APPENDIX C
The Utilization and Impacts of Climate Information on the Development and Operations of the Colorado River System

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I. CLIMATOLOGICAL UNCERTAINTY AND THE HISTORICAL DEVELOPMENT OF THE RIVER

A. A History of Climate Variability

Interest in the Colorado River can be traced back at least to the sixteenth century when Francisco de Ulloa first discovered its mouth (1537). His description of this first encounter and his subsequent voyage up to the confluence with the Gila point out the vast changes in the river that have since taken place[1]:

> We perceived the sea to run with so great a rage into the land that it was a thing to be marvelled at; and with a fury it returned back again with the ebb . . . and some thought . . . that some great river might be the cause thereof.

Today, the Colorado never reaches the sea, nor does the Gila reach the Colorado, so greatly have man's uses of the rivers' waters increased (see Figure C.1). The Colorado has, indeed, become a highly sought-after and tightly controlled resource, quite contrary to the prediction of Southwest explorer J. C. Ives who, in 1850, stated[1]:

> Ours has been the first and will doubtless be the last party of whites to visit this profitless locality. It seems intended by nature that the Colorado River, along the greater portion of its lonely and majestic way, shall be forever unvisited and undisturbed.

John Wesley Powell made the first full-scale exploration of the Colorado in 1869,[2] starting on the Green River in Wyoming and taking a hazardous four-month trip through the Grand Canyon and on to the Gulf of California. Powell's reports were optimistic regarding the future of the region, and the information he provided assisted others in preparing to exploit its resources.

A Mormon settlement in Southwest Wyoming first diverted water for irrigation from the Green River in 1854. The Uncompaghgre Valley was put under irrigation in 1880. Because the natural reliable river flow was small, one of the first Reclamation Service projects (1909), a six-mile tunnel from the Gunnison River into the Uncompaghgre, was built to supplement these waters—an exciting engineering feat for that time.

The Lower Basin grew much faster than the Upper. Samuel Blythe made the first gravity diversions from the

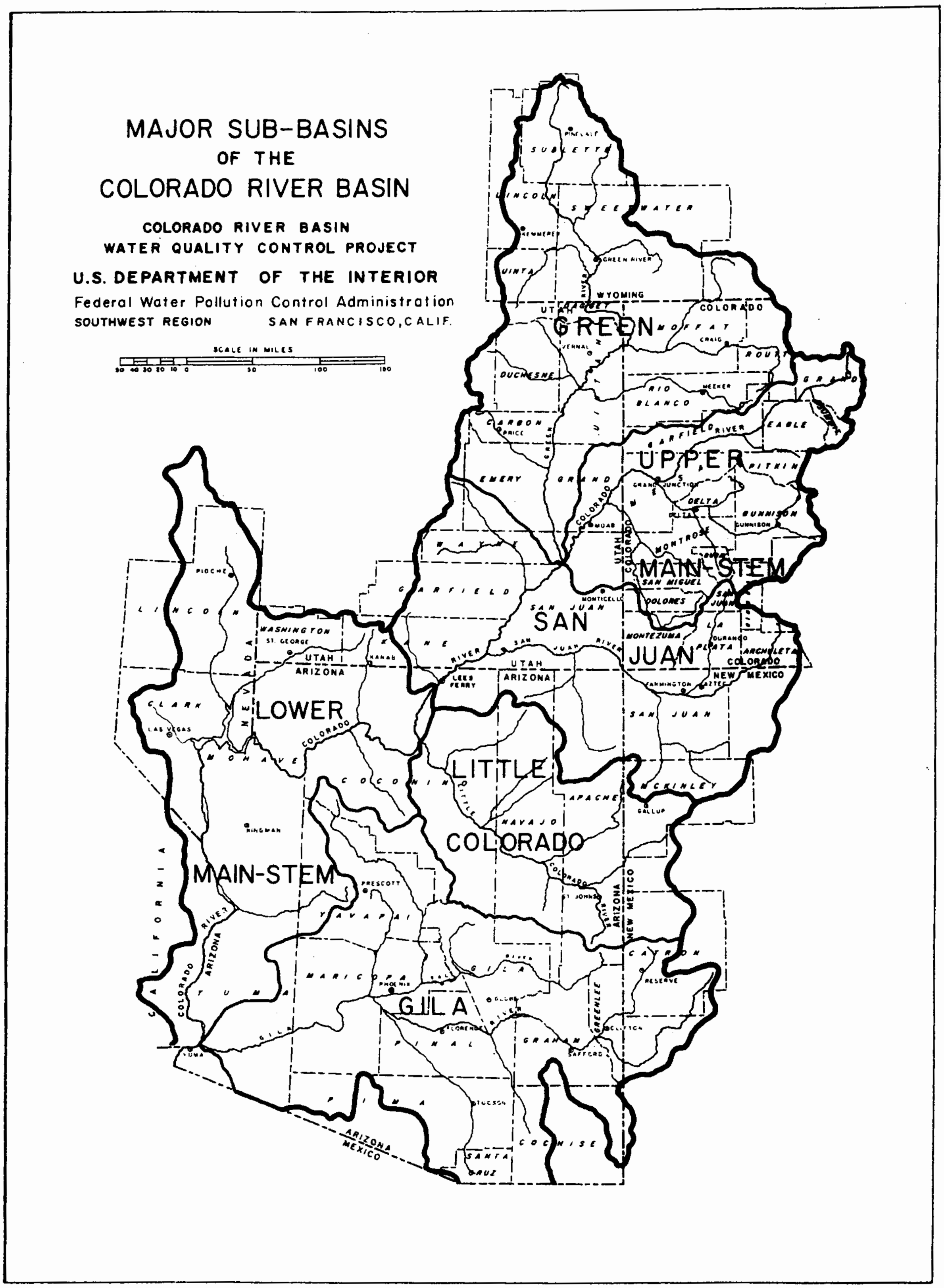

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FIGURE C.1 Major Subbasins of the Colorado River Basin. Colorado River Basin Water Quality Control Project, U.S. Department of the Interior, Federal Water Pollution Control Administration, Southwest Region, San Francisco, California.

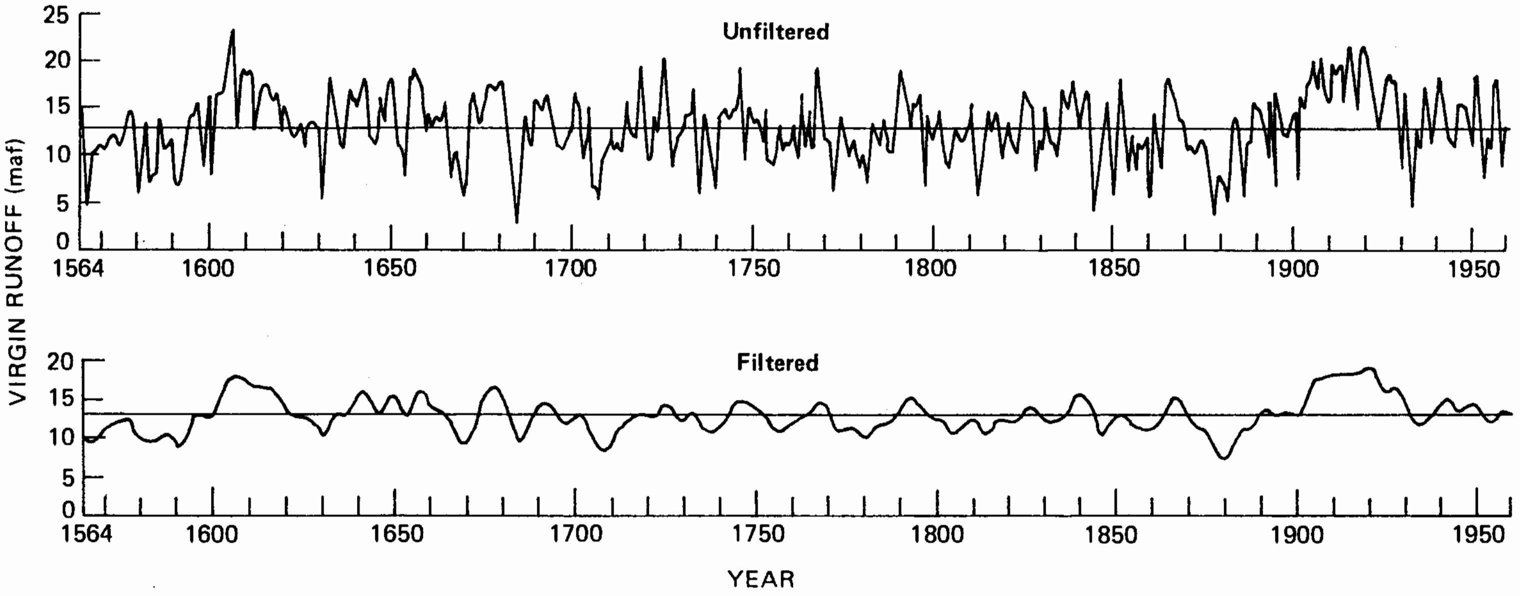

FIGURE C.2 Tentative 400-year reconstruction of annual runoff at Lee Ferry, Arizona. This reconstruction is based on tree-ring chronologies within the Upper Colorado River Basin collected as part of the Lake Powell Research Project and on chronologies that were in the files of the Laboratory of Tree-Ring Research. A future reconstruction will include additional chronologies and more definitive streamflow data. The filtered series is shown so that the low-frequency tendencies can be revealed. The digital filter process separates out the variance with a frequency of greater than once every 10 years. (Source: G. C. Jacoby, Jr., *Lake Powell Research Project Bulletin No. 14*, November 1975, p. 21.)

Lower Colorado into the Palo Verde Valley in 1877. In Arizona, Yuma Valley irrigation began in the 1890's. While the Reclamation Service (1902) would continue to play a major role in the development of the river, it was too late to influence the most spectacular development of all—the Imperial Valley of Southern California. The dramatic story of the early attempts to bring water to this valley has been excitingly told by Nadeau.[3] This story clearly pictures the ferocious variability of the uncontrolled Colorado, not only in its annual changes from a late summer trickle to strong spring floods but in the great variability of the flood flows themselves from year to year. In May 1901, George Chaffey and Charles Rockwood opened the original Imperial Canal to divert water from the Colorado along an ancient, long abandoned channel of the River into the southern head of the Valley. Making the desert bloom worked, and, after two years, 400 miles of canals had brought water to 100,000 acres of land.

The Spring of 1905 exhibited the great variance of flood flows. Winter floods on the Gila that far surpassed any recorded winter floods surged down the Colorado in February, first seriously eroding and expanding the Imperial Canal diversion cut on the Colorado and surging into the Valley itself. Rockwood was not concerned, for there appeared to be plenty of time to repair the damage and erect more adequate control structures before the Colorado's annual flood would begin. However, successive Gila floods prevented completion of the repair work and, in May of 1905, about half the annual flood flow of the main Colorado surged through the cut and into the Valley, forming the Salton Sea and threatening for a while to turn the entire Valley into a sea.

This early episode dramatically emphasizes the importance of climate variability to the Colorado Basin and those who would exploit its resources. The period of record for Colorado flows was then very short and probably inaccurate, as were the other climatological records for the Basin. We now know that the virgin flows of the Colorado River have been highly variable. Figure C.2 shows Stockton's reconstruction of 400 years of annual runoff measured at Lee Ferry, Arizona. The filtered series in Figure C.2 exhibits significant persistence, i.e., sequences of years of positive deviation from the long-term mean [about 13.5 million acre-feet (maf) per year], followed by sequences of negative deviations. Table C.1 gives estimated average virgin flows at Lee Ferry for various subperiods.

It is clear from these data that periods of above-average or below-average flow can persist for periods of 10 to 20 years, i.e., for significant parts of the intended lifetime of a large water project. Given the current impossibility of long-term climate prediction, it is difficult to specify any one number as the average flow to use for planning purposes. Rather, attention must be paid to the *nature and range of climatological variability likely to be faced and to the flexibility of the system being planned.*

TABLE C.1 Estimated Average Annual Virgin Flows at Lee Ferry, Arizona[a]

Period	Flow (maf)	Remarks
1896-1968	14.8	Federal estimates
1896-1929	16.8	34-year "wet period"
1930-1968	13.0	38-year "dry period"
1914-1923	18.8	10-year wettest period
1931-1940	11.8	10-year driest period
1917	24.0	Greatest 1-year flow
1934	5.6	Smallest 1-year flow

[a] Reference 1.

B. Historical Perceptions of Climate Variability in the Colorado Basin

Only the recent work of Stockton[4] and others has clarified the nature of the long-term variability of the Colorado's flows. Naturally, decision makers historically had to rely on available records and primitive conceptual frameworks when early, important legal and engineering decisions were being made about the River.

E. C. La Rue authored a Geological Survey report on the Colorado in 1916 in which a large dam was proposed for a "Colorado-San Juan site," close to the present location of the Glen Canyon Dam.[5] He estimated the "runoff available for storage" to be 15 maf annually. The gauge placed at Lee Ferry in 1921 recorded flows of 16.4 and 16.1 maf for 1922 and 1923, respectively. In 1925, La Rue published graphs of estimated historical flows at Lee Ferry with a mean flow of 16 maf. In the same year, during U.S. Senate hearings, the Executive Director of the National Reclamation Association characterized the Colorado as varying from 8 to 25 maf per year. Clearly, there was no unanimity on the distribution of annual flows.

There was no more consensus regarding likely *evaporation* from the reservoirs that were being proposed. In 1916, La Rue estimated 3.5 feet per year for the Glen Canyon site and 7 feet for the Boulder Canyon site. The Nevada State Engineer estimated 3.5 feet at Glen Canyon and 5 feet at Boulder Canyon. In 1923, the Director of the Reclamation Service estimated 6 feet for Glen Canyon. In 1950, the Bureau of Reclamation estimated 5.25 feet, while current estimates are in excess of 5.8 feet.

Thus it is clear that the early planners of Colorado River development, both engineers and politicians, were dealing not only with a highly variable resource, but one about which available estimates varied widely.

C. Climate Impacts on the Demands for Water

In the early years of Colorado River development, no consideration was given to the effects that climate variation might have on the demands for water. At that time, the uses were small relative to available supplies. In recent decades, one finds great attention paid to the growing demands for water but still little consideration given to the effects of climate variability on demand variability. While water planners generally are quite aware that periods of low stream flow are also likely to be periods of high demand (thus compounding the shortage), descriptions of Colorado River management procedures do not mention the issue.

It is clear that climate-induced changes in water demand do affect system operations and, as we shall argue later, should play an even larger role in the management of the present system. As an example of the former, the Bureau of Reclamation* had to release 700,000 acre-feet of water from Hoover Dam in the May-September 1979 period that was not ordered by downstream water users nor required in the U.S. treaty with Mexico.† This was attributable to unusually high Lower Basin winter precipitation that had increased downstream tributary flow, thereby reducing demands for irrigation releases from Lake Mead (Hoover Dam). The smaller releases had, by May 1979, resulted in a power deficit of 900,000 megawatt hours from Hoover, Davis, and Parker Dams; which the WPRS was eager to make up. The releases resulted in substantial damage along the River in Mexico.

An example that climate impacts on demand *should* play a greater role in management of the system is provided by operating experience at Lake Mead. In 1977 (the year of lowest flow on record), excess water was released in the January-April period to conform to standard flood storage operating rules. Upstream conditions should have made it clear that there could be no flooding. Continuing drought conditions throughout the Basin should have indicated the high value of water held in storage.

D. Sketch of Past Political and Legal Colorado River Development Decisions That Constrain the Present System

The theory of decision making under uncertainty^6 frequently characterizes the decision situation as one in which an action must be chosen in the face of an uncertain "state of nature," with the final payoff determined by the selected action and the true state of nature. This certainly captures the essence of the decisions that were made concerning the development (legal and physical) of the Colorado River, for many of the contemporary and future components of the true "state of nature" were quite uncertain. Some of these components were the demographic, economic, and political composition of the Southwest, but among the others were the climatological parameters partly determining the supply of and demand for water.

Three major classes of decision have been made in the past that continue to affect the operations of and the potential payoff from the Colorado system:

1. Political-legal decisions regarding the distribution of the river-system waters among the riparian states;
2. The location and size of storage and electric-generating facilities; and
3. Operating rules or criteria.

Item 3 will be discussed in Part II of this paper. We now describe the landmark decisions in 1 and 2 that have shaped the present system—decisions frequently made under great uncertainty regarding climate in the Colorado Basin.

The Colorado River Compact, 1922

At the turn of the century, there were already several concerns regarding the distribution of Colorado River water: (1) the more rapid economic development in the Lower Basin (especially Southern California) caused the Upper Basin states to become apprehensive about possible permanent claims by the Lower Basin states on the basis of prior appropriations; (2) the Lower Basin states feared a shutoff of water by the Upper Basin states wherein lay their sources and the best reservoir sites; (3) the states in both basins feared the effects that a federal agreement with Mexico might have. In years of low flow, water was already a constraint on Imperial Valley agriculture, since Imperial Canal water had to be shared with Mexico. It was clear that the kinds of storage projects needed to firm up added supplies and reduce annual flooding would require federal participation under the 1902 Reclamation Act. All of these factors pointed to the need for concerted Basin action and cooperation by the riparian states.

Under the chairmanship of Herbert Hoover in 1921, the Colorado River Commission first attempted to apportion the water among the seven Basin states. Partly because of the uncertainties surrounding the amount of water and the irrigable land in each state, this attempt was abandoned in favor of an agreement "evenly" dividing the waters between the Upper and Lower Basins, the state-by-state divisions to be arrived at later within each basin. The Compact was quickly ratified (1922) by all states except Arizona. The major provisions were

(a) To define Lee Ferry, Arizona, as the dividing point between Upper and Lower Basins;

(b) To limit the Upper Basin to 7.5 million acre-feet of beneficial consumptive use per year;

(c) To limit the Lower Basin to 8.5 million acre-feet of beneficial consumptive use per year;

(d) To require the release from the Upper Basin of 75 million acre-feet over every 10-year interval;

(e) To require the two basins to share equally any future Mexican delivery requirement not met by surplus waters; and

(f) To forbid the Upper Basin from withholding any water that could not reasonably be applied to domestic and agricultural use.

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*Now the Water and Power Resources Service (WPRS).

†Bureau of Reclamations press release dated May 1, 1979.

The effective provisions of the Compact have been (d) and (e). In 1922, it was felt the average annual flow at Lee Ferry was *at least* 15 maf (the 1914-1923 average was 18.8 maf). The Lower Basin would therefore receive at least 7.5 maf at Lee Ferry, plus Lower Basin tributary inflows including those from the Gila) minus evaporative and other instream losses. As noted in Table C.1, the 1930-1968 average was 13.0 maf, so the Compact appears not to have effected an "even" distribution. Provisions (d) and (e) above have been the single most important factors influencing subsequent developments in the system, as well as influencing current operating procedures.

The Boulder Canyon Project Act, 1928

This act provided for the construction of Boulder (later Hoover) Dam for Lower Basin water supply, flood control, and electric generation. As noted earlier, both Boulder and Glen Canyons had been under investigation and debate as the site for the first major Colorado River dam. Arizona (which had not ratified the Colorado Compact and which would not do so until 1944) would have preferred the Glen Canyon site because it might have been possible to divert water from that site into central Arizona and because the Boulder Canyon site was too close to California.

This Act also prescribed a division of waters among the Lower Basin states: 4.4 maf annually for California, 2.8 maf for Arizona, and 0.3 maf for Nevada. Arizona refused to accept either these figures or the principle that Congress could dictate the division of waters of an interstate stream, and this controversy continued until its resolution by the U.S. Supreme Court in 1963.

As *quid pro quo* for the Upper Basin, the Act provided for the study of the development of Upper Basin water. These studies eventuated in the "Krug Report" of 1946, which identified the projects later included in the Colorado River Storage Project (1954). The Report also noted that meaningful basinwide planning was handicapped by absence of specific state-by-state water allocations from the river.

Treaty with Mexico, 1944

To resolve long-standing conflicts with Mexico and to effect President Roosevelt's Good Neighbor Policy, a treaty was signed in 1944 that guaranteed Mexico a minimum of 1.5 maf annually. Under the Colorado Compact, this increased the minimum annual release at Lee Ferry from 7.5 to 8.25 maf annually. Significantly, the treaty did *not* cover water quality.

The Upper Basin Compact of 1948

As noted in the Krug report, the federal government felt it important that interstate divisions be clarified to facilitate long-term planning. While this order of events seems backwards, it made it unlikely that substantial federal aid for further water development would be forthcoming until basin waters were divided. The Upper Basin states managed agreement in spite of quite divergent initial state desires. Recognizing by that time the great uncertainty surrounding the water available to the Upper Basin, the states agreed to a percentage allocation of annual available water: Colorado 51.75%, Utah 23%, Wyoming 14%, New Mexico 11.25%, and Arizona a fixed 50,000 acre-feet per year. Obviously, this Compact places potentially severe constraints on the efficient management of the Upper Basin river system.

The Colorado River Storage Project Act, 1956

This Act intended to provide for the development of the Upper Basin waters in the way that Boulder Dam had controlled Lower Basin waters. It identified the major storage sites and generating facilities for an integrated Upper Basin system. Its passage involved the first major environmental fight over a dam proposed for Echo Park in Dinosaur National Monument. The dam was deleted from the final authorization that included Fontenelle and Flaming Gorge in Wyoming; Blue Mesa, Morrow Point, and Crystal in Colorado; Navajo in New Mexico; and Glen Canyon in Arizona (see Figure C.1). The identification of these sites was based on the best hydrological and geological analysis possible, so there was no dearth of input of relevant climate data. The Act thus determined the major physical configurations of Upper Basin development.

U.S. Supreme Court: Arizona v. *California, 1963*

In spite of the attempt at Congressional resolution of the division of Lower Basin waters contained in the Boulder Canyon Project Act of 1928, the fight continued between Arizona and California, ending up in the U.S. Supreme Court. The Court issued a ruling in 1963, affirming the following points:

(a) The distribution of water according to the Boulder Canyon Act;

(b) The powers of Congress to allocate the water of interstate, navigable streams; and

(c) The reservation of waters for all federal lands, including the Indian reservations, such waters to be counted as part of the allocation of the state in which the federal lands are located.

Thus California ended up with 4.4 maf annually, Arizona with 2.8 maf, and Nevada with 0.3 maf. Points (b) and (c) raised great apprehension among the western states concerning protection of already established water rights and future federal claims. Indian Reservations were authorized waters sufficient to irrigate "all practicably irrigable lands" without stating whether "practicably irrigable" was to be interpreted from an economic or engineering point of view.

The Colorado River Basin Project Act, 1968

This Act authorized the Central Arizona Project (CAP), long sought by Arizona as a way of transferring water from the Colorado to central Arizona where groundwater was being overdrawn by some 5 maf annually. While such a project had been studied for decades, the economics of such a project were so poor that only huge federal subsidy could ever pay for the project. Major environmental fights occurred over proposed power dams in Bridge and Marble Canyons, revenues from which would presumably (in a bookkeeping sense) help to pay for the CAP. A large thermal power plant was finally included for this purpose.

In addition to the CAP, this Act included the following steps that further defined or constrained development of the river:

(a) Assigned priority to California's 4.4 maf, so that Arizona should absorb any shortages that may occur;

(b) Authorized various Upper Basin projects, plus Hooker Dam on the Gila;

(c) Declared the Mexican Treaty obligation to a "national obligation" to be satisfied (at federal expense) from any future supply augmentation plans;

(d) Forbade any federal studies of importation of water from other river basins (to placate the fears of Columbia River Basin interests);

(e) Authorized Upper Basin retention of waters not needed to satisfy Compact and Mexican obligations so as to build up reservoir stocks sufficient to give "reasonable" protection to the Upper Basin's established consumptive uses:

(f) Required approximate equality in the volumes of water in storage in Lake Powell and in Lake Mead (Glen Canyon and Hoover Dams).

Thus, the system was further expanded and more constraints were placed on its operation.

E. Future Impacts of Historical Decisions

The foregoing shows that economic development of the Colorado Basin involved much more rapid growth in the Lower Basin than in the Upper. The legal status of Colorado River water was quite uncertain and was potentially affected by U.S.-Mexico relationships and agreements. The states involved might have chosen to fight over the River's waters, largely through the courts (although violence did occur over claims to water). However, the development of the Colorado was taking place within a national context, within reach of programs that could greatly aid that development. The most obvious of these programs was the Reclamation Program (1902), but the Geological Survey, the Department of Agriculture, and large subsidies for railroad development were also potentially important.

To obtain aid from national programs, a consensus among Basin states was necessary to compete successfully with other regions. The potential magnitude of federal aid outweighed any gains likely from one state taking advantage of its neighbor. Federal aid changed a zero-sum game into a positive-valued game for the Colorado Basin states.

Obtaining consensus meant agreement on policies and projects like rules for distributing the River's waters and locating major storage projects. The effectiveness of the policies and projects chosen very much depended on the true climatological and hydrologic regimes of the region, about which little was known at the time of many key decisions. Yet, the consensual process had to continue once started, even if the scientific data base and desired study results were not at hand. The political costs of failure were perceived to be greater than any likely economic or physical inefficiencies that might result from decisions based on inadequate data.

Thus, key decisions often proceeded without adequate information (although they sometimes triggered new data and research programs). As a result, today's system is saddled with a configuration and major operating constraints that would be unlikely if the system could be redesigned today. While it is not possible to say that this evolution was wrong, it is clear that major decisions had inadequate scientific inputs, including climate information.

As a real example of costs likely to be incurred in the future because of past commitments, Morris[7] studied trade-offs between agriculture and various forms of energy development in the Upper Basin. All existing economic activities and new energy activities were identified by subbasin areas (12 in all). Water availability constraints took two forms: natural surface water availability in each of the 12 subbasins, specified by deciles of annual flows; and the legal constraints imposed on water availability by the Colorado River Compact and the Upper Basin Compact. The legal constraints proved to be much more binding than the water availability constraints, even when the latter were set at the 30th or 40th decile levels. Trade-offs against agriculture were *sharply* increased, and the "optimal" pattern of energy development was strongly affected.

II. USE OF CLIMATE INFORMATION IN CURRENT SYSTEM MANAGEMENT

The preceding section highlighted the poor quality of climatological information that was generally available when the major legal and engineering development decisions were made for the Colorado River system. This section provides a partial description of the procedures used in the annual, seasonal, and daily operating decisions of the system, indicating both where climate information is used and where it could be used to greater advantage.

A. Outputs of the System and Trade-offs among Them

The purposes of the developed Colorado system are hydroelectric power, irrigation water supply, municipal and industrial water supply, flood control, and recreation. Fish and wildlife maintenance or enhancement and aesthetic impacts might be mentioned as minor purposes that are largely incidental to the main functions. Power generation occurs at Flaming Gorge, at the three dams on the Gunnison (tributary to the main stem Colorado), at Navaho Dam on the San Juan River, at Glen Canyon Dam, and at Hoover Dam. The major irrigation withdrawals occur in Western Colorado, Southwestern Arizona, and Southern California, although the Central Arizona Project (CAP) will become a major diversion within a few years. The only major municipal–industrial use at present is for the Los Angeles area, but a significant part of CAP water is likely to be used for municipal purposes.

Regarding flood control, all reservoir operating rules are influenced by the seasonal runoff pattern from snowmelt that feeds the system, but the major flood storage is in Lake Mead, where the Corps of Engineers has a joint management function with the Water and Power Resources Service to protect the Lower Basin from serious seasonal flooding. Recreation is an important activity at all major reservoirs.

Naturally there exist both complementary and competitive relationships among these outputs. Flood control and water supply are complementary because the water-supply function requires capturing the spring runoff and storing it until needed in mid and late summer. Uncaptured, this same water would be the source of flooding in the main-stem river areas.

The main competitive relation is between electric power generation and water supply, since there is no inherent reason why demand for water supply should be highly correlated with the demand for power. While this is quite clear on a daily basis, it can also lead to problems on a seasonal basis as illustrated earlier by the effects that heavy Lower Basin precipitation in 1979 had on irrigation-water demand, resulting in the retention of water in Lake Mead and the accrual of a large power deficit. When water was ordered released by the Secretary of the Interior to make up the power deficit, various flooding problems were experienced in the lower valley and Mexico.

Another competitive relation is that between flood control, water supply, and power releases and recreation on both reservoir surfaces and the river itself. Varying reservoir levels uncover mud flats and stained canyon walls, while white water boating and rafting are impaired by fluctuating flows.

B. Annual Plans and Seasonal and Daily Operating Decisions

An annual operating plan is prepared for each water year, based on the anticipated stocks in each reservoir and the routing of different levels of runoff through the system. Releases, power generation, and available water supply are simulated by month for each major reservoir in the system using a simple routing model and inputs of average, first quartile, third quartile, and worst *historical* runoff rates. No attempt is made to forecast climatological conditions. The annual plan is circulated to the Congress and the state governors for information and comment.

Daily operating decisions appear necessary at each reservoir to provide power and water supply. For the latter, however, all Upper Basin diversion points find plenty of main-stem water for direct diversion (since at least half must be passed to the Lower Basin), while the large irrigation demands of the Lower Basin are supplied in the short run by releases from the Lower Colorado dams (Davis, Parker, and Imperial). Thus, the daily operating decisions at the power dams relate essentially only to power, while the water is re-regulated at Glen Canyon and Hoover for keeping the other Lower Basin dams filled to accommodate irrigation and municipal demands.

Seasonal decisions relate primarily to flood control, based on snowpack information and its relationship to anticipated runoff. This relationship will be described more fully in later paragraphs.

For each set of decisions, an "ordinary operating range" has been defined, so that if all conditions fall in that range, local operating personnel follow the usual decision rules. For example, the Western Area Power Administration (of the Department of Energy) office at Montrose, Colorado, makes the hour-by-hour power-release decisions; the Water and Power Resources Service (WPRS) offices in Salt Lake City and Boulder City, Nevada, make other weekly and monthly balancing decisions, all subject to the seasonal flood storage needs at Lake Mead as estimated by the Corps of Engineers.

When extraordinary conditions occur, decisions get passed to higher authority with the possibility of reaching the Secretary of the Interior in conference with the governors. This happened in 1979 with the unusual conjunction of very low irrigation demands and high power demands. The decision to release unusual volumes of water from Lake Mead was politically sensitive because of potential flood damages in the Lower Basin and Mexico, which did, in fact, occur.

Where does climatological information enter this decision process, and where might more effective uses be made?

Runoff predictions. Currently, *monthly* runoff predictions are made for operating purposes using a set of regression equations estimated from historical data. The forms of these equations are

$$\begin{aligned} R_{\text{Jan.}} &= f\,(\text{precipitation in Oct., Nov., Dec.}),\\ R_{\text{Feb.-May}} &= g\,(\text{snowpack at beginning of month}),\\ R_{\text{June}} &= h\,(\text{snowpack, May precipitation}), \end{aligned}$$

where R is the runoff. The WPRS wants to improve these equations and to derive equations for a much shorter time period, perhaps daily, especially for the heavy runoff period when river flows can change quickly. Work is currently under way with the National Oceanic and Atmospheric Administration in this direction.

Predicting the demands for output. The demands for power, irrigation water, and municipal water are strongly affected by climate and current weather conditions. Hot and cold weather both raise the demand for electric power; whereas hot, dry weather sharply increases evapotranspiration and, if it persists, will raise the demand for water. Such relationships are already frequently used by power and gas companies to anticipate loads, while excellent agronomic-soil moisture research has provided a data base for establishing predictive relationships between climate and weather information and water demands. At present, *no demand predictions* are used in the management of the system.

III. CONCLUSIONS AND RECOMMENDATIONS

1. The major legal and engineering decisions about the development of the Colorado River were made in the period 1922-1956 when the climate information base was weak. The political costs of waiting and "losing momentum" were perceived to be greater than potential losses stemming from decisions taken on the basis of unreliable data.

This emphasizes the value of anticipating the need to make decisions so that a sufficient data and information base will be available.

2. It seems clear that improvement can and will be forthcoming in the prediction of runoff for each major river segment. The WPRS has the opportunity to incorporate more sophisticated "rainfall-runoff" models (say, of the Stanford type) in its operating decisions.

3. Attempts should be undertaken to predict water and power demands based, in part, on climatological conditions and current weather. Well-known econometric techniques are available for estimating such relationships.

4. Overall, it appears that excessive volumes of storage have been built into the Colorado system, perhaps obviating the immediate need for more efficient short-term management. However, as output demands increase, more sophisticated management will yield increasingly high returns.

For other, new systems, the Colorado system experience strongly suggests that more sophisticated operating procedures based in part on climate and weather information can substantially reduce the volume of storage needed for the system.

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