

PROPOSALS TO MANAGE SNOWPACK FOR THE ECONOMIC BENEFIT OF THE COLORADO RIVER BASIN

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ABSTRACT

The growing population as well as the industry and agriculture of much of the American Southwest is based largely on water supplied through the Colorado River. Most of that River's water supply is derived from snow melt in the alpine regions above 9000 feet in elevation which comprise only about 6 percent of the basin area. Consequently, an effective means of managing snowpack could yield substantial benefits to the basin which has over-appropriated its actual water resources and to the users who will experience increasing water shortages in the next century.

As new water projects were authorized and projected demand increased, the U.S. Congress directed the Department of the Interior to investigate methods of augmenting the Colorado flow by about one-sixth or a total of 2.5 million acre-feet per year. The 1968 Colorado River Basin Projects Act authorized studies of measures to increase the Colorado flow in order to supplement the natural supply and provide for commitments defined in the "Law of the River". Those earlier commitments had been made when the average annual flow was believed to be substantially higher than the 14.7 million acre-feet figure which now is generally accepted.

Several potential methods of augmentation have been investigated in the Colorado River Basin. Of these, vegetative management and snowpack enhancement through cloud seeding seem to offer significant prospects for possible application. Further analysis is required to thoroughly evaluate both these techniques. The economic potential of either or both of these techniques is enormous. In the case of weather modification, the Bureau estimates that benefits could outweigh the operational costs by approximately 10:1.

INTRODUCTION

The Colorado River is a vital resource in the arid Southwest as it satisfies a wide variety of needs - power generation, water supply for municipalities, industry, and agriculture, recreation, and provides habitat for fish and wildlife. It would be difficult to overestimate the importance of the Colorado River as it is the only major source of surface water in the region. While energy production is somewhat constrained by delivery and consumptive use of Colorado River water, there are several important possibilities for increasing the both the quantity and utility of the hydropower produced in the Basin.

THE RIVER

Geography and Hydrology

The Colorado River winds its way some 1440 miles from the high mountainous areas in central Colorado to Mexico's Gulf of California. The Colorado River Basin comprises some 244,000 square miles in seven states in the arid Southwest and, despite the enormous size of the drainage area, its average annual flow (for the period 1900 to 1978) is approximately 14.7 million acre-feet (MAF) (or about 20,7000 cubic feet per second) is comparable to that of the Delaware River which drains only 11,440 square miles of the humid Northeast.

Most of the flow of the river is from seasonal snowpack in the alpine and subalpine watersheds above 9000 feet in elevation where winter precipitation amounts are high and evapotranspiration losses low due to colder temperatures. The area of the important runoff-producing watersheds comprises only a small portion of the entire Colorado River Basin. The portion of the watershed above Lees Ferry, Arizona, the recognized dividing point between the Upper and Lower Colorado River Basins, is about 110,000 square miles in area, yet 75 percent of the Upper Colorado River flow originates in 14,200 square miles (13 percent of the area of the Upper Basin) of mountainous terrain where average annual runoff is about 13 inches. The major portion of the Colorado River flow originates in the Upper Basin as there are few significant runoff-producing areas below Lee's Ferry.

It is also of critical importance that the river falls about 12,000 feet over its course and a full third of this drop occurs after the major tributaries contribute their flow to the main stem of the Colorado River. The significance of this feature is, of course, related to the hydroelectric power potential.

The powerful and erratic flow of an unregulated Colorado River would be quite incapable of consistently meeting the needs of the arid Southwest. Spring runoff from snowmelt formerly resulted in a raging torrent while only a small stream was necessary to accommodate low flows at other times of the year. The annual flow of the Colorado River has historically varied from 5.5 MAF in 1977 to 24 MAF in 1917 and there has been a tendency for the high years or the low years to be grouped, thus accentuating problems of river regulation and use. For example, the natural flow during the wettest ten-year period averaged 18.8 MAF while during the driest period it was only 11.8 MAF. Due to these wide variations in distribution and runoff patterns in the watershed, economic development in the region has been dependent upon the construction of storage and conveyance facilities to provide adequate and dependable water supplies.

Prior to the construction of any engineering structures on the Colorado River, it was essential that agreement be reached by the seven Basin States on the apportionment of the flow. For nearly half a century there have been continuing disputes concerning the Colorado River which have permeated the political, social, economic, and legal facets of the Basin States as the result of an inadequate water supply for competing uses. To provide a basic understanding of the various aspects of the Colorado River and its complex operations, it is necessary to discuss some of the historical events and decisions which have shaped the present situation.

Law of the River

The institutional constraints placed upon the Colorado River are unequalled on other river systems elsewhere in the United States. The various agreements and directives which govern the operations of this complex river system are collectively known as the Law of the River. The major feature of the Law of the River is the Colorado River Compact which became effective in 1929 and provides for the following requirements: the Upper and Lower Basins were each entitled to annual beneficial consumptive use of 7.5 million acre-feet (MAF); the Lower Basin was given the authority to increase its annual consumptive use by one MAF; water to Mexico is to be provided from the surplus flow and the deficiency is borne by both the Upper and Lower Basins in times of shortage; and the Upper Basin is to provide 75 MAF over a ten-year period to the Lower Basin.

The Boulder Canyon Project Act (1929) authorized the construction of Hoover Dam and Powerplant and the All-American Canal and authorized the States of Arizona, California, and Nevada to enter into an agreement whereby the 7.5 MAF allocated to the Lower Basin annually would be further apportioned as follows: to California - 4.4 MAF, to Arizona - 2.8 MAF, and to Nevada - 0.3 MAF. In addition, California was required to agree to limit annual water use to 4.4 MAF plus not more than one half of surplus water made available to the Lower Basin. The 7.5 MAF allocated to the Upper Basin under the terms of the Colorado River Compact were further apportioned by the Upper Colorado River Basin Compact (1948) as follows: 50,000 acre-feet to Arizona and the remaining flow to be divided by the following percentages - Colorado - 51.75, Utah - 23.00, Wyoming - 14.00, and New Mexico - 11.25.

Under the Mexican Water Treaty (1944), the United States is obligated to provide Mexico with 1.5 MAF annually and additional quantities up to 0.2 MAF when surplus water is available.

The Colorado River Storage Project (CRSP) Act of 1956 authorized the construction of several long-term carryover reservoir storage units (Glen Canyon, Flaming Gorge, Blue Mesa, Morrow Point, Crystal, and Navajo Dams) in the Upper Basin. These projects enable the Upper Basin to maximize storage potential and make required deliveries to the Lower Basin during years of low natural flow. In addition, 11 participating projects in the Upper Basin were authorized for irrigation and related uses; other participating projects were authorized by other legislation.

The agreement by the Lower Basin States to allocate Colorado River flow was cemented with the Decree of the Supreme Court of the United States in *Arizona v. California* (1964) which held that the previously cited apportionment values in the Boulder Canyon Project Act for the individual states were appropriate.

The Colorado River Basin Project Act of 1968 authorized the construction of the Central Arizona Project (CAP) by the Bureau to divert Colorado River water to Phoenix and Tucson in south-central Arizona and stated that diversions to the CAP would be limited to guarantee that California would receive its full annual entitlement of 4.4 MAF. A declared objective of the Act was to provide for a comprehensive water resources development program for the Basin to include augmentation of water supplies for Upper and Lower Basin use. The Mexican Water Treaty was declared to be a National objective which shall be the first obligation of any augmentation project.

The Colorado River Compact apportioned a water resource that, at the time of negotiations, appeared significantly larger than the river has subsequently yielded. Based upon streamflow records available from 1896 to 1920, it was estimated that the long-term average annual natural flow at Lees Ferry was greater than 18 MAF. This estimated flow value has been of considerable importance as currently the long-term average appears to be more nearly 14.7 MAF. Thus, the apportionment of Colorado River water to the Upper and Lower Basins, based upon unrealistic and overly optimistic average flow estimates, will ultimately result in the inability to meet all demands as full consumptive-use development is approached in the Basin.

BUREAU OF RECLAMATION PROJECTS AND PROJECT OPERATIONS IN THE BASIN

Principal Features

Due to the apportionment of water between the Upper and Lower Colorado Basins, Bureau projects and their operations essentially reflect the existence of two separate, yet interdependent, rivers. The Upper Colorado River is largely a natural drainage system with several major tributaries - the Green, Gunnison, Yampa, Dolores, and San Juan Rivers - contributing flow to the mainstem of the Colorado River which flows to Lake Powell behind Glen Canyon Dam, 15 miles upstream of Lees Ferry near the Arizona-Utah border. The Lower Colorado River, conversely, responds similar to a municipal waterworks with one source of supply - releases from Glen Canyon Dam - and numerous destinations. Table 1 reveals the relative sizes of the key storage reservoirs and powerplants in the Basin.

Glen Canyon Dam, which impounds Lake Powell, on the Arizona-Utah border, is the key Bureau structure in the Colorado River Storage Project (CRSP) in the Upper Basin designed to regulate the erratic natural flow of the Colorado River and its main tributaries. Other features in the CRSP with long-term storage capability include Fontenelle and Flaming Gorge Dams and Reservoirs on the Green River; Blue Mesa, Morrow Point, and Crystal Dams and Reservoirs on the Gunnison River (together comprising the Bureau's Wayne N. Aspinall Unit); and Navajo Dam and Reservoir on the San Juan River. All of the key storage dams in the CRSP are operated by the Bureau, and with the exception of Navajo Dam, have powerplants. There are also 24 CRSP participating projects (24 have been authorized and 15 have been constructed or are under construction) that are primarily operated by local water users and responsible for the delivery of water and are not intended for either long-term storage or power generation.

The key feature in the Lower Basin is Hoover Dam of the Bureau's Boulder Canyon Project which was completed in 1936, the first project on the Colorado River to help solve the recurring flood and drought conditions downstream. Below Hoover Dam, which impounds Lake Mead, on the mainstem of the Colorado River are Davis and Parker Dams which create Lakes Mohave and Havasu, respectively, and together comprise the Parker-Davis Project; powerplants are integral features of all of these structures. There are several lesser dams without powerplants on the Colorado River in the Lower Basin below Parker Dam, including Palo Verde Diversion Dam and Headgate Rock, Imperial, Laguna, and Morelos Dams. Headgate Rock Dam is a Bureau of Indian Affairs dam designed and built by the Bureau of Reclamation. Located just upstream of Imperial Dam is an offstream pump-generating facility at Senator Wash Dam and Regulating Reservoir designed to improve water scheduling of the Colorado River.

Glen Canyon Dam and Hoover Dam are the cornerstones of the Bureau's Colorado River operations and together comprise over 85 percent of the storage and nearly 80 percent of the generating potential in the Basin. Bureau reservoirs in the Basin are capable of storing in excess of 60 MAF or approximately 4 years of average Colorado River flow. This ability to regulate flow and largely eliminate the former flow variability enables the Bureau powerplants to generate significant quantities of hydroelectric power. Bureau structures, particularly Hoover and Glen Canyon Dams, due to their significantly greater size, have had great impact upon the amount of annual as well as seasonal Colorado River flow variability. At Glen Canyon Dam site, the average spring high flows were formerly approximately 80,000 cubic feet per second (cfs) and occasionally in excess of 100,000 cfs. Today, however, bypass of the powerplant, which has a capacity of 33,600 cfs, is infrequent; the maximum release was 55,700 cfs in 1965.

Water Supply Forecasting

Effective operation of water projects in the Colorado River Basin requires reliable hydrometeorologic data which are capable of relating currently available and projected water supply in the Basin. It is imperative that the Bureau reasonably anticipate future conditions in the Basin and develop operating plans to maximize the use of a valuable water resource to meet Basin water demand and generate hydropower. Thus, preparation of a water supply outlook and streamflow forecasting for the near future are important tools in the Bureau's operating plan to effectively mitigate potential adverse impacts resulting from surplus or deficit water supply conditions. The National Weather Service's (NWS) River Forecast Center (RFC) in Salt Lake City prepares monthly forecasts for runoff which provide the basis for Bureau operation studies. The Bureau is a contributing member of the Colorado River Forecasting Service (CRFS), which consists of the National Weather Service (NWS), Soil Conservation Service (SCS), U.S. Geological Survey (USGS), U.S. Army Corps of Engineers (COE), Western Area Power Administration (WAPA), and the Bureau's Lower and Upper Colorado Regional Offices, all of which have an interest in some aspect in water supply forecasting - either in the collection of data to generate the forecasts or in the use of the forecasts.

Since the major portion of the streamflow is the result of snowmelt, careful monitoring of snowpack conditions is essential for forecasting. The SCS SNOTEL (snow telemetry) system provides information on snowpack conditions throughout the Basin to the RFC in Salt Lake City. Weather information from selected locations throughout the Basin collected by the NWS is also obtained by the RFC. In addition, Bureau reservoir stage data and USGS stream gage data are provided to the RFC. From these data, which include precipitation parameters, snowpack water equivalent information, reservoir and streamflow levels, and other data necessary to calculate evapotranspiration, estimates of the available water supply are issued by the RFC.

Water supply forecasts for the Colorado River based upon anticipated snowpack conditions are issued by the RFC the first of each month beginning in January and ending in June. These forecasts, which are available by interrogating the NWS' DATACOL system by telephone, are essential to the Bureau in scheduling reservoir releases. In addition to water supply forecasts, the Bureau can obtain information from the DATACOL system on current conditions such as river stages at selected locations in the Basin.

The current snowpack, weather, and other data are useful to the Bureau in preparing forecasts for smaller reservoirs in the Basin which can be useful to local water users since the CRFS forecast is prepared for only the more significant points of interest in the Basin (e.g., at Glen Canyon Dam).

The RFC water supply forecasts provide the basis for the Bureau's 24-month water supply study for reservoirs in the Basin. The predicted inflow values, evapotranspiration, bank storage, and releases or diversions for the next month for Bureau reservoirs are input into the Colorado River Simulation System (CRSS) model to estimate water availability. The CRSS model can simulate the complex physical responses in the system to estimate the amount of storage in key reservoirs at the end of the month which provides the basis Bureau operations for the next month. For the evaluation of storage beyond the time of 30 days, average values for the various parameters are input into the model due to lack of other more reliable data.

Once a year the Bureau also prepares a 90-year study which evaluates 15 different water supply scenarios in the entire Basin and considers new projects coming on line as well as anticipated new depletion schedules. This study is particularly useful in evaluating power repayment results and partially provides the basis for power rate increases. In this study, water level values having a 50 percent probability of occurrence are used as real-time and forecasted data would be both cumbersome and not particularly useful.

On October 1, the Bureau uses the CRSS model to simulate five different input scenarios: adverse, lower 25%, average, upper 25%, and upper 10% water supply conditions and evaluates the potential impacts of each of these possible scenarios for the next year upon Bureau project operations. This information is submitted in an annual report to the Congress as was required by the Colorado River Basin Project Act.

Project Operating Criteria

The terms of the various agreements and documents which comprise the Law of the River must be met by the Bureau of Reclamation as it manages the water for the Basin States. In the order of higher to lower priority, releases in the Colorado River Basin from Bureau reservoirs are to be made for flood control and river regulation, water demands for beneficial consumptive use for agriculture or municipal water supply, and the generation of hydroelectric power.

The criteria for the operations of Bureau storage reservoirs in the Basin were set forth in 1970 in "Coordinated Long-Range Operation of Colorado River Reservoirs." The operating criteria as required by the Colorado Basin Project Act of 1968 control the operation of storage reservoirs in the Basin constructed under the authority of the Colorado River Storage Project (CRSP) Act for Upper Basin reservoirs and the Boulder Canyon Project Act (Lake Mead). A brief summary of the major features of the operating criteria for the Upper Basin reservoirs and Lake Mead follows:

Operation of Upper Basin Reservoirs in CRSP:

The Secretary of the Department of the Interior shall make a determination of the amount of storage considered necessary at the end of the year. A minimum release of 8.23 MAF annually to the Lower Basin is required if either active storage forecasted for Lake Powell is less than the Lake Mead active storage forecast or CRSP storage is less than the amount determined by the Secretary. However, releases exceeding 8.23 MAF may be necessary to ensure that 75 MAF is delivered to the Lower Basin over a 10-year period.

If storage in CRSP reservoirs exceeds the amount determined by the Secretary, releases from Lake Powell exceeding 8.23 MAF are acceptable to meet Lower Basin needs, to avoid spilling water from Powell, or to maintain equal amounts of active storage in both Lakes Mead and Powell, although it is stipulated that these releases are to be passed through the Glen Canyon Powerplant to the extent that it is practical.

Operation of Lake Mead:

Water stored in Lake Mead is available to meet Mexican Treaty obligations, satisfy downstream demands, and to compensate for net river and reservoir losses and regulatory wastes. The Secretary of the Interior is responsible for determining normal water supply conditions or a shortage or surplus of water based upon forecasted water supply and anticipated demand since the releases from Lake Mead pursuant to the Supreme Court Decree in *Arizona v. California* are tied to water availability.

In addition, the Colorado Basin Project Act requires that an annual report be prepared by the Bureau for submission to the Congress which describes the actual Colorado River operations for the previous water year and the projected plan of operation for the current year. The projected plan of operation is to consider the uses of the reservoirs for all purposes including flood control and river regulation, downstream water demands, power production, water quality control, recreation, fish and wildlife enhancement, and other environmental factors. The plan of operation may be revised to reflect the current hydrologic constraints, that is, the present reservoir storage and the future anticipated reservoir inflow in the Basin.

Optimization of Hydroelectric Power Generation

The power generating potential of the Colorado River was not highly prized at the time of the construction of Hoover Dam. Critics thought that the Bureau would have a difficult time finding sufficient demand for its power in the desert. For several years before the Second World War, Hoover generators supplied Los Angeles with a large portion of its power while today Colorado River hydropower is a resource both coveted and used by many, both in and outside of the Basin. In 1981, Bureau Colorado River projects generated in excess of 10 billion kilowatt-hours.

Hydroelectric power revenues from the projects (Boulder Canyon, Parker-Davis, and CRSP) are used to repay the Federal power investment and replacements with interest and are available to assist in the repayment of costs of other features in the units, principally in the irrigation costs of the projects that are beyond the payment capability of the irrigation water users. The generation of power is extremely important as it serves the dual purpose of paying for a large part of the project costs as well as providing relatively inexpensive power, particularly peaking power, to consumers. Thus, it is desirable to maximize power output within the framework of the institutional, hydrological, and power system constraints.

Typically the Bureau day-to-day operations of Colorado River Basin projects in the Upper Basin are similar but not identical to operations in the Lower Basin due to some inherent differences. The greater extent of water consumptive-use development in the Lower Basin results in less flexibility in project operations. In the Upper Basin, the Bureau provides Western Area Power Administration (WAPA) with a monthly schedule of anticipated reservoir releases and the Bureau's estimate of power output. WAPA, as a result of its greater familiarity with the power system and projected times of surplus or inadequate power will adjust Bureau figures to obtain an optimum power generation scenario from powerplants. However, the releases must meet all higher priority requirements, that is, we must comply with the requirements of the Colorado River Compact relating to releases from Lake Powell, we must consider minimum flow releases for fish and wildlife and recreation, and we must ensure that sufficient flow is being provided for downstream beneficial consumptive use. In the case of Lower Colorado River Basin operations, all water released from Hoover and Parker-Davis Projects must be for downstream water demands, with the exception of flood control releases, or to meet the requirements of the Mexican Water Treaty.

THE FUTURE OF THE COLORADO RIVER SYSTEM

The migration of millions of Americans to the Southwest, particularly those areas served by the Colorado River during the past half-century has increased the demands on the river by orders of magnitude. The population-induced demand, particularly in Southern California, Arizona, and along the Colorado and Utah mountain ranges will shortly exceed the supply of water, perhaps before the end of the 20th century. The alternatives after that period are somewhat limited, presumably urban and industrial demands will continue to

be met, but at the price of drying up some agricultural land.

Growth in Demand for Power

The demand for Colorado hydropower is even more intense than the quest for more water. Power made available by damming the river and sold for the cost of production was initially interesting only for California, but now is the subject of intense competition among the Basin states.

The price of Federally produced hydropower makes it one of the all-time bargains in the energy field. Power generated by the Colorado River dams and marketed by WAPA sells for less than a penny per kilowatt-hour. By comparison, new coal-fired generating capacity from one of Colorado or Utah's newest plants costs a nickel and peaking power sells for a dime per kilowatt-hour.

The most obvious conclusion from these comparisons is that Colorado hydropower is a very valuable, if under-priced commodity that will continue to be the subject of strong competition among the states and utilities. Its low cost plus the flexibility to use much of it for peaking power requirements result in great savings to the power consumers of the region. Of course the Federal government didn't set out to subsidize power users; rather, much of this power was sold under the terms of long-term contracts which were considered adequate to repay the Federal investment in dams and irrigation projects.

It follows that any means to improve the efficiency and power output of the Colorado River system would be highly desirable for consumers who could then avoid some of the upward pressure on energy costs. Some significant steps have been taken; Hoover and Glen Canyon are getting extra generating capacity and ability to create more peaking power. Headgate Rock Dam will be equipped with turbines for the first time to create modest increases in capacity, and consumptive use of municipal and industrial water in the Upper Basin is being priced at a level which reflects the cost of foregone power generation in downstream dams.

Demand for Quality Water

There is a similar demand for more fresh water in the Colorado River Basin; while conservation and better management can alleviate the severity of the problems of water supply, only substantial augmentation of the flow can help meet the future demands of the system. The alternatives to augmentation include increasing pressure on nonrenewable supplies of groundwater and turning off some of the agricultural supply. Removal of salt from irrigation return flows such as that to be performed by the Yuma Desalting Plant is generally too expensive to be used widely in the Colorado Basin.

Despite the apparent difficulties in augmenting the flow and improving the quality of the Colorado, the Colorado River Basin Project Act of 1968 and the Colorado River Salinity Control Act of 1974 commit the Federal Government to at least investigate these possibilities. The 1968 Act was based on the premise that 2.0 to 2.5 additional MAF would be required to meet the existing water apportionments and commitments of the 1944 Mexican Water Treaty. Congress seemed convinced that somehow the virgin flow of the Colorado could be increased by at least 2 MAF to offset the 1922 Compact's optimistic forecast of future streamflow. If so, the Central Arizona Project which was authorized by the same Act might be able to operate somewhere near its designed capacity and California might be able to continue consuming near its present rate.

Augmenting the Colorado

To date, five possible measures for augmenting the Colorado River have been identified: (1) importation from other river basins, (2) desalting of seawater and geothermal brines, (3) vegetation management to increase runoff, (4) evaporation suppression, and (5) weather modification to increase runoff. The task of augmenting the river was immediately complicated by a prohibition in the 1968 Act which forbade the Secretary of the Interior from studying the importation option. Before a decade had passed this restrictive amendment was renewed and now extends through 1988. Thus, if any

near-term augmentation strategies are to be tested in the Colorado Basin, they will have to rely on the existing climatic resources and hydrologic constraints.

Exploration of geothermal potential in the Lower Colorado Basin was performed by the Bureau of Reclamation to determine whether existing heat sources could be tapped for practical quantities of energy for water purification. Results were disappointing as the U.S. geothermal sources in that region were decidedly inferior those in Mexico which are being used commercially.

Investigations into the construction of large scale seawater desalting plants have shown that high construction costs and energy-intensive operations of the desalting process make this a generally infeasible alternative. Like the geothermal studies, these investigations concluded that seawater conversion was impractical for use on a sizeable reclamation project.

The Bureau conducted research for a number of years on ways of reducing evaporation losses in its reservoirs. This work was centered on the use of a fatty alcohol monolayer film to cover water surfaces, but the principal problem with this concept was that even light winds broke up the film. After thorough consideration by the Bureau and evaluation by a private research institute, the conclusion was that evaporation suppression would not be effective for significantly augmenting water supplies in the foreseeable future.

Vegetation management is another possibility proposed to improve the effectiveness of the watershed by creating more stream flow from existing precipitation. The U.S. Forest Service has confirmed that streamflow can be increased by managing blowing snow and vegetation on forested watersheds. A 1979 reconnaissance report by the Forest Service shows that theoretically, management practices aimed solely at increasing water yield could give the basin an additional 6 MAF annually. However, alteration of existing forests and the consequent environmental disruption could preclude application of this method over much of the 16 percent of the Basin area which the Service was using for its hypothetical evaluation.

While the aforementioned level of management is probably unrealistic, further studies indicate that increasing the Colorado River flow by 1 MAF may be possible within acceptable limits of watershed management practice. Still there would be a 20 to 30 year lag from the time these practices were instituted until the planned level of augmentation was achieved. (Holburt, 1982, p.22-23)

Weather modification was suggested by the Bureau as a promising means of augmenting the Colorado in the mid-1960s and it is currently considered to be the most promising and most cost-effective alternative. Cloud seeding could increase the natural efficiency of the Basin's mountain ranges in collecting atmospheric moisture by enhancing snowpack. The Bureau estimates that it is possible to increase flow of the Colorado by approximately 12 percent given a proven technology of weather modification tailored for specific watersheds.

Colorado River Enhanced Snowpack Test (CREST)

The Bureau has a long-standing planning effort to develop a comprehensive plan for the testing of cloud seeding techniques in the Colorado River Basin. In recent years, Congress has supported the development of this augmentation strategy by a series of appropriations beginning in 1978 when funds were provided for a Colorado River Augmentation Demonstration Program. During the past 5 years over \$2 million has been appropriated for this effort to formulate a program plan. In 1982 the Department of the Interior proposed the Colorado River Enhanced Snowpack Test, (CREST) a demonstration program which is considered absolutely essential to any wide-spread operational use of weather modification. Initiation of this 8-year demonstration program could provide a certified technology of flow augmentation by the early 1990s when the first real water shortages are likely to occur in the Colorado Basin.

The beauty of this proposal for augmentation is that weather modification could theoretically amplify the climatic resources of the Colorado Basin, producing greatly

increased benefits in existing structures without any known detriment to surrounding or downwind areas. Cloud seeding would not require major permanent construction nor would the operational costs be high. Moreover, a decision to employ cloud seeding is reversible on a year-to-year basis or even from storm-to-storm within a season as dictated by weather patterns, public response or Basin hydrology.

Projected Benefits

Expected benefits from weather modification outweigh operational costs by impressive margins. Even the CREST demonstration program which is a prerequisite to operational use would likely cover most of its cost with new energy and more and better quality water. During its 6 years of randomized seeding in two selected sub-basins of the river, the Bureau estimates that several hundred thousand additional acre-feet of water would be realized annually in the Upper Basin. With eventual operational use of cloud seeding this figure should increase to roughly 1.4 MAF per year.

The Bureau has calculated partial economic benefits of a basinwide operational program by introducing estimates of additional water supply into runs of its CRSS. This research model projects water availability; salinity; demands on water by municipal, energy, agricultural, and other water users. The impact to river water supply and quality as a result of proposed changes to the operation of the river system or alternative development schemes can be analyzed with the model.

The results of applying the expected snowfall augmentation to the CRSS model indicate that an average annual augmentation of 1.432 million acre-feet would produce \$123.4 million in benefits from the following sources: \$34.4 million from increased hydroelectric capacity and energy production based on an assumed value of 20 mills per kilowatt-hour, \$56.5 million from salinity reduction based on an average value of \$513,300 for each milligram per liter reduction in dissolved solids at Imperial Dam and \$32.5 million from additional water supplies to reduce deficits and for new uses in the Colorado Basin. Estimated increases in flow of adjacent river systems resulting from more snowpack accumulating in the divides between river basins total 533,000 acre feet and would be expected to produce net benefits of \$16 million annually with new water having an estimated value of \$30 per acre-foot. Total benefits of an operational program are therefore estimated to be \$139.4 million per year.

Costs for a basinwide operational program would be expected to vary between \$12 and \$16 million per year depending on the relative use of ground and aircraft seeding and the extent of the continuing requirements for environmental monitoring. Expected production costs would be for new water is estimated at from \$6 to \$8 per acre-foot.

The cost of developing this weather modification potential in the Colorado River Basin is considerable, but could likely be liquidated in a single year of an operational program. The CREST program will cost approximately \$88 million which would be spread over an 8-year period. This test would consist of preparation of field sites, installing equipment and performing calibration tests. During the following 6-years, randomized seeding would be conducted in two subbasins to confirm the runoff production and quantify the actual water supply increases. Concurrent with the randomized seeding, data will be collected which will allow successful augmentation techniques to be transferred to all important runoff producing areas of the Basin.

Benefits from the demonstration tests include a proven technology and an estimated 340,000 acre-feet of water produced annually during the 5-year test period. This additional water has an approximate value of \$11.9 million per year from increased hydroelectric capacity and energy production, salinity reduction, and additional water supply.

Energy Benefits

Added hydroelectric capacity and energy production is the most tangible benefit to be realized from enhanced streamflow and can be immediately incorporated into the existing power marketing system. We estimate that an operational program would produce an

additional 1.5 billion kilowatt-hours of electrical energy in the system. Preference customers of the hydropower system could benefit directly from the new energy resources made available through the demonstration program and any subsequent operational application of cloud seeding technology. Present practice in allocating Federally-generated power gives preference customers first priority to increases in energy production so there would appear to be ample incentive for consumers to support the CREST program. Likewise, the availability of increased hydropower would reduce the amount of power WAPA must now purchase in order to honor existing firm power contracts.

The consumer surplus or the benefit to power consumers realized by the substitution of new, cheap hydropower for more expensive, thermally-generated electricity is quite impressive. Utilities could presumably purchase new power at approximately the existing Federal rates, substitute it for more expensive power, and pass some of the savings on to consumers. In the Colorado River Basin we are talking about an additional 1.5 billion kilowatt-hours annually which would replace power costing up to 10 times as much.

4. Summary and Conclusions

The large seasonal fluctuations in the flow of the Colorado River and the wide yearly variation in its total flow together with the nearly complete dependence of much of the Southwest on this stream as a source of water led to the construction of a series of Reclamation projects throughout the river basin. The Bureau's dams and associated water projects now completely control the flow of the main stem of the river. Development and agriculture have been made possible in many areas which could not have otherwise been made productive or even inhabitable.

With the appropriation of all available water came the necessity of concisely apportioning the river's flow. The "Law of the River" has evolved from a series of agreements, legislation, and court decisions to distribute all available water among the Upper and Lower Basin States and to provide uninterrupted deliveries to Mexico. Optimum management of water and power resources requires input from the Colorado River Forecasting Service as integrated in the Bureau's Coordinated Long-Range Operation of Colorado River Reservoirs Plan. Automated data collection and use of the Colorado River Simulation System assist in monitoring the variations in flow and adjusting reservoir and power generation operations to maximize benefits.

Growing demand for water plus the authorization and construction of new water projects will shortly create water deficits in the Colorado River Basin. Recognizing the potential shortages, Congress has authorized the Secretary of the Interior to provide additional and adequate water supplies for use in the Upper as well as the Lower Colorado River Basin in the 1968 Colorado River Basin Act. More specifically, this Act requires Interior to produce a feasibility plan showing the most economical means of augmenting the Lower Colorado River flow by an additional 2 1/2 MAF per year.

After investigating a number of alternatives, weather modification and perhaps vegetative management appear to be the most promising means of augmenting the natural flow of the Colorado. The Bureau estimates that an operational program of snowpack enhancement has the potential to produce an additional 1.4 MAF in the Upper Basin as well as sizeable increases in flow for the Lower Colorado and in several adjacent river basins. This increased flow would have the potential to produce an additional 1.5 billion kilowatt-hours of hydroelectric energy in existing Bureau facilities annually as well as to offer a means of alleviating most of the anticipated future water deficit in the Basin. Vegetative management could potentially provide more water to completely erase the 2.5 MAF deficit defined by the Colorado River Basin Act, but it would require 20-30 years to fully implement.

Cloud seeding is considered to be the most cost-effective and environmentally acceptable means to meet the Colorado River Basin's water augmentation needs. Its adoption does not preclude continued planning and development of other augmentation alternatives nor lessen the commitment of the Department of the Interior and the Bureau to improved conservation practices. It does not require major permanent construction nor fixed operation and maintenance costs. Moreover, a decision to employ cloud seeding is

reversible on a year-to-year or even storm-by-storm basis should basin hydrology, weather patterns, or public response dictate. Our recent studies involving WAPA as well as the Bureau's Regional Offices show that this technology could be productively managed within the context of the entire Colorado River System.

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TABLE 1

UPPER BASIN DAMS AND RESERVOIRS

DAM	STATE	RESERVOIR	STATE	RIVER	STORAGE*	POWERPLANT**
Glen Canyon	AZ	Lake Powell	AZ-UT	Colorado	25,002	1,0211,
Navajo	NM	Navajo	NM-CO	San Juan	1,696	
Blue Mesa	CO	Blue Mesa	CO	Gunnison	83	60
Morrow Point	CO	Morrow Point	CO	Gunnison	117	120
Crystal	CO	Crystal	CO	Gunnison	18	28
Flaming Gorge	UT	Flaming Gorge	UT	Green	3,749	108
Fontenelle	WY	Fontenelle	WY	Green	345	10

LOWER BASIN DAMS AND RESERVOIRS

DAM	STATE	RESERVOIR	STATE	RIVER	STORAGE*	POWERPLANT**
Hoover	AZ-NV	Lake Mead	AZ-NV	Colorado	27,377	1,345
Davis	AZ-NV	Lake Mohave	AZ-NV	Colorado	1,810	240
Parker	AZ-CA	Lake Havasu	AZ-CA	Colorado	619	120
Senator Wash	CA	Senator Wash	CA	Senator Wash		

* In thousands of acre-feet

** In thousands of kilowatts