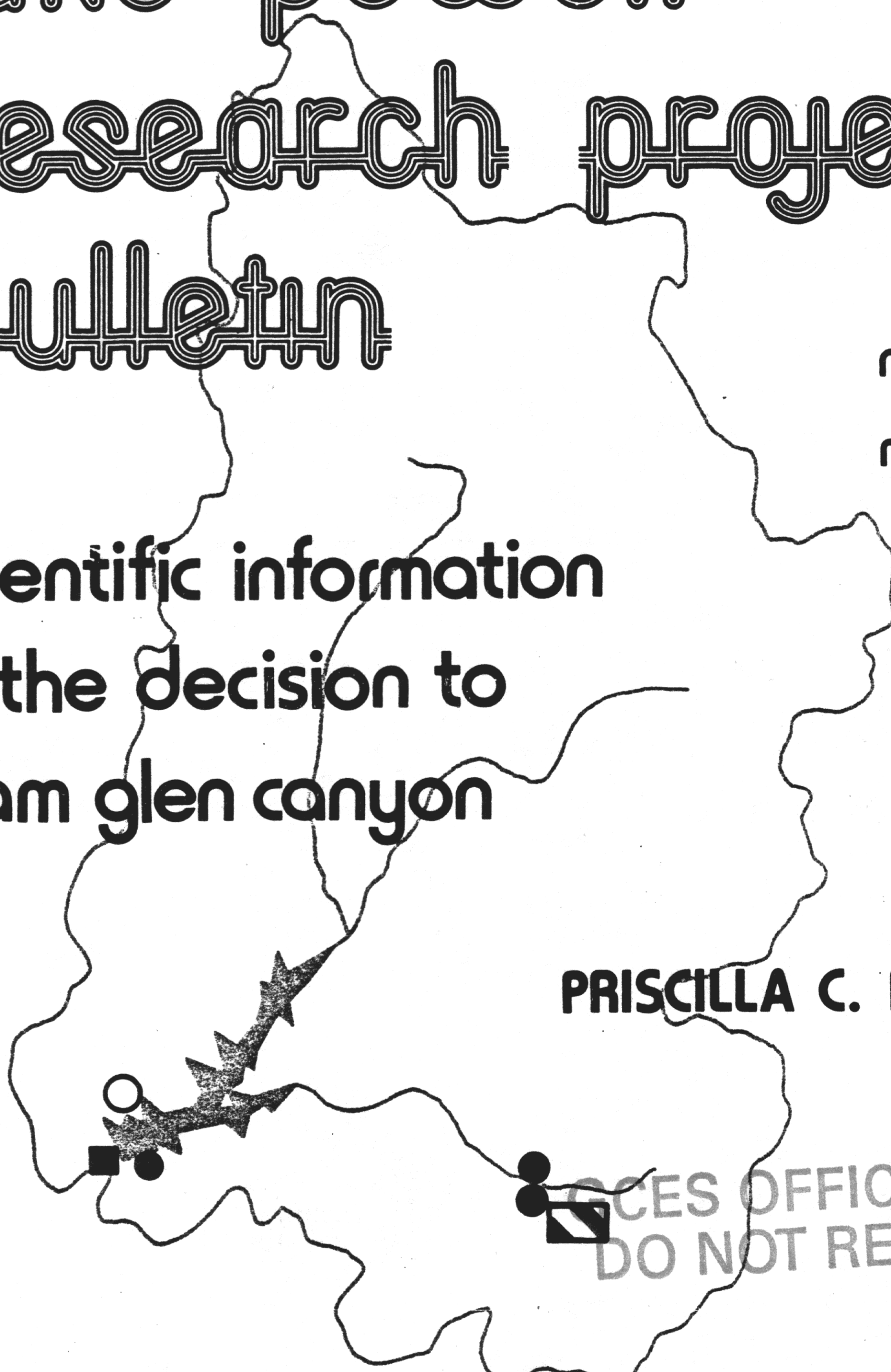
lake powell research project bulletin

number 9
may 1975



scientific information in the decision to dam glen canyon

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National Science Foundation
Research Applied to National Needs

LAKE POWELL RESEARCH PROJECT BULLETIN

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a publication of the research project

COLLABORATIVE RESEARCH ON ASSESSMENT OF MAN'S ACTIVITIES IN THE LAKE POWELL REGION

<u>NSF-Funded Institutions</u>

Arizona State University
Dartmouth College
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Price: $1.50, Payable to the Regents of the University of California

SCIENTIFIC INFORMATION IN THE DECISION TO DAM GLEN CANYON

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May 1975

LAKE POWELL RESEARCH PROJECT

The Lake Powell Research Project (formally known as Collaborative Research on Assessment of Man's Activities in the Lake Powell Region) is a consortium of university groups funded by the Division of Advanced Environmental Research and Technology in RANN (Research Applied to National Needs) in the National Science Foundation.

Researchers in the consortium bring a wide range of expertise in natural and social sciences to bear on the general problem of the effects and ramifications of water resource management in the Lake Powell region. The region currently is experiencing converging demands for water and energy resource development, preservation of nationally unique scenic features, expansion of recreation facilities, and economic growth and modernization in previously isolated rural areas.

The Project comprises interdisciplinary studies centered on the following topics: (1) level and distribution of income and wealth generated by resources development; (2) institutional framework for environmental assessment and planning; (3) institutional decision-making and resource allocation; (4) implications for federal Indian policies of accelerated economic development of the Navajo Indian Reservation; (5) impact of development on demographic structure; (6) consumptive water use in the Upper Colorado River Basin; (7) prediction of future significant changes in the Lake Powell ecosystem; (8) recreational carrying capacity and utilization of the Glen Canyon National Recreational Area; (9) impact of energy development around Lake Powell; and (10) consequences of variability in the lake level of Lake Powell.

One of the major missions of RANN projects is to communicate research results directly to user groups of the region, which include government agencies, Native American Tribes, legislative bodies, and interested civic groups. The Lake Powell Research Project Bulletins are intended to make timely research results readily accessible to user groups. The Bulletins supplement technical articles published by Project members in scholarly journals.

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ABSTRACT

Many of the physical impacts of the creation of Lake Powell now studied by Subprojects of the Lake Powell Research Project were anticipated in legislative debates which preceded the authorization of Glen Canyon Dam. Not only were these impacts considered in the 1950s during debate of the Colorado River Storage Project, but many were discussed in the 1920s at the time Glen Canyon was considered as an alternative to Boulder Canyon for the site of the first great dam to be built on the Colorado.

Scientific issues considered during the debate preceding authorization of Glen Canyon Dam included: (1) streamflow--uncertainties in the future flow of the Colorado due to the absence of a long history of stream gage records for the Basin; the uncertainties would plague attempts to meet water allocations guaranteed by Compact and legal assignments; (2) geological foundations of the dam site--weakness of the Navajo sandstone, particularly when exposed to water, would require the design of a dam with low bearing pressure on the rock abutments; (3) suitability of Chinle shale to contain a reservoir, due to its propensity for slumping; (4) evaporation--large reservoirs, needed to store water in the desert, would evaporate more water with greater surface area; (5) sedimentation--reservoirs would fill with silt possibly at rates significantly rapid compared with their anticipated economic lifetimes; and (6) water quality--developments in the Upper Colorado Basin would worsen water quality downstream, although some chemical constituents would be precipitated within the reservoirs. In addition, one physical science issue raised during the 1950s was that of bank storage. It was debated whether very large amounts of water might leave the Glen Canyon reservoir and enter the banks due to the high porosity of the Navajo sandstone walls.

SCIENTIFIC INFORMATION IN THE DECISION TO DAM GLEN CANYON

Evidently the flow of the Colorado and its tributaries is not sufficient to irrigate all the irrigable lands lying within the Basin.

The water available for irrigable lands below the Virgin may finally be derived almost entirely from the runoff of that part of the Colorado River Basin above the mouth of the Paria River.

E. C. La Rue (1916)[1,2]

Mr. HALEY. I am a layman as you gentlemen are and I, as you, must depend on the experts and authorities for scientific information.

Congressional Record (1956)[3]

INTRODUCTION

The first evaluation of the water supply of the Colorado River Basin, published by the United States Geological Survey in 1916, showed that water would be a scarce resource in the Basin even if dams were eventually built to regulate the erratic flow of the silt-laden Colorado River. Public demands for dependable water supplies, hydroelectric power, and flood protection would necessitate the construction of dams which in turn would cause increased water losses due to evaporation from reservoirs in Basin deserts. Furthermore, large exports of water from the Colorado to areas outside the Basin in Southern California were planned, even though the water survey had shown the inadequacy of the water supply to serve irrigable lands within the Basin.

E. C. La Rue, the author of the Geological Survey study, urged careful planning for development of the river which would "prevent an unnecessary waste of water."[4] Since La Rue's study, decision-makers have looked to scientists and engineers for information to support their arguments for and against various water projects in the Colorado Basin. Information from scientists and engineers has become political capital in legislative debate.

The problem of decision-making under the risk of mismanaging a scarce water resource involved (1) political judgment of the willingness of society to invest in large, public development projects, (2) anticipation of the costs and benefits of development, and (3) reliance on (and dispute of) scientific forecasts of the likely consequences of dam construction.

To improve the quality of decision-making and to enhance rational choice with respect to the scarce water resources of the Colroado River Basin, authoritative observers have urged greater use of planning and "better technological forecasting"[5] in the process of decision-making. In view of the present national effort encouraging improvement of scientific prediction of the impact of large resource developments (exemplified by the National Environmental Policy Act, NEPA, of 1969), it is of interest to investigate the historical use of "technological forecasting" in the controversial decision to construct Glen Canyon Dam on the Colorado River. The construction of a dam near Lees Ferry, proposed by La Rue in 1916 and finally authorized in 1956 as the "cash register" of the Colorado River Storage Project (CRSP), was the subject of intermittent political debate for 40 years. In the debate, scientific evidence, conjecture, and prediction were used to bolster arguments for and against the dam. The lengthy consideration of the project represents an unusually long planning period during which the use of scientific forecasting may be traced in the decision-making process.

The public record of the debate about construction of a dam in Glen Canyon has been examined by the Law and Political Science Subproject of the Lake Powell Research Project (LPRP) to determine "whether, and to what extent, scientific data and evidence was presented to and considered by the decision-making body."[6] This study has revealed that many of the physical impacts of dam construction now studied by Subprojects of the LPRP were not only extensively discussed in the legislative record of CRSP but in fact had been anticipated and discussed in the 1920s at the time when Glen Canyon was considered as an alternative to Boulder Canyon for the site of the first great dam to be built across the Colorado.

Gilbert White has pointed out that in some cases of creation of large reservoirs in the tropics, "those people responsible for deciding to go ahead with the construction projects were unaware of the consequences to which later studies are addressed."[7] In the case of the Glen Canyon reservoir, however, it appears that most of the physical impacts were at least qualitatively anticipated before construction.

This Bulletin mainly concerns the contribution of physical sciences and engineering to the Glen Canyon Dam debate. Consideration of the biological consequences forms a very small part of the argument in the legislative history. The role of social sciences in the debate is not described in this Bulletin, but it must be noted that economic arguments form a much more extensive part of the record than do those concerning issues in physical sciences.

ESTIMATES OF THE WATER SUPPLY OF THE COLORADO RIVER BASIN

In his original evaluation of the water resources of the Colorado River Basin in 1916, La Rue stated that "the average annual runoff available for storage at the Colorado-San Juan reservoir site [his name for a reservoir behind a proposed dam just above Lees Ferry] is about 15,000,000 acre-feet, or 92.6 percent of the mean annual runoff of the Colorado River at Laguna Dam [near Yuma, Arizona]."[8] This estimate was made using data from stream gage records along the three main tributaries of the Colorado River: the Green, the Grand (later called the Colorado), and the San Juan. However, all those gages were located far above Lees Ferry, due to the impassable terrain of the Canyonlands. There was, in 1916, no gage at Lees Ferry, and depletion estimates for water use in the Upper Basin were vague.

La Rue reasoned that the flow in the middle section of the Colorado could be approximately evaluated by measurements of flow in the main channel in the Lower Basin where more reliable data had been accumulated since the turn of the century. La Rue's estimates of flow in the Colorado near the Boulder site, which he gave for Hardyville [at the site of the present Davis Dam reservoir], were derived by deducting the "measured flow of the Gila from the measured flow at Yuma."[9]

In the summer of 1921, the United States Geological Survey, in cooperation with Southern California Edison Company, established the first gaging station at Lees Ferry.[10] In 1922, the Colorado River Compact was signed, which allocated water to the Upper and Lower Basins with a division point at Lee Ferry. By the summer of 1923, the Lees Ferry gage had recorded two full years of data, giving a measured discharge of 16,372,000 and 16,135,000 acre-feet for 1922 and 1923 respectively.[11]

Records for streamflow at the time of the signing of the Colorado Compact and the planning for the first big dams on the Colorado were not of sufficient duration to give very much credence to estimates of future supply. However, it should be recalled that "the middle section of the basin of the Colorado...[was at that time] probably the most remote and inaccessible region within the domain of the United States exclusive of Alaska"[12] so that the lack of information for that area is understandable.

In 1925, three years after the signing of the Colorado Compact, La Rue published graphs showing "estimated annual discharge of Colorado River at Lees Ferry, Arizona 1851-1922."[13] The graphs depicted (1) annual flow "without correction for depletion" with a mean of 16,000,000 acre-feet; (2) annual flow "corrected for past irrigation depletion," with a mean of 14,300,000 acre-feet; and (3) flow with "complete irrigation development in the upper basin" with a mean of 8,810,000 acre-feet.

Although measurements had only been made at Lees Ferry for two years at the time of preparation of La Rue's 1925 report, he estimated the past flow at Lees Ferry for the period beginning in 1895 by extrapolating records from gages on the tributaries of the Colorado in the Upper Basin. Records in the Lower Basin had been kept at Yuma since 1878 (by the Southern Pacific Company from 1878 to 1902 and by the Bureau of Reclamation after 1902). La Rue extended the extrapolation even further by using records kept of the level of the surface of Great Salt Lake (which is located in the Great Basin, not in the Colorado River Basin). A gage height record of the Great Salt Lake had been kept since 1875, and before that date "the location of the shoreline...at several definite dates before 1875...[was] very clearly fixed in the memories of the pioneers."[14] Thus the estimates of annual flow at Lees Ferry for one-third of the 1851-1922 period averaged by La Rue were based on the memories of the pioneers in another drainage basin.

In 1925, hearings on the Colorado River Basin were held before the Committee on Irrigation and Reclamation of the United States Senate. During the hearings, George H. Maxwell, Executive Director of the National Reclamation Association, stated that "the Colorado River is a very erratic stream, its annual flow varying from about 8,000,000 acre-feet to 25,000,000 acre-feet. A standardization of that flow of the river averaged over twenty years would produce a regulated flow of 16,000,000 acre-feet."[15] Such estimates of river flow were used to support proposals in the 1920s for a large dam to be built on the Colorado River. A vigorous debate ensued between California and Arizona on whether the first big dam should be built at Boulder Canyon or at Glen Canyon.

The Boulder site was eventually chosen, and construction of a dam was authorized in 1928. After World War II, proposals were again revived for a large dam in Glen Canyon. In renewed debate in the 1950s over CRSP, streamflow in the Colorado was again an issue. By this time, the Colorado Compact was in force, and there was a legal commitment on the part of the Upper Basin to deliver 75 million acre-feet to the Lower Basin every ten years. Accumulated records of streamflow indicated that estimates made at the time of the Compact formulation were probably too high.

In 1955, Senator Kuchel of California inserted into the record the text of a paper dated December 7, 1954, by Raymond A. Hill, employed as an engineer by the State of Colorado, entitled "Colorado River Deficits." In the paper, Hill remarked that at the time of the signing of the Colorado Compact in 1922, "it was believed that the flow of Colorado River would be in excess of all probable uses. Some still believe, others have awakened to the fact that nature was not bound by that compact."[16] He added that "the flow of the Colorado River has not been great enough during the past 40 years to have satisfied consumptive demands of even 15.5 million acre-feet per year...The historical flow of Colorado River at Lee Ferry ...[for the period 1914-1945] was 13.79 million acre-feet per year...[and] the natural undepleted flow was found to be 15.64 million acre feet per year"[17] in studies made in connection with plans for the Upper Basin Compact of 1948.

Hydrological studies by the Lake Powell Research Project have recently yielded an estimate of the reconstructed virgin runoff from the Upper Colorado River Basin. Using techniques of dendrochronology, a reconstruction of runoff for the past four centuries has been made. The reconstructed runoff in this period has a mean value of about 13.5 million acre-feet per year.[18]

SCIENTIFIC ISSUES INFLUENCING DAM SITE SELECTION

Early Proposals for a Dam at Glen Canyon

In 1916, La Rue proposed a "Colorado-San Juan"[19] storage reservoir to be located behind a 244-foot dam between the Paria River and Lees Ferry. There were inadequate topographic surveys of the area to be flooded by the reservoir, which led La Rue to suppose erroneously that the reservoir behind this dam would back water up to Cataract Canyon beyond Hite, Utah, with a capacity of 3 million acre-feet.

In the summer of 1921, in cooperation with the Southern California Edison Company, the Geological Survey made a topographic map of the Glen Canyon dam site identified by La Rue.[20] Later, in 1923, La Rue published a paper in which he suggested that an enormous rock-filled dam could be constructed at the Glen Canyon site by "blasting in the canyon walls."[21] He proposed a "780-foot dam...with a capacity of about 50,000,000 acre-feet" with backwaters "nearly to the junction of the Green and the Grand Rivers."[22] This suggestion was greeted with amazement by the engineering community, since it was well-known that rock-filled dams of much more modest dimensions had failed in a number of localities. In response to criticism, La Rue reduced his proposal to a dam "400 feet high with 8 million acre-feet of storage."[23]

In 1928, W. F. Durand, Special Advisor to the Secretary of the Interior, prepared a report on "A Proposed Reservoir and Dam at Glen Canyon." In the report he stated that "topographically, the Glen Canyon site is well adapted to the construction of a high dam, with large capacity reservoir and power equipment. Geologically the formation is of dubious reliability for a dam exceeding perhaps 400 feet in height and giving a reservoir of some 800,000 acre-feet in capacity, of which perhaps one-half might be active storage."[24]

Public leaders in Arizona favored the site at Glen Canyon because it was the only site for a large dam which lay entirely within the State of Arizona.[25] Furthermore, water from a reservoir at Glen Canyon might be carried by gravity in tunnels to central Arizona for irrigation, while water in an impoundment at Boulder would be more accessible for use by California.

In 1925, H. S. McCluskey, Secretary to the Governor of Arizona, discussed a storage reservoir at Glen Canyon with a diversion canal from Bridge Canyon to central Arizona.[26] However, he admitted that "we do not believe it is absolutely essential to go to Glen Canyon."[27] However, Arizona was seriously considering La Rue's proposal for the rock-filled dam. Rep. Carl Hayden wrote in 1924 that the "proposal that the State of Arizona shall build a rock-fill dam at Glen Canyon will be closely scrutinized by the engineers of the Federal Power Commission. There is so much doubt about the safety of this type of dam that every precaution will undoubtedly be exercised."[28] Arizona seemed to be operating at a disadvantage as far as engineering information was concerned. Senator Fred T. Colter wrote in 1924 that "Arizona has not sufficient money to obtain engineering data and facts to protect her sufficiently and protect these filings [for dams with the Federal Power Commission]."[29] In addition, the rock-filled dam appealed to Arizona because of its relatively low cost and its suitability for a site 135 miles from the nearest railroad.

Bedrock at the Glen Canyon Dam Site

La Rue's bold proposal for a high rock-fill dam drew many critical comments from engineers and geologists.[30] Kirk Bryan, a geologist with the Geological Survey, wrote of the Glen Canyon dam site: "the crushing strength of the rock is low, but the fact that it stands in great walls in a state of nature indicates that its crushing strength is ample for a high structure."[31]

A board of three engineers of the Bureau of Reclamation and a geologist, F. L. Ransome (later called in to analyze the failure of the St. Francis Dam in California in 1928[32]), stated in a report dated December 20, 1922, that the Navajo sandstone was composed of "grains...imperfectly cemented...It crumbles under shock, such as that of ordinary blasting...a conspicuous feature [of the canyon walls]... is the presence of a series of vertical fractures or joints...at such places, the sandstone is divided into great vertical, closely fitting slices. The joints...appear to be as a rule cemented by films of calcite. Under the action of the weather, however, the joints form zones of relative weakness, and where they occur there is a tendency for the rocks to fall off in blocks..."[33] A. J. Wiley, one of the three engineers, later wrote in a letter dated November 27, 1923: "It does not seem feasible to build any type of masonry dam of the necessary height for effective storage on the soft sandstone at Glen Canyon, at least no type or height requiring maximum pressures of more than 20 tons per square foot."[34]

H. W. Dennis, chief construction engineer for the Southern California Edison Company, in a memorandum dated December 19, 1924, described the results of tests on samples of Navajo sandstone from the Glen Canyon site obtained from core drilling undertaken by the Company between November 1922 and January 1923. He reported that three samples from a depth of 88 feet had an average compressive strength of 2,220 pounds per square inch, while those from a greater depth of 210 feet showed strengths of 12,900 and 10,480 pounds per square inch.[35] He noted that "the lowest crushing strength...is 1,315 pounds per square inch, which is very much in excess of any unit stress which would be permitted in concrete of which the dam itself would be made."[36] He therefore concluded that he had "no hesitation in recommending the site of the Lees Ferry dam for a flood-control reservoir of such height as may be financially justified in the complete comprehensive development of the Colorado River."[37] Colonel William Kelly of the U.S. Corps of Engineers agreed, stating in 1925 that "the rock will certainly bear more than the load which it is safe to place on concrete in a dam."[38] Arthur P. Davis, however, at that time Chief Engineer of the East Bay Municipal Utility District, Oakland, was more conservative about the "poor rock in Glen Canyon."[39] He remarked that "the rock in Glen Canyon is so soft that it is difficult to break off a sample without crushing it; and such a sample carried in one's luggage for a few days is apt to yield more fine sand than rock."[40]

Praising the foundation at the competing site of Boulder Canyon, William Mulholland of the City of Los Angeles assured Senators that the foundation at Boulder "is very hard granite in the form of syenite. The foundation there is as secure as the foundation can be in any dam site I ever looked at."[41] Thus, although there were other arguments in addition to geologic ones in favor of the Boulder site, the character of the Navajo sandstone at the Glen Canyon site was a distinct disadvantage to those wishing to argue that the first big dam should be constructed near Lees Ferry.

Questions about the weak sandstone at Glen Canyon were revived in the CRSP debate of the 1950s by David Brower[42] and by Rep. Craig Hosmer of California[43] as arguments against Glen Canyon Dam. Kenneth

B. Keener, Chief Designing Engineer of the Bureau of Reclamation, assured Congressmen in 1955 that a "series of laboratory tests made in 1950 on 6-inch cores from the Navajo sandstone showed average direct stress failure at 4,400 pounds per square inch without lateral stress...the preliminary trial load analysis...indicated that a high concrete dam can be designed for the Glen Canyon site with stresses at the concrete-to-rock contact surface not exceeding 750 pounds per square inch."[44] In the final design of the dam, the maximum value of "principal stress at abutments" is 645 pounds per square inch.[45]

EVAPORATION

Evaporative loss of water is a price which must be paid for the storage of water in regulatory reservoirs. La Rue understood this principle and attempted to estimate the rate of evaporation for different parts of the Colorado Basin where reservoirs might be constructed. He estimated that the average loss due to evaporation in the region between Green River and Hardyville (on the Arizona-Nevada border) would be 3.5 feet per year, and that it would be 7 feet per year for the region south of Hardyville. (The Bureau of Reclamation obtained a value of slightly more than 7 feet for Lake Mead in 1953[46].)

Given the figure for evaporation in feet per year, the loss for a reservoir may be calculated from the surface area. In 1923, Arthur P. Davis, then Director of the U.S. Reclamation Service, estimated that evaporation from the Glen Canyon reservoir proposed by La Rue would be 6 feet per year,[47] and consequently, since the surface area was supposed to be "an extra 100,000 acres" over the area which Davis thought would be reasonable, the high Glen Canyon dam would cost an extra 600,000 acre-feet of evaporation per year.[47] He argued that La Rue's reservoir would "waste a large quantity of water by evaporation."[47]

The proposals for Boulder Dam were greeted with similar objections. C. Merrill, Executive Secretary of the Federal Power Commission, stated in 1925 at a Senate Hearing that the chief drawback of the 605-foot dam proposed for Boulder Canyon was the excessive evaporation loss which would be caused by the rapid increase in surface area of the reservoir in the upper 100 to 200 feet of dam elevation.[48] La Rue argued that due to the lower elevation of Boulder Canyon compared to Glen "evaporation at Boulder Canyon would be greater than at Lees Ferry for a given area of water surface."[49]

In the 1920s, engineers and scientists could not agree on a standard figure for evaporation. George W. Malone, State Engineer of Nevada, thought that evaporation at Glen Canyon would be 3.5 feet per year, and at Boulder Canyon 5 feet per year.[50]

Similar arguments about comparative evaporation rates for alternate reservoir sites were revived in the CRSP debate in the 1954-1956 period. The Bureau of Reclamation's report of 1950 had stated that the gross evaporation rate from Glen Canyon reservoir would be 63 inches per year, and the "net rate of evaporation at the maximum water surface level" would be 54 inches per year.[51] (The present evaporation is considered to be possibly as much as 72 inches per year.[52])

In the debate over the proposed Echo Park Reservoir, Under Secretary of the

Interior Tudor reported the increased amount of evaporation to be expected if alternate sites (Desolation, Dewey, and Gray Canyon combinations) were chosen instead of Echo Park. Anticipated losses by the construction of alternatives to Echo Park ranged from 70,000 to 228,000 acre-feet per year.[53] The Upper Colorado River Commission calculated increased evaporation of up to 560,000 acre-feet per year for an alternative to Echo Park.[54] During the hearings, David Brower identified mistakes in the presentation of evaporation figures by Tudor, which apparently resulted from "misreading of an elevation versus evaporation curve."[55] Afterwards, Tudor wrote to the House subcommittee: "I am aware that this error in the evaporation calculations for the high Glen Canyon reservoir may cast doubt as to the reliability of the calculations for other reservoirs."[56]

SEDIMENTATION

When La Rue was proposing a 380-foot dam in Glen Canyon in 1925, he was asked by Senator Charles L. McNary of Oregon, Chairman of the Senate Committee on Irrigation and Reclamation, whether he had taken into account "the rapid deposition of silt on the bottom of the reservoir" and what estimate he had made "of the deposit annually at Glen Canyon expressed in acre-feet."[57] La Rue replied "I would estimate it somewhere around 70,000 acre-feet a year."[57] La Rue stated that he estimated the rate of silt deposition to be about 100,000 acre-feet "at Yuma, and somewhat less at Boulder and still less at Glen Canyon."[57]

A figure of 70,000 acre-feet per year for Lake Powell was used by the Bureau of Reclamation in 1971, by which time considerably more information had been accumulated about the problem than was available to La Rue. In a letter dated August 19, 1971 (copy supplied to the Lake Powell Research Project by Bureau of Reclamation), R. W. Gilbert, Acting Director of Region 4, wrote to Howard A. Nibecker of Guadalajara, Mexico, that "records indicate that the annual flow of sediment into Lake Powell with the present regulation upstream by Flaming Gorge, Blue Mesa, and Navajo Reservoirs, is about 70,000 acre-feet per year...it appears that Lake Powell would fill with sediment in about 400 years"[58] if other factors did not reduce the sedimentation rate. In the 1950 report, the Bureau used a figure of "long-time average sediment deposition at Lees Ferry" of approximately 100,000 acre-feet annually.[59]

SILTATION AND IMPACT ON GRAND CANYON

In the 1925 Senate hearings, there were already indications that there would be opposition to constructing dams near Grand Canyon. Senator Oddie of Nevada asked La Rue what "the American people will have to say about damming the river in Grand Canyon National Park for power purposes?" La Rue answered "outside of our own party in 1923, there are not more than five men now living who have seen the Grand Canyon from the inside. I say they will have to let them construct dams, and they can put motor boats on them so that the people can see the inside of the canyon. I would not object at all to presenting that subject to the Park Service as a policy to be prosecuted 50 years from now."[60]

Almost 30 years later, the Bureau of Reclamation prepared the 1950 report which was published in 1954 as House Document 364. Dams at Glen, Bridge, and Marble

Canyons were considered in the report. In replying to the report, the National Park Service commented that Grand Canyon National Park would be affected by the construction of a dam at Glen Canyon. Since the San Juan River was known to be a heavy silt contributor, the Park Service noted that the Glen Canyon project "would materially reduce the silt content of the Colorado River through the Grand Canyon" and "on the basis of maintaining the natural conditions of National Park Service areas, any alteration of the silt content or stream flow could be considered as an adverse effect."[61] In addition, assuming that Bridge Canyon Dam were to be constructed, the Park Service noted that "reduction in silt and river debris which would occur as a result of the Glen Canyon Dam would likewise reduce the unsightly effects of fluctuation in the lower reservoir."[61] However, illustrating the lack of predictability of ecological effects, the Park Service admitted that "it is not possible to determine exactly, at this time, how extensive effects on Grand Canyon National Park would be."[61]

The Sierra Club took a similar position in 1949, actually insisting on the construction of Glen Canyon Dam to prevent rapid siltation of the Bridge Canyon reservoir.[62]

One of the major present impacts of the Glen Canyon reservoir is on white-water boating on the Colorado in Grand Canyon, a recently developed sport post-dating the decision to build Glen Canyon Dam. The erosion of beaches in the canyon by the water released from Glen Canyon Dam is an important present impact. The principle of erosion by such water was recognized by William Kelley, Chief Engineer of the Federal Power Commission, who in 1925 wrote that "complete desilting at Boulder will greatly accentuate the ever-present tendency to erode banks and pick up a heavy load of silt from the...bottoms... between that point and Yuma."[63] However, such an argument was apparently not used to oppose the construction of Glen Canyon Dam, because the use of the beaches in the Grand Canyon was not considered at the time that the decision was made.

BANK STORAGE

The Navajo sandstone, which forms much of the walls of Glen Canyon, has a high porosity. Water from an impoundment in Navajo sandstone seeps into the canyon walls which are porous and permeable, and the quantity of water transferred into the rocks from the reservoir is called bank storage."

The problem posed by bank storage was recognized by Kirk Bryan, who in 1921 worked in the vicinity of Lees Ferry. He criticized La Rue's proposal for unlined bypass tunnels in Navajo sandstone mentioned in the rock-fill dam proposals. Bryan wrote "it seems likely that there will be losses to the adjacent porous sandstone if the water in the tunnel is under great pressure, and this water...in the sandstone may eventually find or work out channels large enough to produce serious losses."[64]

A Geological Survey document accompanying the 1950 Bureau of Reclamation report suggested an annual seepage loss of 100,000 acre-feet for the proposed Glen Canyon reservoir.[65] J. Neil Murdock, regional geologist for the Regional Office of the Bureau in Salt Lake City, testified in 1955 that "2 million acre-feet is the maximum [for bank storage at Lake Powell]. And that will take a period, we figure, of approaching a hundred years to complete and fill. So that annually it is insignificant. It might be of interest to know that the bank storage at Lake Mead has been calculated at 3,200,000 acre-feet. So this is only two-thirds as much in this reservoir as we have down at Lake Mead."[66]

By contrast, the Minority Report of the House stated that "it has been independently calculated, assuming 250 miles of canyon wall and an average depth of 200 feet, that 32 million acre-feet would be absorbed by the canyon walls."[67] There is no description of the basis for this calculation in the Minority Report. However, one of the authors of the Report, Rep. Craig Hosmer of California, presented similar numbers in his debate with geologist Murdock, stating "I have calculated this, that assuming you have 250 miles of canyon walls and an average depth of 200 feet, you would have a volume of around 32 million acre-feet of rock into which this water might go through the porous Navajo sandstone."[68] Perhaps 32 million acre-feet of rock became 32 million acre-feet of water in the course of argument.

Hosmer stated later in 1956 that the Kaiparowits and Henry Mountains structural basins might eventually be filled with bank storage water, amounting to "350 million acre-feet of water, or at least 26 years' flow of the whole Colorado River."[69]

Recent estimates of bank storage for Lake Powell, compiled by the Bureau of Reclamation, give a cumulative bank storage of 6,327,000 acre-feet as of June 30, 1971.[70] The figures for the rate of accumulation of bank storage, namely a million acre-feet in each of the years 1964, 1965, and 1970, considerably exceed the differences in evaporation cited as reasons for choosing among reservoir sites. However, further refinement of evaporation measurements will be necessary to ascertain more precisely the amount of water in bank storage at Lake Powell.

IMPACT ON RAINBOW BRIDGE

Rainbow Bridge National Monument was established in 1910. In 1925, La Rue included a picture of the Bridge in his report on the Colorado River, calling it "one of the scenic wonders of the world."[71] The Glen Canyon reservoir which he proposed "would not in any way interfere" with the Bridge and would back up water only "to a point 1-1/4 miles below the Bridge. In fact, if the Glen Canyon dam were constructed [with a higher reservoir elevation]...to raise the water to the abutment of the Rainbow Bridge... [it]...would provide an easy means of access...by motor boat to the bridge. It is estimated that after the completion of automobile highways leading to the reservoir the number of tourists to this region would exceed 200,000 annually."[71]

The National Park Service, in comments to the Krug report of 1950, stated that a "maximum water elevation...at the site of the bridge, would rise approximately 56 feet within the restricted channel...more than 11 feet below the lower of the two abutments."[72]

"Water backing up Rainbow Bridge Creek under the Rainbow Bridge would leave unsightly deposits of flotsam, as well as staining the walls of the gorge. However, by far the most serious effect of floodwaters reaching the bottom of the watercourse beneath the span would be the danger of undermining the buttresses of the bridge itself."[72] The Park Service took the position that "no potential recreational values which could otherwise be determined to be inherent in the reservoir could compensate for the loss of this irreplacable natural feature..." and the Park Service "would be opposed to the Glen Canyon Reservoir on any basis or plan of operation which threatened the stability or natural scenic value of this national monument."[72] The Park Service suggested a modification of the proposed height of the reservoir, to reduce the maximum water level "from the proposed 3710 feet to 3650."[72]

The Park Service thus took a different position from the one later adopted by environmental interests in the 1950s hearings. The Park Service suggestion of maximum lake level was not based on the boundary of the National Monument (3,600 feet), but on the estimated impact of water backed up Bridge Canyon. The environmentalist position[73] has been that no waters from a reservoir should encroach on boundaries of a National Park or Monument.

BIOLOGICAL CONSEQUENCES OF DAM CONSTRUCTION

In the reply of the Fish and Wildlife Service to the Krug report of 1950, the inadequacy of ecological investigations is illustrated by the following comment: "biological investigations...were begun in 1949 [on the effect of proposed developments] but due to the immensity of the individual projects, the complexity of the habitat, the shortage of time and personnel available, complicated by the inaccessibility of the area, the information obtained was necessarily meager."[74]

The Fish and Wildlife Service presented a table compiled from information given by the Bureau of Reclamation Region 4 in November 1950, which stated average annual water level fluctuations anticipated for various reservoirs. The value for Glen Canyon reservoir was given as 20.3 feet.[74]

In a general statement about the plans for CRSP, the Service stated that the reservoirs would "expand the production of already abundant rough fish at the expense of more desirable forms of wildlife."[76] But it was also noted that "where sediment loads are reduced by deposition in the reservoirs and...favorable releases of cool water are achieved below the dams, highly desirable sport fishing may be increased."[76] The Service also noted that the "damage that would result to fish and wildlife" would be highest in mountain areas and lowest in the relatively inaccessible canyon of the Colorado River where the wildlife only consisted of "those animals which live in its muddy waters, or are able to subsist on the sparse vegetation among the cliffs."[76]

Therefore, they concluded that Glen Canyon reservoir "would inundate 153,000 acres of poor-quality wildlife habitat... The presence of the reservoir...would make the entire area accessible to boats... Fishery values in the Colorado and San Juan Rivers without the project based on present harvests would be insignificant."[77] But it was expected that "reservoir fishing would not be fully utilized" in the Glen Canyon reservoir because "of its inaccessibility and the fact that there are other fishing areas nearer important centers of population."[77]

CONCLUSIONS

In this review of scientific issues in the decision to dam Glen Canyon, several general themes have emerged. The general features of most impacts in the physical sciences were already anticipated by 1925. These estimates of impact were not necessarily the quantification of correct values, but for legislative decision-making the sense of the impacts was sufficient.

These issues were: (1) streamflow--uncertainties about the future flow of the Colorado due to the absence of a long history of stream gage records for the Basin; the uncertainties would plague attempts to meet water allocations guaranteed by Compact and legal assignment; (2) geological foundations of the dam site--weakness of the Navajo sandstone particularly when exposed to water, which would require the design of a dam with low bearing pressure on the rock abutments; (3) questions about the suitability of Chinle shale to contain a reservoir, due to its propensity for slumping; (4) evaporation--large reservoirs, needed to store water in the desert, would evaporate more water with greater surface area; (5) sedimentation--reservoirs would fill with silt possibly at rates significantly rapid compared with the economic lifetime of the dams and impoundments; and (6) water quality--developments in the Upper Basin would worsen water quality downstream, although some chemical constituents would be precipitated within the reservoirs. In addition, one physical science issue not raised until the CRSP discussions in the 1950s was that of bank storage, by which significant amounts of water might leave the reservoir and enter the banks due to the high porosity of the Navajo sandstone.

There were few major physical consequences which are now being investigated by the Lake Powell Research Project which were not anticipated. However, the debate shows that little attention was given to the impact of the creation of the dam on biological processes. Although it was remarked that a reservoir in Echo Park would have a deleterious effect on the shoreline ecology in that area, the effect on the Glen Canyon area was considered to be one of inundation of a "poor-quality" habitat.

The history of the role of science in the Glen Canyon dam controversies suggests that the "environmental" or "ecology" movement, which has developed since the Glen Canyon reservoir was being debated, is a movement seeking better forecasting of biological effects to match that conventionally achieved in the physical sciences. It would seem that Gilbert White's statement is correct, that it is in the area of prediction of biological and social impact (exclusive of economics) where deficiencies are most evident. White has observed that "typically, the national agency responsible for planning a new dam does not have competence in either biological matters or those related to social organization and process."[78]

A hypothesis which emerges from the record of the Glen Canyon dam debate is that even the physical issues would not have been so well defined in the absence of a vigorous debate with a strong, vocal, and informed opposition to the dam's authorization. Further, it may be conjectured that in the absence of such opposition, in order for impacts to be adequately considered, there has to be imposed from outside a regulation (such as requirements of NEPA) that physical impacts be investigated thoroughly. It may be that one reason why the physical issues were better defined in the case of Lake Powell than they were for the tropical examples cited by White is that some large development projects in the tropics have been national projects without a vocal, scientifically based opposition, and it is in this situation that potentially disastrous impacts can be ignored.

We might consider, for example, the case of the St. Francis Dam, built on a fault in California.[79] One-half of the dam rested on sandstone which dissolved in water, and the sandstone had not been tested before the dam was constructed. Perhaps the geological inadequacies of the foundation had not been considered because of the lack of opposition to question the rationale of building the dam.

Another general feature of the 40 years of debate about Glen Canyon is that the dam was considered several times in the context of alternates. In the 1920s the question was a choice between Boulder Canyon and Glen Canyon for the first big dam; in the 1950s there were the choices of a "high Glen" or a combined "low Glen" and Echo Park. In the first case, Glen Canyon dam was postponed, and in the second, the high Glen was eliminated together with Echo Park. Thus the ultimate decision to build Glen Canyon dam was based on consideration of alternates, and on evaluation of estimated physical impact, two goals which are considered desirable today in evaluation of environmental impact. The more outlandish suggestions did not materialize: an enormous rock-fill dam impounding ten times the volume of the present Glen Canyon dam was never built, and the bank storage shows no signs of approaching 26 years' flow of the whole Colorado River. Instead, factors which were thought to be known with some precision, such as the compressive strength of Navajo sandstone, and values for evaporation, had a greater influence on decision-making.

Scientific issues were examined from many points of view and by people with technical and non-technical backgrounds. The tone of the Glen Canyon decision is well described by Representative Udall, near the close of debate in 1956: "We have heard, just to give you a few illustrations, of collapsible dams, counterdams, counterpropaganda, counterblueprints, counterengineers, countergeologists, counterhydrologists, counteragronomists, countergeographers, and countercartographers..."[80] This was in fact the means by which the decision to dam Glen Canyon was scientifically informed.

ACKNOWLEDGMENTS

The author thanks Dean E. Mann, Gary D. Weatherford, Philip Nicols, and Orson Anderson for helpful discussions and encouragement of this study. She is also grateful to David C. Crandall for comments on a draft of the manuscript, but accepts full responsibility for the conclusions of this paper. This research was supported by the Research Applied to National Needs Program of the National Science Foundation, grant NSF GI-34835 (Natural Sciences Coordinator's Office, Lake Powell Research Project).

manuscript received August 28, 1974
revision received April 28, 1975

FOOTNOTES

[Ed. Note] The form of citing many of the documents in the following footnotes may be found in A Uniform System of Citation, published by the Harvard Law Review Association, Cambridge, Massachusetts (1967). Explanations of the abbreviations follow:

102 Cong. Rec. 3620 = Congressional Record, Volume 102, page 3620

supra = refers to source mentioned previously in this list

S. 500 = Senate Bill Number 500

H. R. 2903 = House of Representatives Bill Number 2903

at 258 = on page 258

H. R. Doc. 364, 83rd Cong. 2nd Sess., 153 (1954) = House of Representatives Document Number 364, 83rd Congress, Second Session, on page 153

H. R. Rep. No. 1087 = House of Representatives Report Number 1087

1. La Rue, E.C., 1916, "Colorado River and Its Utilization," U.S. Geological Survey Water Supply Paper 395, p. 167.

2. Ibid. p. 169.

3. 102 Cong. Rec. 3620 (Feb. 29, 1956) (remarks of Rep. Haley of Florida in a discussion of Chinle shale).

4. La Rue, 1916 op. cit. p. 167: "If diversion to other drainage basins were prohibited by law, about 340,000 acre-feet annually might be saved for use on the lower Colorado, but this quantity is small when compared to the shortage which may be expected. The adoption of a policy or plan of development tending to prevent the unnecessary waste of water cannot be too strongly urged."

5. Committee on Water, National Research Council, 1968, Water and Choice in the Colorado Basin, Publication 1689, National Academy of Sciences, Washington, D.C., p. 93.

6. Mann, Dean E., Monroe Price, and Gary D. Weatherford, 1927, "The Legal-Institutional Aspects of the Impact of 20th Century Man's Activities on the Upper Colorado River Basin," in Anderson, O.L., and J. E. Levy, eds., Collaborative Research on Assessment of Man's Activities in the Lake Powell Region. Proposal to the National Science Foundation. Institute of Geophysics, University of California, Los Angeles, p. 311.

7. White, Gilbert, 1972, "Organizing Scientific Investigations to Deal with Environmental Impacts," in Farvar, M.T., and J.P. Milton, The Careless Technology: Ecology and International Development: The Record, Natural History Press, Doubleday, Garden City, New York, p. 921.

8. La Rue, 1916, op. cit. p. 215.

9. La Rue, 1916, op. cit. p. 168.

10. La Rue, E.C. and G.F. Holbrook, 1925, Appendix A: Water Supply in "Water Power and Flood Control of Colorado River below Green River, Utah," U.S. Geological Survey Water Supply Paper 556, p. 101.

11. Ibid., p. 103.

12. Ibid., p. 101: "Throughout the canyon region, from the mouth of Green River to the Grand Wash [near the Virgin-Colorado confluence] a distance of 500 miles, there are only three points at which it is possible to reach the river with a wheeled vehicle."

13. La Rue, E.C., 1925, "Water Power and Flood Control of Colorado River below Green River, Utah," U.S. Geological Survey Water Supply Paper 556, Plate 74.

14. La Rue and Holbrook, 1925, op. cit. p. 121.

15. U.S. Senate, Committee on Interior and Insular Affairs, Colorado River Basin, Hearings on S. Res. 320 before the Subcommittee on Irrigation and Reclamation, 69th Cong., 1st Sess., pt. 6, at 872 (1925).

16. U.S. Senate, Committee on Interior and Insular Affairs, Colorado River Storage Project, Hearings on S. 500 before the Subcommittee on Irrigation and Reclamation, 84th Cong., 1st Sess., at 258 (1955).

17. Ibid. at 259.

18. Weatherford, Gary W., and Gordon C. Jacoby, Jr., 1975. "Impact of Energy

Development on the Law of the Colorado River," Natural Resources Journal, 15, p. 184.

19. La Rue, 1916, op. cit. p. 218.

20. La Rue, 1925, op. cit. Plate V facing p. 22.

21. La Rue, E.C., 1923, "Tentative Plan for the Construction of a 780-foot Rock-Fill Dam, on the Colorado River at Lees Ferry, Arizona," Am. Soc. Civil Engineers, Trans., 86, p. 200.

22. Ibid. p. 205.

23. La Rue, E.C., 1923, Reply to "Discussion on Rock Fill Dam, Lees Ferry, Arizona," Am. Soc. Civil Engineers, Trans., 86, p. 266.

24. Hearings on S. 728 and S. 1274 Before the Senate Comm. on Irrigation and Reclamation, 70th Cong., 1st Sess., at 414 (1928) ("Colorado River Basin").

25. Information in connection with H.R. 2903 presented to House Comm. on Irrigation and Reclamation, 68th Cong., 1st Sess., at 31 (1924) ("Protection and Development of Lower Colorado River Basin: Statements by Citizens of Arizona relative to the Colorado River Problem").

26. Senate Hearings on S. Res. 320 (1925) supra pt. 3 at 351.

27. Ibid. at 353.

28. Information on H.R. 2903 (1924) supra at 31.

29. Ibid. at 98.

30. Various authors, 1923, "Discussion on Rock-Fill Dam, Lees Ferry, Arizona," Am. Soc. Civil Engineers, Trans., 86, pp. 218-258.

31. Bryan, Kirk, 1923, Ibid., p. 228.

32. Ransome, F.L., 1928, "Geology of the St. Francis Dam Site," Economic Geology, 23, pp. 553-568.

33. Quoted in La Rue, 1925, op. cit. p. 20.

34. Kelly, William, 1925, Reply to Discussion of "The Colorado River Problem," Am. Soc. Civil Engineers, Trans., 88, p. 430.

35. Quoted in La Rue, 1925, op. cit. p. 21: "Memorandum regarding foundation for dam at Lees Ferry (Glen Canyon), by H.W. Dennis, chief construction engineer, Southern California Edison Co., Dec. 19, 1924."

36. Ibid. p. 22.

37. Ibid. p. 22.

38. Kelly, 1925, op. cit., p. 431.

39. Davis, Arthur P., 1925, "Davis on the Colorado River Problem," Am. Soc. Civil Engineers, Trans., 88, p. 390.

40. Ibid., p. 391.

41. Senate Hearings on S. Res. 320 (1925) supra pt. 1 at 116-117.

42. Senate Hearings on S. 500 (1955) supra at 635-636.

43. 102 Cong. Rec. 3756 (March 1, 1956) (remarks) of Rep. Craig Hosmer of California).

44. U.S. House of Representatives, Committee on Interior and Insular Affairs, Hearings on H. 270, 2386, 3383, 3384, and 4488 before the Subcommittee on Irrigation and Reclamation, 84th Cong., 1st Sess., ser. 4, pt. 1, at 258 (1955).

45. U.S. Bureau of Reclamation, 1970, Glen Canyon Dam and Powerplant: Technical Record of Design and Construction, Denver, Colorado, p. 70.

46. Harbeck, G. Earl, Jr., Max A. Kohler, Gordon E. Koberg, et al., 1958, "Water-Loss Investigations: Lake Mead Studies," U.S. Geological Survey Professional Paper 298, p. 1.

47. Davis, Arthur P., 1923, "Discussion on Rock-Fill Dam, Lees Ferry, Arizona," Am. Soc. Civil Engineers, Trans., 86, p. 224.

48. Senate Headings on S. Res. 320 (1925) supra at 513.

49. La Rue, E.C., 1923, Reply to "Discussion on Rock-Fill Dam, Lees Ferry, Arizona," Am. Soc. Civil Engineers, Trans., 86, p. 267.

50. Senate Hearings on S. 728 and S. 1274 (1928) op. cit. at 509. (Report by George W. Malone entitled "Boulder Canyon, Lower Colorado River, Power and Water Set-up, January 1, 1928--Presenting the Facts").

51. H.R. Doc. 364, 83rd Cong., 2d Sess., 149 (1954).

52. Jacoby, G.C., Jr., and C.W. Stockton, 1974, "Water Budget at Lake Powell and Its Relation to Surface-Water Supply in the Upper Colorado River Basin," AAAS Meeting, San Francisco, February 25, 1974

53. U.S. House of Representatives, Committee on Interior and Insular Affairs, Hearings on H. 4449, 4443, and 4463 before the Subcommittee on Irrigation and Reclamation, 83rd Cong., 2nd Sess., ser. 11, at 20-21 (1954)

54. Upper Colorado River Commission, 1952, Third Annual Report, p. 46.

55. For an extensive discussion of the evaporation arguments, see Stratton, Owen, and Phillip Sirotkin, 1959, The Echo Park Controversy, Inter-University Case Program, Inc. #46, Bobbs-Merrill Co., New York, pp. 28-31.

56. Ibid. p. 30.

In a letter to the author dated 20 June 1974, David C. Crandall, Regional Director of the Bureau of Reclamation Upper Colorado Regional Office, stated: "During this particular part of the hearings on the storage project, alternatives were being investigated for Echo Park Reservoir which had been recommended as an initial unit of the Colorado River Storage Project. One such alternative was to build Glen Canyon Dam high enough so that the storage capacity of Lake Powell would have been equivalent to the proposed Lake Powell up to elevation 3700 feet plus the capacity that had been proposed for the Echo Park Reservoir. The error that was made was simply the misreading of an elevation versus evaporation curve for Lake Powell... [It should not be implied that all] the calculations relating to reservoir evaporation behind any high dam at Glen Canyon were in error."

57. Senate Hearings on S. Res. 320 (1925) supra at 553.

58. Copy of letter sent to Orson L. Anderson, Natural Sciences Coordinator, Lake Powell Research Project.

59. H. R. Doc. 364, 83rd Cong. 2nd Sess., 153 (1954).

60. Senate Hearings on S. Res. 320 (1925) supra at 571.

61. H. R. Doc. 364, 83rd Cong. 2nd Sess. 193 (1954).

62. Sierra Club Bulletin, 34, p. 4 (1949).

63. Kelly, 1925, op. cit., p. 429.

64. Bryan, Kirk, 1923, op. cit. p. 234.

65. H.R. Doc. 364 83rd Cong. 2nd Sess. 181 (1954)

66. House Hearings on H. 270, et al. (1955) supra at 373.

67. H.R. Rep. No. 1087, 84th Cong., 1st Sess. 41 (1955).

68. House Hearings on H. 270, et al. (1955) supra at 372.

69. 102 Cong. Rec. A1144 (February 6, 1956).

70. Bureau of Reclamation, 1971, Bank Storage and Residual Losses, Salt Lake City.

"Bank storage accumulations... [are not] of the same nature as evaporation... [They would be only]..if none of the water entering the fractures, talus slopes, or the sandstone itself, during the filling stages of the reservoir operation, is returned to the surface storage or river when the reservoir is drawn down. The flow in and out of the open formations is likely to be as useful in the storage of water for downstream regulation and beneficial use as the surface storage itself. It is misleading not to cover this aspect of the total bank storage phenomena." (Letter to the author from David C. Crandall, Regional Director, Bureau of Reclamation, Upper Colorado Regional Office, dated 20 June 1974.)

71. La Rue, 1925, op. cit. p. 25.

72. H.R. Doc. 364, 83rd Cong., 2nd Sess. 192 (1954).

73. 102 Cong. Rec. 3756 (March 1, 1956).

74. H.R. Doc. 364, 83rd Cong., 2nd Sess. 265 (1954).

75. Ibid. Table 2 facing 267.

76. Ibid. at 267.

77. Ibid. at 268.

78. White, 1972. op. cit. p. 923.

79. Ransome, 1928, op. cit.

80. 102 Cong. Rec. 3736 (March 1, 1956).