 1983.

2. Allocation and management of the Colorado River

"Taming" the Colorado River has been a pervasive goal for water resource managers in the American Southwest for decades. The river's main stem and tributaries directly affect the economic, social, and political welfare of millions of people in seven western states. The Colorado River is more important than its average annual flow might suggest. The Colorado drains about 243 000 square miles ($629\,370 \text{ km}^2$) of the contiguous United States (Dracup, 1977), about the same as the Columbia River's watershed. However, the annual flow of the Columbia is, on the average, 9 to 10 times larger than that of the Colorado. One of the most telling examples of the Colorado River's importance is that, except for occasional floods, as in 1983, its waters no longer reach its "natural" outlet in the Gulf of California in Mexico. By the time the river is diverted for the last time onto the dry lands of Baja, Calif., each drop has been used an average of three times (Fradkin, 1981).

Another reflection of the river's importance is the myriad agreements, court suits and decrees, interstate and interbasin compacts, and public laws that together comprise the "Law of the River." The Colorado may be the most legislated and institutionalized river in the world.

The history of the Colorado River Basin has been characterized by conflict and competition between and within regions and states, as well as nations, over control of, and guarantees to, a share of the water resource. During the early 1920s, the development of reclamation projects for fast-growing California was opposed vigorously by upper basin states because of their concern that without their own interests safeguarded, the more rapidly developing lower basin would claim much of the water long before the upper basin developed enough to begin consuming water for its own uses (Fradkin, 1981; Sibley, 1977; Hundley, 1983). The Colorado River Compact of 1922 settled the interregional rivalry and stipulated that the upper basin states must deliver a minimum of 75 million acre-feet ($93 \times 10^9 \text{ m}^3$) to the lower basin in each successive 10-year period. Thus, in order to take into account the variability of the interannual runoff, the lower basin is guaranteed a minimum flow over a decade rather than a specific yearly flow. Further, the upper basin states are required to cut their consumption should they fail to deliver the minimum because of their own overuse or a series of dry years.

The interstate allocation within the lower basin was accomplished in the Boulder Canyon Project Act of 1928, and reaffirmed in *Arizona vs. California* (1964), as follows: California, 4.4 maf ($5.4 \times 10^9 \text{ m}^3$); Arizona, 2.8 ($3.5 \times 10^9 \text{ m}^3$); and Nevada, 0.3 ($0.4 \times 10^9 \text{ m}^3$). The upper basin states found a formula for the division of their water in the Upper Colorado River Compact of 1948, apportioning it as follows: Colorado, 51.75%; New Mexico, 11.25; Wyoming, 14.0; and Utah, 23.0. The use of percentages rather than acre-feet reflected uncertainty about how much water might be available for use by the upper basin states after they fulfilled their compact obligation to the lower basin⁴ (Stockton and Jacoby, 1976; Hundley, 1983). While states are not strictly limited by the agreements to these allocations in years of ample water supply, they constitute the formal division of water and minimum guarantees.

At the international level, the delivery obligation to Mexico is 1.5 maf ($1.9 \times 10^9 \text{ m}^3$) annually, presumably with 0.75 maf ($0.93 \times 10^9 \text{ m}^3$) coming from each basin. However, there is disagreement as to which basin must supply water to Mexico

³ maf = million acre-feet: one acre-foot is equal to the amount of water that will cover one acre to a depth of one foot, or 325 851 gallons.

⁴ At the time of the Colorado River Compact of 1922, the average annual flow of the Colorado was thought to be over 15 maf ($19 \times 10^9 \text{ m}^3$), (probably closer to 16.4 maf ($20.3 \times 10^9 \text{ m}^3$)), and thus the compact split evenly between the basins what was considered to be a conservative estimate of the available waters, that is, 7.5 maf ($9.3 \times 10^9 \text{ m}^3$) each. However, more recent work has put the long-term average annual flow closer to 13.5 maf ($16.7 \times 10^9 \text{ m}^3$) (Stockton and Jacoby, 1976). Because the lower basin gets an absolute amount of water and the upper basin gets what is left, the upper states have expressed a desire to renegotiate the 1922 compact and redivide the waters based on this new assessment (Hundley, 1983, p. 40).

if several dry years force consumptive cuts in a state's use of the Colorado's water (Dracup, 1977).

As a result of the "Law of the River," each basin currently possesses many storage facilities, including a large reservoir (Lake Powell for the upper basin and Lake Mead for the lower basin) capable of storing substantial amounts of water, as well as of generating substantial amounts of hydroelectric power.⁵ The reservoir system now stores about four times the annual flow of the river. This volume of water in storage reflects the determination of the basin states to conserve as much water as possible, thereby providing a margin of safety in the event that a run of dry years occurs, and at the same time strengthening their claim to it. In particular, the upper basin states, in practice, prefer that the releases to the lower basin be the absolute minimum required by law, even though the upper states may not have current "beneficial" uses for all of the water. The concern for balance between the basins is well illustrated by the current operational requirement that the bureau maintain Lakes Mead and Powell at or near an equal volume at the end of each water year (30 September), assuring "equal ownership" of the river following the season of greatest water consumption.

In addition to meeting the objective of water storage in the Colorado Basin's reservoirs, the river's manager, the Bureau of Reclamation, must provide flood control protection to residents, farms, and businesses below Hoover Dam.

Flood control operations rest on two central elements:

- 1) scheduled dedicated water storage space; that is, storage space made available to catch the spring runoff in Lake Mead;
- 2) a forecast of how much water will enter Lake Powell from 1 April through 31 July, produced by the National Weather Service Colorado Basin River Forecast Center in Salt Lake City, Utah.

The objective of the flood control procedure currently in effect is to create enough storage space, through reservoir releases from August to January, to catch the average (based on historical data) April–July runoff. The plan, in action since 1968 and slightly modified in 1982, utilizes a monthly forecast generated for the period January–May that predicts the spring inflow to Lake Powell. Adjustments in the storage space for the forecasted inflow can then be made to keep downstream releases below damaging levels and at the same time conserve as much water as possible.⁶

To meet these goals, the Bureau of Reclamation begins increasing flood control space in Lake Mead⁷ (alone, or to-

gether with storage space in upstream reservoirs) on 1 August of each year in order to have 5.35 maf ($6.60 \times 10^9 \text{ m}^3$) available on 1 January (see Table 2).⁸

The bureau's scheduled outflow release rates (water passed through the dams) and storage space availability based on the NWS inflow forecasts has worked well in recent decades to minimize water lost through unneeded anticipatory releases and flooding below Hoover Dam. This has helped to optimize hydroelectric generation, water conservation storage, and flood control. However, the conditions prevalent in the Colorado Basin in the 1980s have become radically different from those of the 1960s and 1970s. The new conditions contributed significantly to the flooding that occurred in the spring and summer of 1983.

3. Events of 1983

Reclamation Bureau Commissioner Robert Broadbent (1983) said of the year's situation,

The 1983 runoff was such an unusually large event that no realistic changes in reservoir operations or improvements in runoff forecasts could have prevented the high flow levels and subsequent flood damages that occurred along the Colorado River.

The bureau entered 1983 with 6.6 maf ($8.1 \times 10^9 \text{ m}^3$) of storage space available in Lake Mead and upstream, more than the required 1 January target of 5.35 maf ($6.60 \times 10^9 \text{ m}^3$). Yet even with the surplus storage space available, the reservoir system was overwhelmed by the magnitude of the spring inflow to Lake Powell. Dozier and Brown (1983) note that

This has been an extraordinary year from the standpoint of snowfall and snowmelt runoff. It may be the largest runoff of record since 1906 . . . and will probably exceed a "100 year" event.

Because of late precipitation and cool weather throughout the upper basin, snowpack continued to increase during April and May (Dozier and Brown, 1983). One observer noted that "It was only the late-season precipitation that boosted the season-long precipitation of all of the Basin's immense areas to above-average levels" (Holburt, 1983). Figure 1 shows the rapid and abnormal changes in the forecasted inflow to Lake Powell from January through July 1983.

of error in response to the 1983 runoff conditions (Zimmerman, 1984).

⁷ According to the flood control plan for the Colorado River, Lake Mead is the only major basin reservoir with an explicit flood control space schedule.

⁸ Prior to the construction of Glen Canyon Dam and prior to the U.S. Army Corps of Engineers 1982 report (see Table 2), the standard flood control procedure was to have 5.8 maf ($7.2 \times 10^9 \text{ m}^3$) of storage available on 1 January, as recommended by Eugene Debler (Debler, 1930). This storage requirement was increased each month until a maximum requirement of 9.5 maf ($12 \times 10^9 \text{ m}^3$) was reached on 1 April. These procedures were formalized by the Corps of Engineers in 1955 and continued in effect until 1968.

⁵ The term "Law of the River" refers to the aggregate public laws, court decrees, interstate compacts, and other institutional arrangements that comprise the context within which the Colorado River is managed. For a concise review of these items, see Hundley (1983).

⁶ The National Weather Service's Colorado Basin River Forecast Center uses monthly estimates of error to arrive at forecasts of the maximum and minimum probable April–July runoff. Values are added to and subtracted from the most probable runoff forecast to obtain the maximum and minimum probable runoff forecasts, respectively. The added and subtracted values decline from January through July because later forecasts improve in accuracy. Table 1 displays the estimates of error that were used in Water Year 1983. It is interesting to note that NWS recently revised its monthly estimates

TABLE 1. The estimates of error to obtain the maximum probable or minimum probable April through July runoff forecast.

Date of forecast	Used in Water Year 1983		Units—million acre-feet (10^9 m^3)	
	Lake Powell inflow		Lake Mead inflow	
	Maximum probable forecast	Minimum probable forecast	Maximum probable forecast	Minimum probable forecast
1 January	+3.970 (4.897)	-3.010 (3.713)	+4.415 (5.446)	-3.255 (4.015)
1 February	+3.130 (3.861)	-2.400 (2.960)	+3.510 (4.330)	-2.620 (3.232)
1 March	+2.310 (2.849)	-1.815 (2.239)	+2.645 (3.263)	-2.020 (2.492)
1 April	+1.600 (1.974)	-1.300 (1.604)	+1.885 (2.325)	-1.490 (1.838)
1 May	+1.040 (1.283)	-0.900 (1.110)	+1.280 (1.579)	-1.075 (1.326)
1 June	+0.557 (0.687)	-0.557 (0.687)	+0.770 (0.950)	-0.720 (0.888)

TABLE 2. Hoover Dam flood control available space schedule (source: U.S. Army Corps of Engineers, 1982).

Date	Available flood control storage space	
	maf	(10^9 m^3)
1 August	1.50	(1.85)
1 September	2.27	(2.80)
1 October	3.04	(3.75)
1 November	3.67	(4.53)
1 December	3.96	(4.89)
1 January	5.35	(6.60)

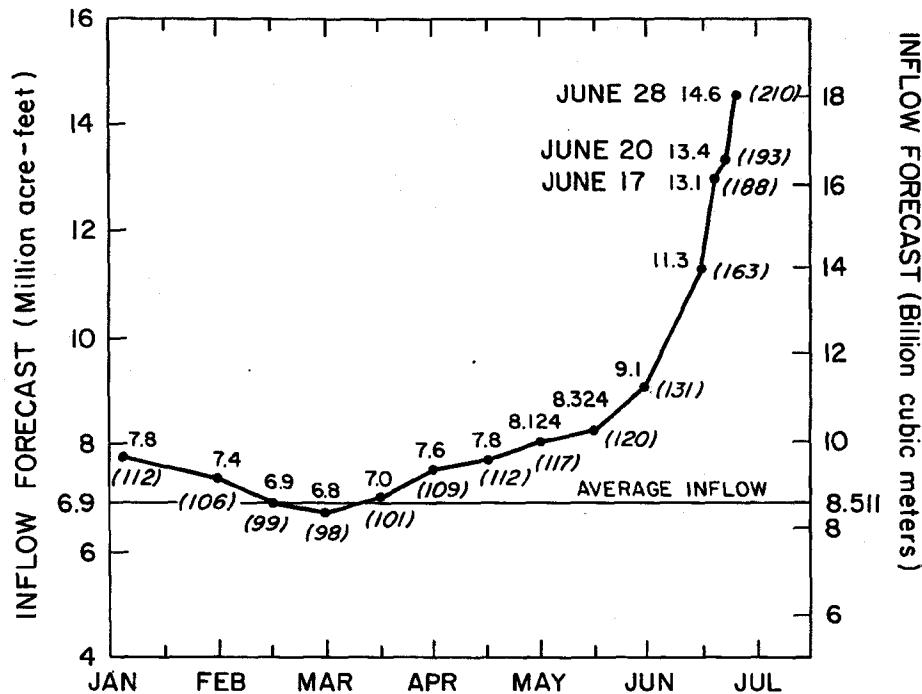


FIG. 2. 1983 Lake Powell April-July inflow forecasts as compared to average inflow (source: Dozier and Brown, 1983). Note: Numbers in parentheses represent percent of normal inflow, based on the 1963-77 average.

Table 3 presents the projected inflows to Lake Powell for the April–July period, the required Hoover Dam release rates according to the flood control operating procedure, and the actual Hoover release rates decided upon by bureau officials in the Lower Colorado Basin. Figure 2 illustrates the relationship between Lake Powell inflows, Lake Powell outflows, and Hoover Dam releases from April through July 1983. Because of the massive influx of water into Lake Powell, bureau officials downstream had to increase outflows from Glen Canyon Dam. This in turn obliged lower basin officials to raise outflows from Hoover Dam. The releases at Hoover Dam, which historically had been held to about 25 000 cfs ($708 \text{ m}^3 \cdot \text{s}^{-1}$), had to be elevated to over 40 000 cfs ($1132 \text{ m}^3 \cdot \text{s}^{-1}$) in July. One acre-foot (1233.5 m^3) equals 43 560 cubic feet; thus a flow of 40 000 cfs ($1132 \text{ m}^3 \cdot \text{s}^{-1}$) equals nearly one acre-foot (1233.5 m^3) per second. This is a critical point, for 40 000 cfs ($1132 \text{ m}^3 \cdot \text{s}^{-1}$) was the targeted maximum outflow rate from Lake Mead under the 1968 revised flood control procedures. Indeed, bureau operators successfully limited Hoover release rates to 40 000 cfs ($1132 \text{ m}^3 \cdot \text{s}^{-1}$) except for the month of July, during which Hoover releases averaged 41 854 cfs ($1185 \text{ m}^3 \cdot \text{s}^{-1}$).

The rapid sequence of meteorological events occurring late in the spring, coupled with the problem of attempting to move massive amounts of water through Lakes Powell and Mead in a short period of time, resulted in streamflows above those lower basin residents and businesses had come to expect.

4. Why the flooding occurred

a. Operation of a full system

The filling of Lake Mead began in February 1935 and the filling of Lake Powell began in March 1963. During the filling

periods for the lakes, flood control operations on the Colorado River were routine because runoff in excess of hydro-power generation needs and water supply demands downstream of Hoover Dam could be stored easily. Over the nearly two decades of controlled filling of Lake Powell, ample storage space was available to hold virtually any spring inflow without elevated releases downstream. Figure 3 illustrates the amount of water in storage during the Lake Powell filling period through the end of water year 1982. However, in the 1980s conditions changed: the entire Colorado River reservoir system now is considered full, and the 1 January required minimum flood control storage space in Lake Mead, which was reduced to 5.35 maf ($6.60 \times 10^9 \text{ m}^3$) during the Lake Powell filling period, was continued at that amount after Lake Powell was filled. These conditions require that forecasts be accurate and that rapid changes in inflows to Lake Powell be monitored carefully. Monitoring inflows allows corrective management responses if conditions permit. However, in 1983, Lake Powell inflows rose so rapidly that there was no time for mitigating responses. For example, on 24 May 1983, the unregulated inflow to Lake Powell was approximately 37 000 cfs ($1047 \text{ m}^3 \cdot \text{s}^{-1}$). Eight days later, on 1 June, the unregulated inflow was 102 000 cfs ($2887 \text{ m}^3 \cdot \text{s}^{-1}$) (U.S. Bureau of Reclamation, 1983b).

The operation of a full system may be improved with an optimal operation policy (Loucks *et al.*, 1981) using real-time telemetered precipitation and streamflow data. However, even real-time data may not be enough to manage a very wet year such as 1983, because it takes substantial time to move water through dams with structurally limited release rates. Table 4 shows the time required to evacuate 7 maf ($9 \times 10^9 \text{ m}^3$) of storage at various outflow rates. Since the 1983 April–July inflow into Lake Powell was more than 14 maf

TABLE 3. 1983 runoff forecasts—Colorado River above Lake Powell. Inflow forecasts and operations at Hoover Dam. See Dozier and Brown (1983) and U.S. Bureau of Reclamation (1983b).

Forecast	Date	April–July Runoff estimate		Percent average	Minimum required Hoover release		Actual average Hoover release		
		maf	(10^9 m^3)		cfs	($\text{m}^3 \cdot \text{s}^{-1}$)	cfs	($\text{m}^3 \cdot \text{s}^{-1}$)	
January 1983	Preliminary	12/30/82	7.8	(9.6)	112	19 000 (538)	19 130	(541)	
	Final	01/06/83	7.8	(9.6)	112	19 000 (538)			
February 1983	Preliminary	02/02/83	7.4	(9.1)	106	None	6590	(187)	
	Final	02/04/83	7.1	(8.7)	102	None			
	Mid-Month	02/15/83	6.9	(8.5)	99	None			
March 1983	Preliminary	03/02/83	6.8	(8.4)	98	None	10 270	(291)	
	Final	03/04/83	6.7	(8.3)	96				
	Mid-Month	03/16/83	7.0	(8.6)	101	2200 (62)			
April 1983	Preliminary	04/01/83	7.6	(9.4)	109		17 810	(504)	
	Final	04/06/83	7.9	(9.8)	114	12 900 (365)			
	Mid-Month	04/15/83	7.8	(9.6)	112	10 800 (306)			
May 1983	Preliminary	05/03/83	8.12	(10.0)	117		19 800	(560)	
	Final	05/06/83	8.12	(10.0)	117	14 600 (413)			
	Mid-Month	05/17/83	8.32	(10.3)	120	16 200 (458)			
June 1983	Preliminary	06/02/83	8.85	(10.9)	127		31 700	(897)	
	Final	06/07/83	9.10	(11.2)	131	19 000 (538)			
	Mid-Month	06/13/83	11.3	(13.9)	163	47 300 (1339)			
	Special	06/17/83	13.1	(16.2)	188	52 900 (1497)			
	Special	06/20/83	13.4	(16.5)	193				
	Special	06/28/83	14.6	(18.0)	210				
Actual runoff:		April 1983 = 1.124 maf ($1.386 \times 10^9 \text{ m}^3$)	June 1983 = 6.559 maf ($8.091 \times 10^9 \text{ m}^3$)						
		May 1983 = 3.314 maf ($4.088 \times 10^9 \text{ m}^3$)	July 1983 = 3.513 maf ($4.333 \times 10^9 \text{ m}^3$)						

($17 \times 10^9 \text{ m}^3$), the number of days must be doubled to give a legitimate representation of the 1983 spring runoff.

Decisions made regarding flood control releases from all the dams on the Colorado River must be made early enough to avoid the backing up of large amounts of water in the system. The system as a whole is operated in such a way as to maximize the amount of water in storage as protection against dry years. However, a full system does not provide much latitude for flood control.

Because the system generally has been maintained at a full capacity since the summer of 1980, the operating strategies might have been altered to take account of the fact that some flooding could occur until the Central Arizona Project (CAP) begins drawing water out of Lake Havasu behind Parker Dam for Phoenix and Tucson (Freeny, 1981). CAP is considered to have flood control benefits in the sense that it will divert water from the Colorado River above those areas that were damaged by the 1983 streamflow. However, when a cost-benefit analysis using nine different operating strategies was run by the Corps of Engineers, the optimal yield was produced by the current operating strategy; the result was that the river management scheme that has been in effect since 1968 was retained virtually unchanged (U.S. Army Corps of Engineers, 1982). Yet the original flood control operating plans of 1935 and 1968 were intended, as a recent bureau report states, "to control flooding to the greatest extent

TABLE 4. Storage evacuation of 7 000 000 acre-feet at various outflow rates (source: U.S. Bureau of Reclamation, 1983a).

cfs	Outflow discharge	Time (days)
	($\text{m}^3 \cdot \text{s}^{-1}$)	
10 000	(283)	352
20 000	(566)	176
30 000	(849)	117
40 000	(1132)	88
50 000	(1415)	70

possible" (U.S. Army Corps of Engineers, 1982). The Boulder Canyon Project Act (1928), which authorized the construction of Hoover Dam, established that the river be managed "First, for river regulation, improvement of navigation, and flood control; second, for irrigation and domestic uses and satisfaction of present perfected rights . . . ; and third, for power." However, since that time, people have moved into the flood plain (physical encroachment). Releases that earlier would have caused minimal or no damage inflicted serious losses in 1983. According additional flood protection to interests in the lower basin was outweighed by the benefits accruing to other lower basin as well as upper basin interests.

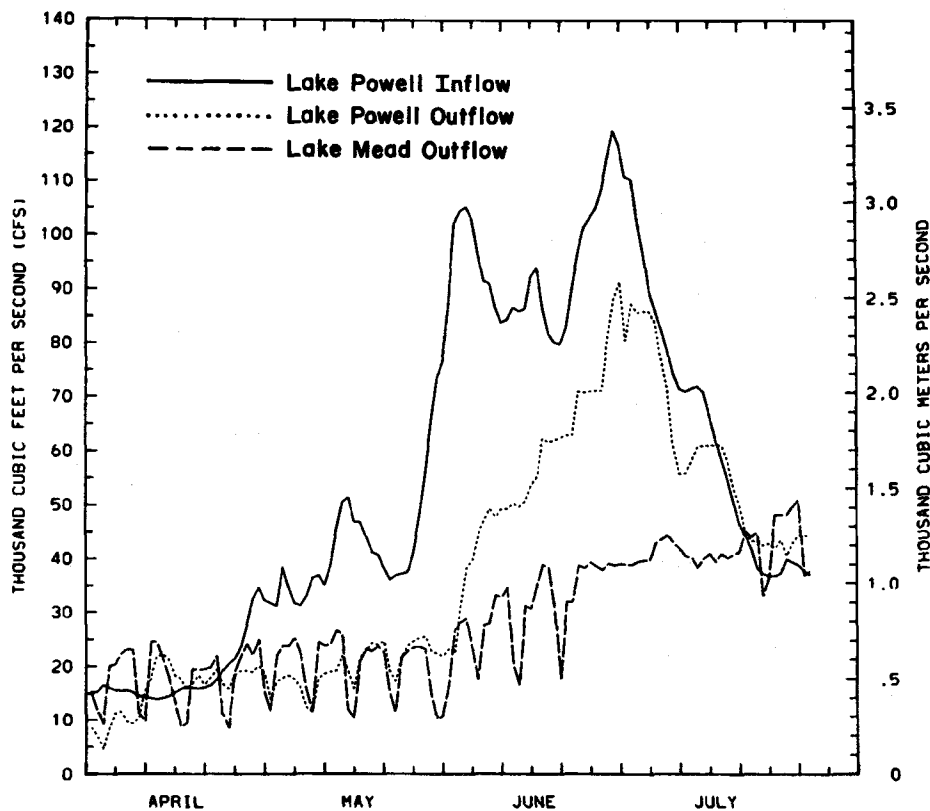


FIG. 3. Lake Powell inflows, outflows, and Hoover Dam release rates, April-July 1983 (source: U.S. Bureau of Reclamation, 1983b).

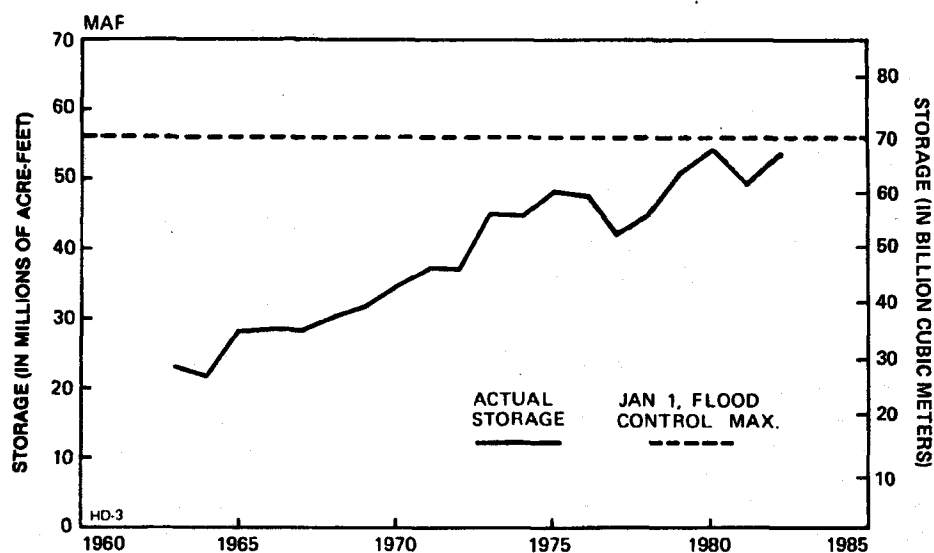


FIG. 4. Colorado River reservoir system: Water in storage 1963–82, including the Lake Powell filling period (source: U.S. Army Corps of Engineers, 1982).

b. Physical encroachment into the flood plain

Physical encroachment into the lower basin flood plain is the result of where one defines a flood plain and of observed stability in the interannual streamflow, which can result in changes in perceptions of land-use alternatives. Thus the encroachment into the lower basin flood plain, which would not have occurred in the absence of the big dams, was encouraged by a combination of technological fixes and lax zoning practices in counties bordering on the Colorado River (*Arizona Republic*, 1983a,b).

The two major dams on the Colorado River have performed as planned in controlling the variability of streamflow rates (see Fig. 4). Glen Canyon and Hoover Dams consequently have provided substantial protection to the lower Colorado flood plain in terms of their ability to reduce the meandering and backwashing associated with high spring streamflows. Even in 1983, releases at Hoover Dam did not significantly exceed 50 000 cfs ($1415 \text{ m}^3 \cdot \text{s}^{-1}$) (see Fig. 3).

The history of development in the flood plain began roughly with the construction of earthen levees in the area around Yuma, Ariz. The levee system was constructed to protect agricultural land (fertile flood plain soil) from the annual rush of spring snowmelt (U.S. Army Corps of Engineers, 1982). With the completion of Hoover Dam and the subsequent decrease in the spring streamflow's variability, more flood plain acreage became less flood-prone. This resulted in the construction of residential and commercial structures in these areas, along with the settlement of areas farther from the streambed, but still subject to inundation prior to the construction of Hoover Dam. As the 1982 review of flood control operating procedures notes (U.S. Army Corps of Engineers, 1982):

Few, if any, structures were located in the 40 000 [cfs] ($1132 \text{ m}^3 \cdot \text{s}^{-1}$) flood plain in the lower Colorado River at the time of the closure of Hoover Dam (1935) and for some years thereafter. For many years the flood control operation plan for Hoover Dam has incorpo-

rated a "target maximum" flood control release of 40 000 [cfs] ($1132 \text{ m}^3 \cdot \text{s}^{-1}$).

Streamflow variability narrowed sharply with the construction of Glen Canyon Dam. This coincided with the period of greatest physical encroachment into the flood plain, which included construction in and development along the streamflow profile of less than 28 000 cfs ($792 \text{ m}^3 \cdot \text{s}^{-1}$) (U.S. Army Corps of Engineers, 1982). The Bureau of Reclamation was aware of the encroachment, particularly the development that occurred during the Lake Powell filling period (Freeny, 1981; Broadbent, 1983). However, the bureau has no authority over land-use decisions in the basin states.

The period of time during which the Colorado reservoir system was filling was a period in which true exposure to climatic impacts, i.e., precipitation variability, did not exist. It was not representative of a new climatic regime in the basin, but only of anthropogenic interference with the flow of the river. The encroachment into the flood plain was possible because water was in storage upstream, and also because the period during which Lake Powell was filled lasted almost two decades. Two decades is more than a sufficient period of time to affect societal perceptions of climate stability.

c. Climate variability in the Colorado Basin

Perceptions of climate stability in the Colorado Basin are not borne out by historical data. In fact, the third factor that contributed to the 1983 flooding in the lower basin was the variability of the climate in the arid Southwest. As Fig. 5 demonstrates, the variability of the river's streamflow is substantial. Only seven years before, the western United States was hit with a severe drought, resulting in a significant drop (to 5.6 maf [$6.6 \times 10^9 \text{ m}^3$]) in the estimated virgin flow of the Colorado in 1977 (Upper Colorado River Commission, 1982).

It is interesting to note that the 1977 drought also played a key role in the decision among the Colorado Basin states to defer any action regarding revision of the river management

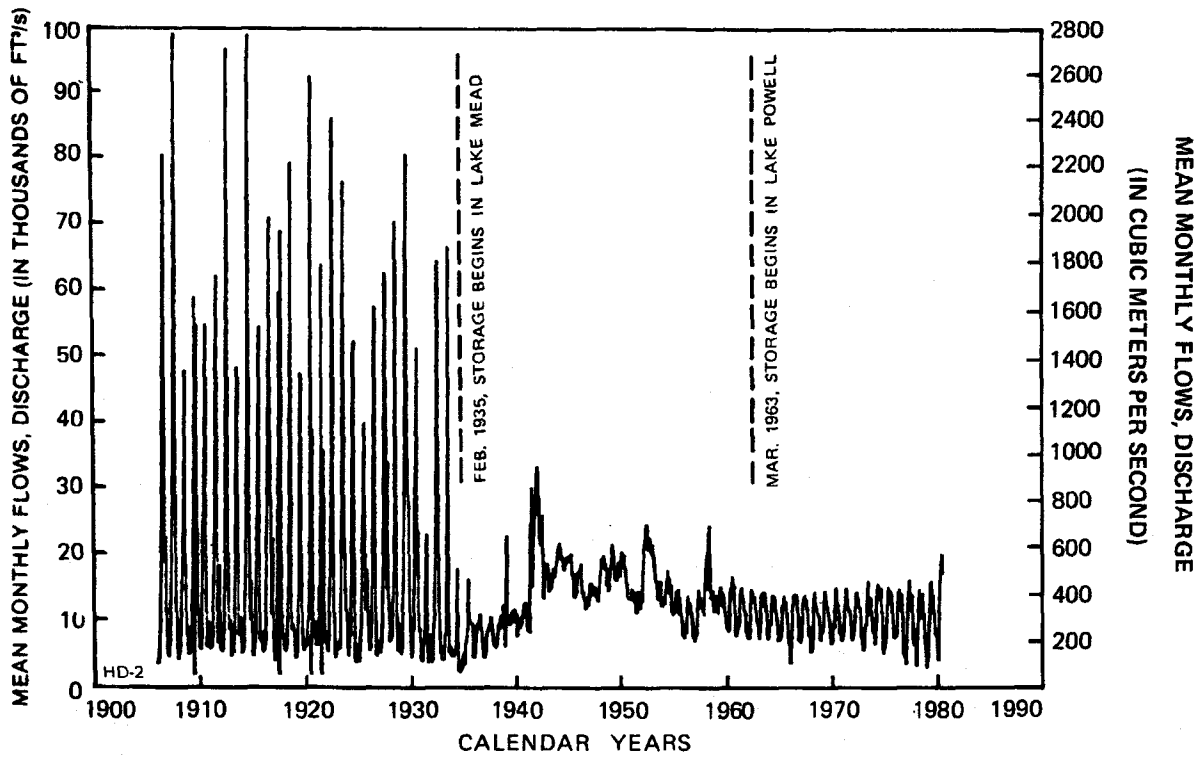


FIG. 5. Mean monthly flows on the Colorado River below Hoover Dam (source: U.S. Army Corps of Engineers, 1982).

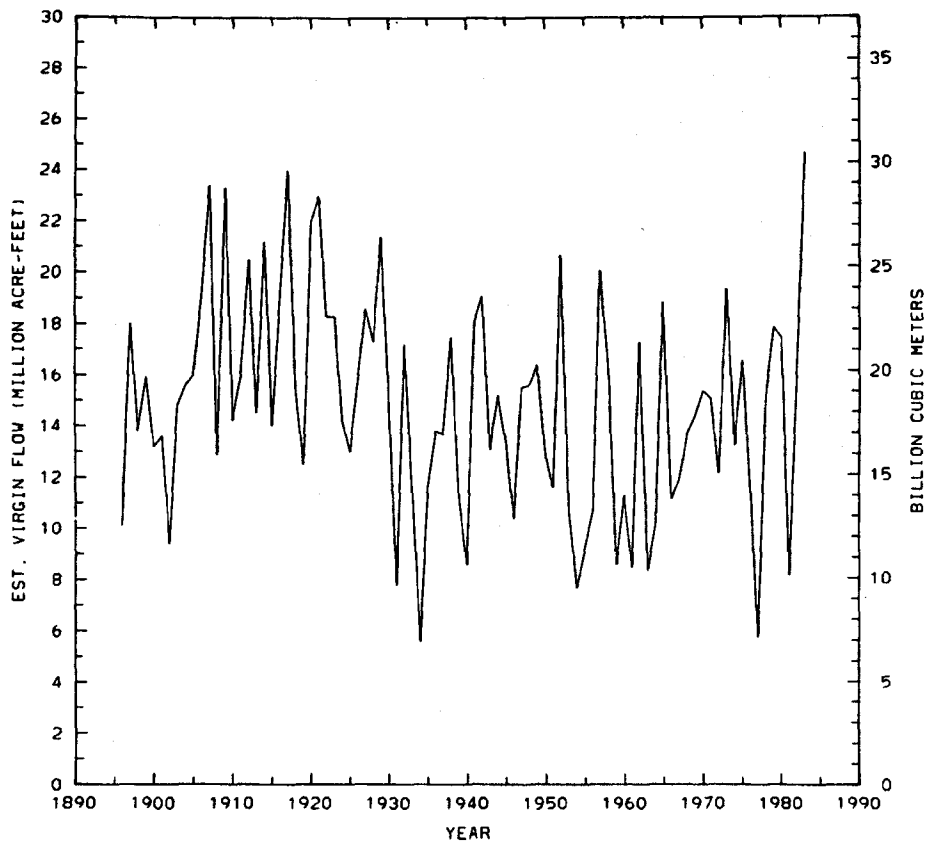


FIG. 6. Estimated virgin flow of the Colorado River at Lee Ferry, 1896-1983 (source: Upper Colorado River Commission, 1982).

scheme (Broadbent, 1983). The concern in the Colorado Basin was reinforced again in terms of the major adverse climate impact to be expected: drought is the concern, a wet year is not.

What is of great importance in Fig. 4, however, is that the river's virgin flow not only has been below the historical average of about 14 maf ($17 \times 10^9 \text{ m}^3$), but frequently has greatly exceeded that average as well. Clusters of wet and dry years are believed to occur (Holburt, 1982), thus contributing to difficulties in flood control management with a full system in wet years and water conservation storage in dry years. Indeed, because of the effect of a full system and a variable climate, a Bureau of Reclamation official had noted in 1979 that "the present operating strategy . . . involves an 85% risk that damaging floodflows will occur between 1980 and 1984"⁹ (Freeny, 1981). Because of climate variability, it has been estimated in a preliminary study by the General Accounting Office that if the river continues to be managed by keeping reservoirs at or near full, controlled flooding similar to that that occurred in 1983 can be expected to be repeated once "every 10 to 15 years" (*Arizona Republic*, 1983c).

Thus one can argue that it was not the streamflow variability in itself that caused the 1983 spring flooding and associated damages. Flood plain encroachment and a full reservoir system, in conjunction with streamflow variability, converged to create appropriate conditions for the events of 1983.

5. For whom is the river managed?

Controlling the Colorado River's variable flows in the spring (and occasionally in the fall) has softened the adverse impacts of climatic variability in the Colorado Basin, while at the same time making the water resource available for multiple uses. Controlling the river also has made real estate downstream in the flood plain more valuable for homesites and productive agricultural activities.

After the large storage facilities along the river were completed, the potential for conflicts developed between those requiring flood control protection, which is achieved only by reserving reservoir storage space, and those desiring the water supply and hydropower¹⁰ (Freeny, 1981). Since the total available storage on the river is about four times the average annual flow, a flood of any magnitude could be controlled if sufficient storage space were placed in reserve. However, the only advocates for keeping a large storage space reserved for flood control are the individuals living and working in the flood plain below Hoover Dam. All other interested parties throughout the upper and lower basins, including recreational users, strongly advocate keeping the reservoirs as full as possible or within a narrow range of fluctuation.

⁹ Freeny (1981). At the time this paper was presented, 1984 was thought to be the year that CAP would become operational. More recent projections point to CAP beginning operations in 1985 or later.

¹⁰ Other conflicts in storage requirements occur between the recreational users, hydroelectric power purchasers, and municipal and agricultural users. Each of these users has priorities for reservoir release rates and timing that are optimal for their needs.

One might argue that storing water has become the dominant theme in the management of the Colorado River. This can be viewed as the result of efforts to satisfy the interests of beneficiaries other than those interested in flood control in the lower basin. Obviously, the beneficiaries of water storage have had their risks and vulnerability reduced as the reservoir system has filled up. However, it also is evident that as the reservoir system has filled, the risk exposure has shifted from those interested in maximal water storage (consumptive users, hydroelectric generation contractees, recreational users) to those interested in flood control. As one discussion (Freeny, 1981) notes:

Regulation of the Lower Colorado system requires that a delicate balance be maintained between three diametrically opposed communities of users. One of the problems faced by system operators arises from the attitudes of the users toward risk: all three groups demand zero risk. The flood control group wants zero risk of damage. Power users want zero risk of generation losses. Water users want zero risk of water shortages 30 years in the future. Somehow, through technology or political science, some way should be devised to change these zeros into more realistic figures so that values can be traded.

During the reservoir system's filling period, there was a substantial capacity for upstream storage of above-average inflows. Therefore, during the Lake Powell filling period, most of the interests of the flood control advocates were fulfilled with a minimum of effort.

The reasons for the 1983 flooding are interrelated and stem more from a regional fear of drought and loss of water rights than from local concerns about floods. The "free ride" accorded to those in the flood plain has ended, at least temporarily (presumably until CAP begins pumping water from Lake Havasu).

The interplay of the three factors that contributed to the 1983 flooding in the Lower Colorado Basin could recur in 1984 as well as in later years. Given that climate variability is beyond the control of the river's managers, attention must be focused on flood plain encroachment and the question of how much storage space should be dedicated to flood control in Lake Mead and upstream.

Flood plain development could be curtailed if county zoning standards are made more rigorous. An effort has been made to tighten those standards in lower basin states, particularly in Arizona. Federal efforts already had been initiated prior to the 1983 flooding, and state and local governments were beginning to exercise greater authority over flood plain developments. For example, Executive Order 11988, signed by President Carter in May 1977, requires federal agencies to help avoid development in the 100-year flood plain, reduce the risk of flood loss, and minimize flood impacts on human health, safety, and welfare (U.S. Army Corps of Engineers, 1982). Other efforts include the Flood Disaster Protection Act of 1973, which requires the purchase of flood insurance by people living in established flood plains and provides for withholding of federal assistance from cities and counties that are lax in controlling flood plain development (U.S. Army Corps of Engineers, 1982).

The issue of dedicated flood control storage space be-

comes a critical point in the management of the Colorado. Accepting the bureau's assumption that CAP will help to alleviate the flooding problem by providing an additional water diversion point, a temporary change in the dedicated flood control space could help to protect property in the lower basin (Broadbent, 1983; Freeny, 1981). However, since 1983's precipitation and runoff were so abnormal, proposals for increasing storage space will not necessarily be received warmly (Broadbent, 1983).

The 1977 response to drought indicated that there is substantial support for maintaining full reservoirs upstream, and that flood control for lower basin residents and other interested groups is not given high priority by the other beneficiaries of the river. Water resources in the American Southwest are managed for dry years, not for extremely wet years such as 1983. This is precisely the reason why the reservoir system is maintained at a full level. The dominant preference to keep the reservoir system full may continue to expose lower basin interests to flood damage during very wet years. This preference is reflected in the words of a California water engineer (Holburt, 1983) who said:

Requiring release of water in excess of beneficial use increases the probability of reduced future use because the water that would have otherwise been in storage will not be there. This fact must be considered in reviewing flood control criteria.

6. Conclusion

Flooding in the Lower Colorado Basin caused damages to homes and businesses in the spring and summer of 1983. The highly abnormal meteorological events that contributed to the flooding were not wholly responsible for the 1983 flooding, however. Other factors that contributed to the flooding were the maintenance of a system of full reservoirs (reflecting societal concern for drought) and physical encroachment into the flood plain (made possible by the dams along the river). These factors can be managed, but there are strong reasons why these choices may not be made in the future. Ultimately, the management of the Colorado River is the product of political and economic constraints imposed by the river's many beneficiaries.

Acknowledgments. The authors are grateful for helpful comments from Michael H. Glantz, Robin L. Dennis, Paulette Middleton, and Thomas R. Stewart in the Environmental and Societal Impacts Group at NCAR and for the editorial assistance of Maria Krenz. The authors also wish to express their gratitude to Mary Downton at NCAR for her help in preparing some of the graphs and to William Mitchell for providing information during the flooding. The opinions expressed are those of the authors and are not those of NCAR, the National Science Foundation, or the American Meteorological Society.

References

- ¹¹ *Arizona Republic*, 1983a: "The Flood Facts" (22 June), p. A2.
- ¹¹ —, 1983b: "Residents Who Built Near River Should Have Expected Trouble, Watt Says" (1 July), p. A2.
- , 1983c: "\$80 Million Flood Was 'Unavoidable'" (3 September), p. B1.
- Arizona vs. California*, 1964: 373 U.S. 546.
- Boulder Canyon Project Act, 1928: 45 Stat. 1057.
- Broadbent, R., 1983: Prepared statement for the U.S. House of Representatives Committee on Interior and Insular Affairs, 7 September 1983, Yuma, Ariz.
- Debler, E. B., 1930: *Hydrology of the Boulder Canyon Reservoir with Reference Especially to the Height of Dam to be Adopted*. U.S. Bureau of Reclamation, Denver, Colo.
- ¹¹ *Denver Post*, 1983a: "Water Over the Dam" (7 July), p. 2B.
- , 1983b: "Floods Point Up the Danger of Looking at a River as Plumbing" (8 July), p. 23B.
- ¹¹ —, 1983c: "Colorado River Floods: Who's to Blame, Man or Nature?" (17 July), p. 1A.
- ¹¹ Dozier, L., and J. Brown, 1983: Management of Colorado River dams. Paper presented at the Eighth Annual Workshop of the Rural Communities Institute, Gunnison, Colo., 1-3 August 1983.
- Dracup, J. A., 1977: Impact on the Colorado River Basin and Southwest water supply. In *Climate, Climatic Change, and Water Supply*, National Research Council, National Academy Press, Washington, D.C.
- Fradkin, P. L., 1981: *A River No More*. Alfred A. Knopf, Inc., New York.
- Freeny, G. B., 1981: Managing conflicts on the lower Colorado River system. In *Proceedings of the National Workshop on Reservoir Systems Operations*, Boulder, Colo., 13-17 August 1979, American Society of Civil Engineers, New York.
- Holburt, M., 1982: Good water year fills Colorado's reservoirs. *Colo. River Assoc. Newslett.*, 17(4), Fall, p. 6, Colorado River Association.
- , 1983: Prepared statement for the U.S. House of Representatives Committee on Interior and Insular Affairs, 8 September 1983, Needles, Calif.
- ¹¹ Hundley, N., Jr., 1983: The West against itself: The Colorado River in historical perspective. Prepared for the Colorado River Working Symposium: Management Options for the Future, Santa Fe, N.Mex., 23-26 May 1983.
- Loucks, D. P., J. R. Stedinger, and D. A. Haith, 1981: *Water Resource Systems Planning and Analysis*. Prentice-Hall, Englewood Cliffs, N.J.
- ¹¹ *MacNeil-Lehrer News Hour*, 1983: "High Water Out West," Transcript No. 2075 (9 September 1983).
- ¹¹ *Rocky Mountain News*, 1983: "Runoff Handling to be Probed" (7 July), p. 4.
- Sibley, G., 1977: The desert empire. *Harper's*, 255(1529) October, 49-68.
- Stockton, C. W., and G. C. Jacoby, Jr., 1976: Long-term surface-water supply and streamflow trends in the upper Colorado River Basin, *Lake Powell Res. Proj. Bull.* 18, RANN, National Science Foundation, Washington, D.C.
- Upper Colorado River Commission, 1982: *Thirty-Fourth Annual Report* (30 September), Salt Lake City, Utah.
- U.S. Army Corps of Engineers, 1982: *Colorado River Basin—Hoover Dam: Review of Flood Control Regulation*. Final Report, U.S. Army Corps of Engineers, Los Angeles, Calif., 65 pp. plus appendices.
- U.S. Bureau of Reclamation, 1983a: *Congressional Briefing Book on the Operation of the Colorado River*, U.S. Department of the Interior, Washington, D.C., 73 pp.
- , 1983b: *Status of Reservoirs, Colorado River Storage Project*.
- Zimmerman, G., 1983: Memorandum to Upper Colorado River Commissioners and Advisers, "Revised Estimates of the Error in the April through July Runoff Forecast," 18 January, Salt Lake City, Utah. ●

¹¹ Material from this source has been reprinted by permission.