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REPORT OF THE COLORADO RIVER BOARD ON THE BOULDER DAM PROJECT

LETTER

FROM

THE SECRETARY OF THE INTERIOR

TRANSMITTING

REPORT OF THE BOARD OF ENGINEERS APPOINTED BY THE SECRETARY OF THE INTERIOR, WITH THE APPROVAL OF THE PRESIDENT, UNDER AUTHORITY OF THE JOINT RESOLUTION APPROVED MAY 29, 1928, "TO APPOINT A BOARD OF ENGINEERS TO EXAMINE AND REPORT UPON THE DAM TO BE CONSTRUCTED"

DECEMBER 3, 1928.—Referred to the Committee on Irrigation and Reclamation and ordered to be printed

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CONTENTS

LETTER OF TRANSMITTAL

THE SECRETARY OF THE INTERIOR,
Washington, December 3, 1928.

The SPEAKER OF THE HOUSE OF REPRESENTATIVES.

SIR: I have the honor to transmit herewith a copy of the report of the board of engineers appointed by the Secretary of the Interior, with the approval of the President, under authority of the joint resolution approved May 29, 1928, "To appoint a board of engineers to examine and report upon the dam to be constructed under H. R. 5773, the Boulder Dam bill" (S. J. Res. 164).

Very truly yours,

ROY O. WEST.

LETTER OF SUBMITTAL

DEPARTMENT OF THE INTERIOR,
COLORADO RIVER BOARD,
Denver, Colo., November 24, 1928.

Hon. ROY O. WEST,
Secretary of the Interior, Washington, D. C.

SIR: The Colorado River Board has the honor to forward herewith five copies (one by air mail) of its report on the Boulder Canyon project, made in accordance with the requirements of Public Resolution 65, Seventieth Congress.

Very respectfully,

WM. L. SIBERT,
Chairman Colorado River Board.

REPORT OF THE COLORADO RIVER BOARD ON THE BOULDER CANYON PROJECT

The board of engineers and geologists appointed in accordance with Resolution 65, Seventieth Congress, approved May 29, 1928, has the honor to submit the following report as to the matters enumerated in said resolution, that were to be reported on prior to December 1, 1928.

The duties of the board, in so far as this report is concerned, are:

To examine the proposed site of the dam to be constructed under the provisions of H. R. 5773, Seventieth Congress, first session, and review the plans and estimates made therefor, and to advise him (the Secretary of the Interior) prior to December 1, 1928, as to matters affecting the safety, the economic and engineering feasibility, and adequacy of the proposed structure and incidental works.

The structures proposed in H. R. 5773, Seventieth Congress, are:

A dam and incidental works in the main stream of the Colorado River at Black Canyon or Boulder Canyon adequate to create a storage reservoir of a capacity of not less than twenty million acre-feet of water and a main canal and appurtenant structures located entirely within the United States connecting the Laguna Dam with the Imperial and Coachella Valleys in California.

The "incidental works" at the dam are construed to be a power house with its equipment of turbines, generators, and all appurtenant appliances needed in the generation and control of electric energy.

The "appurtenant structures" for the main canal are construed to be a higher dam at Laguna, an enlargement of the headworks and desilting basin, together with the necessary flumes, bridges, culverts, and other incidental structures along the line of the canal.

THE COLORADO RIVER

The Colorado River, one of the large rivers of the country, drains an area of about 244,000 square miles and has a total length from source to mouth of about 1,700 miles.

Its total fall is over 7,500 feet, or an average fall of about 4.5 feet per mile. The average rainfall on the drainage area is about 10 inches, over thousands of square miles less than 5 inches, and the average annual run-off is less than 1½ inches. Its main flow is derived from the melting of snow on the mountains of the upper basin. The principal characteristics of its flow are low waters during the autumn and winter months, with a normal flood from the melting snows, usually beginning late in April, reaching its maximum in June, and ending by the middle of August. This flow is modified and intensified by torrential floods of short duration, which come in general from its southern tributaries, and may occur during almost any month of the spring, fall, or winter. Its flood flows afford by far the greater quantity of water produced by the stream, and must

be conserved and impounded in order to be successfully utilized for water supply and power production. Floods of 200,000 second-feet are not unusual, and much larger ones have occurred.

ENGINEERING FEASIBILITY

The engineering feasibility of the proposed dam across the main stream of the Colorado River, at Black Canyon or Boulder Canyon, is basic.

SELECTION OF SITE

The board examined both sites in question, studied the available data concerning them, the geological formations surrounding them, and the seismic history of the region. Conclusions concerning these dam sites are embodied in the following statement:

BOULDER CANYON SITE

The site in Boulder Canyon is about 40 miles distant from the nearest railway line passing through Las Vegas, Nev. The railway approach is comparatively easy to the vicinity of the canyon, where extremely rugged topography adds considerable, though not insurmountable, difficulties.

The canyon walls at this site rise to 1,000 feet above the river and the rock gorge is at least 150 feet deep below low-water level. It is 420 feet wide at the low-water line and approximately 1,020 feet wide at the crest of a dam that would impound 26,000,000 acre-feet of water.

The foundation rock is granite and associated granitic rock of excellent quality. Regular joints and more irregular fractures are very numerous, and there is an occasional fault zone. These weaknesses are prominent on the weathered surface, but test tunnels prove that they are of little consequence to within a few feet from the surface. On the whole, the rock is strong, substantial, durable, and the whole mass is essentially tight. It will stand well in tunneling. There is no danger of the rock failing to meet requirements as a dam foundation.

The rock of the vicinity is suitable for construction material, and there are local sources of good gravel.

If no other site were available, the Boulder Canyon site could safely be used so far as geological conditions are concerned. In comparison with the Black Canyon site, however, the latter has certain advantages.

BLACK CANYON SITE

The most favorable location in Black Canyon is about 40 miles distant from Las Vegas, Nev., and the Union Pacific Railroad. The approach is comparatively easy to the vicinity and not particularly difficult to the site itself. A construction railway from Las Vegas would pass near available gravel deposits and the best quarry sites lie immediately adjacent to the dam-site on the same line of approach. Despite the ruggedness of the surrounding country and the depth of the gorge, the terrain above the 1,500-foot contour, where the quarries,

railway yards, shops, and camps would be located, is open, and its development into such use at reasonable cost is entirely practicable.

The canyon walls at this site rise to about 900 feet above the river and the central part of the rock gorge at this location is 110 to 127 feet deep below low water. The cross section of the gorge at the dam site is 350 feet wide at the low-water line and 880 feet wide at the crest of a dam that would impound 26,000,000 acre-feet of water.

The foundation is a volcanic breccia or tuff, originally an accumulation of fragments of many kinds derived from volcanic eruptions, and now transformed into a well-cemented, tough, durable mass of rock standing with remarkably steep walls and resisting the attack of weather and erosion exceptionally well. The whole rock mass is essentially impervious.

The rock formation is somewhat jointed and exhibits occasional fault displacements, which are now completely healed. It is an almost ideal rock for tunneling, is satisfactory in every essential, and is suitable for use in construction.

The associated rock formations at higher levels, more advantageously situated for development for construction uses, are also volcanic in origin, including both andesite flows and indurated andesitic tuffs, and are of excellent quality for that purpose. Near by there are deposits of angular gravels that have been proven by test to be suitable for use in construction.

COMPARISON OF THE TWO SITES

In general, geologic conditions at Black Canyon are superior to those at Boulder Canyon. The Black Canyon site is more accessible, the canyon is narrower, the gorge is shallower below water level, the walls are steeper, and a dam of the same height here would cost less and would have a somewhat greater reservoir capacity. The rock formation is less jointed, stands up in sheer cliffs better, exhibits fewer open fractures, is better healed where formerly broken, and is less pervious in mass than is the rock of the other site. The Black Canyon rock is not so hard to drill as that of Boulder Canyon, and it will stand better in large tunnel excavations with less danger to the workmen.

There is no doubt whatever but that the rock formations of this site are competent to carry safely the heavy load and abutment thrusts contemplated. It is well adapted to making a tight seal and for opposing water seepage and circulation under and around the ends of the dam. It insures successful tunneling, and, so far as the rock is concerned, the general safety and permanence of the proposed structures.

The board is of the opinion that the Black Canyon site is suitable for the proposed dam and is preferable to that of the Boulder Canyon.

DANGER FROM EARTHQUAKES AND DEFORMATION

In former geologic times this district was subjected repeatedly to volcanism and deformation. These events must have been accompanied by earthquakes. Such evidence as there is, both to be observed in the field and to be gathered from records, indicates that these geological activities ceased long ago and that the region has been

virtually undisturbed for a very long time. The district is recognized as having comparative freedom from present-day earth movements, and the conclusion is that danger from local earthquakes of enough violence to threaten a properly constructed dam in Black Canyon is negligible.

REVIEW OF PLANS AND ESTIMATES

THE DAM AND INCIDENTAL WORKS

The board is of the opinion that it is feasible from an engineering standpoint to build a dam across the Colorado River at Black Canyon that will safely impound water to an elevation of 550 feet above low water. The cost, however, will be greater than that contemplated in the project authorized in H. R. 5773.

The dam.—The dam proposed by the Bureau of Reclamation and assumed to be the one referred to in H. R. 5773 is of the gravity type, curved in plan, with allowable stresses as high as 40 tons per square foot.

It is the opinion of the board that a dam of the gravity type is suitable for the site in question, and that such a dam built across Black Canyon would be safe, provided the maximum stresses allowed do not exceed those adopted in standard practice.

The proposed dam would be by far the highest yet constructed and would impound 26,000,000 acre-feet of water. If it should fail, the flood created would probably destroy Needles, Topock, Parker, Blythe, Yuma, and permanently destroy the levees of the Imperial district, creating a channel into Salton Sea which would probably be so deep that it would be impracticable to reestablish the Colorado River in its normal course. To avoid such possibilities the proposed dam should be constructed on conservative if not ultraconservative lines.

Maximum foundation and structural stresses have until late years been limited, in the best practice, to about 20 tons per square foot. Until perhaps 20 years ago this practice was regarded as standard. The demand for high dams at reasonable expense has, however, induced more economical designs, and such stresses have been increased to 30 tons per square foot in numerous structures which have been in use a sufficient period to cause this practice to be considered conservative. Stresses in excess of 30 tons can not be considered conservative in a structure of this unprecedented magnitude and importance, failure of which would result in such an overwhelming disaster.

In consideration of these facts and possibilities, it is the judgment of the board that the dam should be designed for maximum calculated stresses not exceeding 30 tons per square foot. This will add materially to the cost of the dam, which increase will be included in the estimates.

Cofferdam construction and river diversion.—To control the flow of the river during construction, the proposed plans contemplate the diversion of 100,000 second-feet of water around the dam site by means of tunnels through the canyon walls. The upper cofferdam height was planned to be such that water could rise against it until sufficient head was created to force this amount of water through three tunnels 35 feet in diameter.

The proposed work in this connection comprised:

The building of two rock-fill cofferdams, one upstream 79 feet high, the other downstream 29 feet high, above low water level, involving the placing of 164,000 cubic yards of earth, the quarrying and placing of 757,000 cubic yards of rock; the making and unwatering of open excavations in the river bed about 125 feet below low water, involving 531,000 cubic yards of material (sand, gravel and boulders), with an uncertain amount of water; the preparing of foundations and placing of 235,000 cubic yards of concrete in the heel and tow of the dam in such a way as to form permanent cofferdams to protect the remainder of the work, all of the foregoing operations to be accomplished in one low-water season of less than nine months.

The board is of the opinion that it is not feasible, without undue risk to the men working in the excavations and on the dam, and to the inhabitants of the valley below, to carry out the plan as proposed. It is further of the opinion that the proposed diversion is inadequate and that provision should be made for diverting round the dam site, through tunnels, a flow of at least 200,000 second-feet. It is also the opinion of the board that the height of the water against the upper cofferdam should be ordinarily limited so as not to impound a volume which, if added to the flood waters, would, in the event of failure of the cofferdam, endanger life and property down the valley. This would limit the elevation of the water surface against the upper cofferdam to about 55 feet above low water or 700 feet above sea level.

These modifications would not only add essential elements of safety but also would enable operations to proceed continuously through a normal flood season.

It is the opinion of the board that it is feasible to construct cofferdams of suitable height at this locality and make them reasonably tight.

Permanent spillway.—The spillway capacity planned in connection with the proposed dam was about 110,000 second-feet without overtopping the dam. Floods reaching a maximum flow of 380,000 second-feet have been reported, and old high-water marks are said to indicate a possible flood flow of as much as 500,000 second-feet. The board is of the opinion that water in quantity should not be permitted to flow over a dam of this height.

A permanent spillway utilizing the increased capacity of the diversion tunnels provided in the revised plans will make it practicable to prevent any expected flood from overtopping the dam.

Excavation for the main dam.—The purpose of the revised plans for cofferdams and river diversion is to avoid probable interruption and to insure the safety of the earlier stages of the work, including the excavation for the foundations of the main dam, through a mixed deposit of sand, gravel, and boulders which fills the lower section of the gorge to a depth of more than 100 feet.

The chief factor which may affect the progress of the work is that of water seepage into the excavation, through the river fill under the cofferdams. Seepage into the excavation is to be expected. Its amount and rate can not be foretold.

The effect of water would be twofold. It would involve pumping to keep the pit unwatered and it would add to the difficulties and amount of excavation by causing the slopes to ravel and slump.

If the flow of water is sufficient to cause excessive raveling and slumping, it may be necessary to intercept this underground flow by wells or galleries or by other means. In the event of extreme difficulties it may be necessary to use caissons to carry the excavation down to the rock bottom in the deepest portion of the section.

It is the judgment of the board that it is feasible to make the required excavation for the permanent dam, but it is their opinion that plans and estimates of cost should include provision for the control and handling of a considerable volume of water.

The power plant.—While a power house must be fitted to a particular site and its equipment must be designed and selected for the particular conditions which obtain at such site, the entire installation will nevertheless be largely standard and offers no particular difficulties.

The board is of the opinion that the plans proposed are feasible from an engineering standpoint. Questions of cost will be considered in another part of the report entitled "Estimates."

THE MAIN CANAL AND APPURTENANT STRUCTURES

The bill provides for the construction of a canal connecting the Laguna Dam with the Imperial and Coachella Valleys, whereas the original estimate of $31,000,000 applies only to a canal reaching the distribution system of the Imperial Valley. The revised estimate will include the cost of constructing that portion of the canal leading to the Coachella Valley.

The Imperial Valley receives its water for irrigation and domestic purposes from the Colorado River by means of the Imperial Canal. The water is diverted from the river at Rockwood Gates, about 1 mile north of the international boundary, and is thence carried in a canal through Mexican territory and back into the United States to the Imperial Valley, thus avoiding the high mesa and sand-hill country north of the international boundary. In most of its 50-mile course in Mexico this canal follows the Alamo River channel, which formerly led into the Salton Sea.

The main canal is to be entirely within the United States. Under the proposed plan the water is to be diverted from the river at Laguna Dam, the present intake of the canal for the Yuma irrigation project, 23 miles by river above the intake of the Imperial Canal. This will allow water to be taken from the river at the higher elevation necessary to permit the canal to serve its purposes.

From the intake the proposed line of the main canal leads southwest to a point near the river just north of the international boundary, thence west approximately parallel to that line, to a point about 10 miles west of Calexico, a total length of 75 miles, making connections with the Imperial Valley system. At a point on the east mesa a canal branches off and leads to the Coachella Valley.

Between the Colorado River and Imperial Valley the canal location, for a length of 10 miles, crosses a region of sand dunes, some of which reach a height of about 150 feet above the canal bed. For much of this distance the canal cut will be over 50 feet deep. The grade of this section of the canal is such that the water surface will be below the mesa level and hence below the bases of the sand dunes. Winds above a velocity of 10 miles an hour cause a movement of the surface sand, which increases with the velocity of the wind, and special provision should be made to prevent undue silting of the canal by the

"blow sand" as well as for the removal of the sand that will drift into the canal prism. In order to observe conditions, the board visited the sand-dune belt several times, once during a sand storm. Although it is clear that difficulties are presented by the drifting sand, it is the opinion of the board that it is feasible to construct, maintain, and successfully operate the canal. The overcoming of these difficulties will affect the cost, which has been allowed for in the estimates.

The board believes that the canal should be lined with concrete through the sand-dune region and should be given a slope sufficient to carry the in-blown sand to a suitable place for deposit and removal.

ESTIMATES

The board in its review of the estimates for the proposed structures has reached the conclusion that such estimates should be modified so as to provide as follows:

	Estimated cost
Dam and reservoir (26,000,000 acre-feet capacity)	$70, 600, 000
1,000,000 horsepower development	38, 200, 000
The all-American canal	38, 500, 000
Interest during construction on above	17, 700, 000
Total	165, 000, 000
In this revision stresses in the dam have been limited to a maximum of 30 tons per square foot, and a diversion capacity of 200,000 second-feet is provided.	
Should the canal to Coachella Valley be considered a part of the main canal, the above estimates would be increased by the sum of	11, 000, 000
This would make the total estimated cost for all items in H. R. 5773	176, 000, 000

These estimates are based on a construction period of seven years.

ADEQUACY OF PROPOSED STRUCTURES

A dam of 550 feet above low water, across the Colorado River at Black Canyon, impounding 26,000,000 acre-feet of water, will be adequate, in the opinion of the board, to so regulate the flow of the lower Colorado as to control ordinary floods, to improve the present navigation possibilities, and to store and deliver the available water for reclamation of public lands and for other beneficial uses within the United States.

The high-water flow of the flood of 1884 is reported to have been 380,000 second-feet. Such a flood, or one of greater magnitude, is to be expected. The flood of 1884 is the highest concerning which there is fairly definite information, and as far as can be ascertained, such a flood has occurred but once in the last 50 years. A flood of this magnitude could be so controlled at the dam as to limit the flow in the river below to about 160,000 second-feet. Should such a flow sweep down the lower Colorado River, following a long period of normal regulated flow, with the consequent encroachment of vegetation on the flood plain and the probable neglect of flood protection works, it would be more destructive than a 160,000 second-foot flood under present conditions. It should be noted that the Boulder Dam project in no way affects the flood discharge of the Gila River. In the event of flood damage in the lower river valley from either river,

regulation at the dam would permit repairs to be made on the return of a controllable flow.

The adequacy of the proposed hydroelectric plant to generate generate sufficient power to make the project authorized a self-supporting and financially solvent undertaking is treated in the section on economic feasibility.

THE WATER SUPPLY OF THE COLORADO RIVER

The flow of the Colorado River is one of the fundamental factors on which the success of this project depends. On the stream flow depends the amount of land that can be irrigated and the amount of power that can be generated. The information on which this flow has been estimated is inadequate to furnish an accurate or sound estimate on which to base an important project without using factors of safety sufficiently great to make such estimates conservative and safe. Since the water supply is such a vital element in the problem, the board has inquired into the subject as thoroughly as the limited time would permit.

The estimates of flow on which this project has been predicated are the measurements of the flow of the river made at Yuma continuously since 1902. The methods used in gaging at Yuma were those common at the time the measurements were begun, and while improved methods of gaging were adopted at other gaging stations, these old methods were continued in use at Yuma until 1918, and with little improvement until 1926.

To determine the flow in the Colorado River above Laguna Dam there was subtracted from the Yuma gagings the estimated flow of the Gila River, which joins the Colorado between Yuma and the dam. The flows of the Gila are based on information of very doubtful value and can be considered as little better than fair guesses, whether too large or too small can not be determiued. To the reduced flow as arrived at above, the flow through the Yuma Canal was next added, to get the gross flow above Laguna Dam. The measurements of flow of the Yuma Canal are approximately correct.

From Black Canyon to Laguna Dam there is a loss in flow due to irrigation, evaporation, and possibly to seepage. Comparison of flow of the Colorado River at Topock and Laguna Dam gives some idea of the amount of this loss, but for most years it is so unsatisfactory as to be of little value. The gaugings, however, for 1926 and 1927, both at Yuma and Topock, are believed to have been fairly correct and give a reasonable basis for such an estimate. The figure used in the original flow calculations to represent this loss was 1,200,000 acre-feet per annum, and the addition of this amount to each yearly flow at the Laguna Dam gave the estimated depleted flow (or the normal flow of the river for that year less the water used for irrigation) at Black Canyon.

The information desired was the flow for each year at Black Canyon brought down to present conditions. To calculate this required that to each year's flow, estimated as above, should be added the amount of water used for irrigation that year, after which the amount of water used for irrigation at the present time was deducted. Neither of these quantities was known and they had to be estimated. These

estimates were based on the assumption that the net use or "consumptive use" of water per annum was 1½ acre-feet per acre irrigated. This is as good an approximation as can be made. The amount of irrigation from year to year was calculated on the basis of the census returns for 1902, 1909, and 1919.

In consequence of these methods the net results arrived at in the original estimates for the flow at Black Canyon are exceedingly uncertain, and in the opinion of the board are too high.

YUMA GAUGINGS

The Yuma gaugings, covering the period from 1902 to 1922, have been used as a basis for the original estimate of water supply for the Boulder Canyon project, and were apparently considered to be applicable to the average annual flow for at least the 50-year period of amortization.

The average annual flow at Boulder Canyon is estimated by the Reclamation Bureau at about 16,200,000 acre-feet, with a corresponding annual flow at Laguna Dam of 15,000,000 acre-feet. These figures do not seem to have been questioned in any reports that have come to the attention of the board, except in the memorandum of Herman Stabler, United States Geological Survey, to the Secretary of the Interior, dated March 17, 1924, in which the average flow at Laguna Dam was estimated for the period 1878–1922 at 13,600,000 acre-feet, or about 10 per cent less than the amount estimated by the Reclamation Bureau.

A record of gauge heights for the River at Yuma is continuous from April, 1878, but no actual current meter gaugings were made at the station until 1902. In 1902 the Hydrographic Branch of the United States Geological Survey established a gauging station at Yuma which was maintained until the close of 1906, when the station was taken over for operation by the United States Reclamation Service in connection with the operation of the Yuma irrigation district.

In 1909 the Yuma gaugings were estimated by an engineer of the United States Geological Survey as probably too large, varying from nothing to 15 per cent, and he suggested improved methods, which were, however, not adopted until 1918, and the best modern methods were not installed until January, 1926. The opinion was also expressed to the board by officials at Yuma in charge of the gauging work that the measurements made prior to 1926 were in error and resulted in too high an estimate.

An estimate of the excess of the calculated flow at Yuma above the actual flow of the river could be approximately determined only by paralleling the present more exact methods of measurement with the methods formerly used, through two or more seasons of high-water flow, and thus determine the error involved. Any estimate without such determination is uncertain. In the opinion of the board the results of the Yuma gaugings are at least 10 per cent too high. These corrections would reduce the estimate made by the United States Reclamation Bureau of the average annual flow at Laguna Dam, for the period 1902–1922, to about 13,500,000 acre-feet.

In this connection the estimates of Mr. Herman Stabler should be noted. His estimates, made from the long record of gauge heights and the measured flows at Yuma, were based on the assumption that

the measurements at Yuma were correct. If the Yuma flows were corrected and reduced, Mr. Stabler's estimate would also be reduced. Since the board finds that the Yuma gaugings for the period 1902–1922 are at least 10 per cent too high, Mr. Stabler's estimate based on these gaugings should be correspondingly reduced. Thus modified, his estimate for the average flow of the period 1887–1904 of 10,420,000 acre-feet is reduced to 9,360,000 acre-feet.

One of the most important facts shown by these estimates is the existence of a long dry period in the Colorado River flow prior to 1906. This low period is clearly shown by an inspection of the Yuma gauge heights for that period. Further investigation of this matter has convinced this board that the flows of the Colorado River as determined by the gaugings from 1906 to 1927 are materially higher than the flow for the preceding 20 years, and that a long period of equally low flows must be expected to recur at any time.

STREAM FLOW RECORDS

The evidence on which the above conclusion is based is contained in the following records:

GREEN RIVER

The average flow of the Green River, at Green River Station, Utah, for the period 1906–1917 was 125 per cent of its average flow for the period 1895–1905, and about 143 per cent of its average flow for the 6-year period 1900–1905.

GRAND RIVER

The average flow of the Grand River at Palisade for the period 1906–1922 was 122 per cent of its average flow for the period 1897–1905, and 135 per cent of its average flow for the 6-year period 1900–1905.

GREAT SALT LAKE

The average flow of the tributary rivers into Great Salt Lake, corrected for evaporation and depletion from irrigation, as given in the Weymouth Report, volume 4, for the period 1906–1922 was 134 per cent of the flow for the period 1889–1905 and 146 per cent of the 6-year period 1900–1905.

RIO GRANDE

The average flow of the Rio Grande at Del Norte, Colo., for the period 1906–1921 was 141 per cent of the flow for the period 1890–1905, and 178 per cent of the 6-year period 1899–1904.

THE COLORADO AT LEES FERRY

The estimate of E. C. LaRue, United States Geological Survey, of the average flow of the Colorado River at Lees Ferry for the period 1906–1922 is 130 per cent of the average flow for the period 1886–1905, and 142 per cent of the average flow for the 6-year period 1900–1905.

THE COLORADO AT LAGUNA

The estimate of Herman Stabler, United States Geological Survey, for the average flow of the Colorado River at Laguna Dam for the period 1905–1922 is 161 per cent of the flow for the period 1887–1904.

SALT RIVER

The average flow of Salt River below the Verde River for the period 1905–1920 was 180 per cent of the average flow for the period 1889–1904, and 371 per cent of the average flow for the 7-year period 1898–1904.

RAINFALL RECORDS

These foregoing several estimates showing deficient flow in the earlier period are in part confirmed by the following rainfall records.

THE GREAT SALT LAKE DRAINAGE AREA

The rainfall on the Salt Lake area at Corrine, at Ogden, and at Salt Lake City averaged for the years 1890–1905, 13.92 inches, and for the period 1906–1922, 16.78 inches, or 21 per cent in excess of the earlier period.

THE UPPER COLORADO DRAINAGE AREA

On the upper Colorado River drainage area the average rainfall at Durango, at San Luis, and at Grand Junction for the period 1895–1905 was 11.83 inches, while for the period 1906–1918 it was 14.92 inches, or 20 per cent above the earlier period.

CONCLUSIONS AS TO STREAM FLOW

The estimated future flow of the Colorado River must be based on the flows of the past with the justifiable assumption that they will recur. Unfortunately, there are no actual measurements of the flows of the river for a longer period than 26 years, and these were made at Yuma. The use of these measurements for estimating the flow at Boulder Dam involves the necessity of considering various intervening gains and losses of water, the amounts of which are based on insufficient data, and result in final estimates which are unsatisfactory.

It is also known that the period from 1905 to 1927 was one of relatively high flow in the Colorado and also in neighboring streams, and that this period was preceded by about 20 years of flow much below the average of the whole period of measurement. Records also show that periods of high and low flow occur in cycles of very uncertain magnitude and duration. A low period similar to that which occurred from 1886 to 1905 is sure to recur, and may be expected at any time. It follows that, in addition to the 10 per cent reduction already referred to, the measured flow in the 26 years of record must be further materially reduced to care for climatic variation in order to arrive at a conservative estimate of the amount of irrigation and power that can be successfully maintained during a 50-year period by Boulder Dam.

The records of past performance of the Colorado River and of such other streams in this vicinity as seem pertinent furnish no basis for an exact estimate of long-past flows in the Colorado River. There is naturally considerable leeway in the interpretation of these data, and estimates based thereon may differ materially. The board however, realizes that in determining the economic feasibility of this project its estimates should be on the safe side and it has consequently adopted the following figures for the flows at Black Canyon, without further depletion:

	Acre-feet
Average low flow for a period of 15 to 20 years	10, 000, 000
Average high flow for a similar period	14, 500, 000
Average of high and low periods	12, 250, 000

It is estimated that the present flow is depleted by water taken for irrigation in the upper basin by approximately 2,750,000 acre-feet, which amount, if added to the above estimated average flow, would increase it to about 15,000,000 acre-feet. This is the amount apportioned by the seven States compact for division at Lees Ferry.

MINERAL SALTS IN THE RESERVOIR

The waters of the Colorado are normally high in dissolved mineral salts, chiefly carbonates, sulphates, and chlorides of calcium, magnesium, sodium, and potassium. The amount is well within the limits of accepted practice for irrigation purposes.

For domestic use the salt content is high, several times as high as it is in the water supply of Chicago, Boston, or New York. It is not an ideal water for such purposes, but the fact that it is usable is demonstrated by its use in the cities of the Imperial Valley and in Yuma and in other communities along the lower Colorado.

The waters impounded in the Black Canyon Reservoir will overflow, to a limited extent, lands in the Virgin Valley that contain beds of soluble salts, chiefly sodium chloride, sodium sulphate, and calcium sulphate. These salt beds will be dissolved at their outcrops, where submerged, and this will add appreciably at first to the salt content of the lower Colorado River waters. Much trouble of this kind, however, is not anticipated because most of the outcrops of these deposits lie either above the flow line or within the flood portion of the reservoir and in the back-waters of the Virgin Valley. They will be flooded only a small portion of the time, and all of the source formations below the water line will gradually be sealed off. This effect will be produced both by the silt deposited by the inflowing waters and by the slumping of the overlying shale beds.

It is the opinion of the board, in view of these controlling conditions, that the actual salt content will not be increased to an injurious amount, even in the beginning, and that, in a comparatively short time, the incoming silt will be so effective in blanketing the salt deposits that the salt content of the river waters will be reduced to about the present amount.

SILTING OF THE RESERVOIR

The Colorado River carries a heavy load of silt. This has enabled it to build the great delta which now constitutes the fertile lands of the Imperial Valley of California and the adjacent districts of Yuma, Ariz., and of Mexico.

If a great dam is built, all of the silt normally carried past its site will be deposited in the reservoir created, thus progressively reducing its capacity.

The best determinations available indicate that silt deposition in the proposed reservoir would be at the rate of approximately 137,000 acre-feet per year.

Silt will be deposited at all depths in the reservoir from the very beginning, thus continuously modifying the volumes set aside as silt, irrigation and power, and flood-control reserves. Probably the bottom portion, below the 940-foot contour, intended primarily for silt reserve, will receive and retain the largest quantity, and the top portion set aside for flood control will retain the least; but all will be affected.

When due allowances are made for distribution in the various reserve portions of the reservoir, it appears that approximately three-fourths of the effective reserve capacity for irrigation and power will still be available at the end of the first 50-year period and that a slightly larger proportion of the flood-reserve capacity will still be available.

Ultimately if there is no additional upstream reservoir development resulting in reduction of the rate of silt delivery, all of the remaining unoccupied portions of the reservoir would also be filled with the accumulating silt. To reach such an end would probably take about 190 years.

RIVER SILT BELOW THE DAM

The river below the dam, virtually throughout its course, flows on silt. A comparatively large amount of silt, with associated sand and gravel, swept down by the river, is accumulated on the more open valley bottoms. Some of this, of course, is available for transportation on any favorable opportunity. When the dam is built and clear waters issue from the reservoir, a new load of silt will be picked up along its course through these deposits. In the beginning this load is certain to be about as heavy as it is normally at present, but, with the continuous regulation of river flow and the virtual elimination of high flood waters, a tendency to silt stabilization will follow as the river becomes more deeply entrenched and develops a paved bed. As soon as this stage is reached along the larger part of the course above the diversion dam at Laguna, silt conditions will have improved. This improvement is certain to increase with time.

It is quite impossible to estimate the rate of improvement or the time it will take the river to reach such a condition of stability as to eliminate the silt burden. The quantities of silt along the river, however, are limited. Assuming that these silt beds will be attacked vigorously enough so that the river will carry its normal load for a few beginning years, it appears probable that so large a proportion of the immediately available supply will have been removed and the bed of the river will be so effectively paved with the residual coarser material that thereafter an increasingly smaller load will be carried. Ultimately the silt content will be virtually eliminated. We believe that marked improvement will be shown within the first 10 years, especially in reduction of the amount of extremely fine suspended silt which at present causes most damage to irrigated lands. Thereafter improvement will be gradual though erratic, on account of occasional floods.

POWER

Based on the foregoing estimates of the variation of flow of the Colorado River, it is believed that under present conditions of irrigation a continuous output of 550,000 horsepower, or 1,000,000 horsepower on a 55 per cent load factor, could be maintained even during the years of normal low flow.

A fairly rapid irrigation development is, however, to be expected in the entire Colorado River Basin, provided the seven States compact is consummated, and, if the Boulder Canyon project is undertaken, preparations for such development may be expected in both the upper and lower basins during the construction of such project.

As the use of water for irrigation increases, the amount of water available for power will decrease, and a time will arrive when, during periods of low water, the full estimated amount of power can not be maintained. Within a 30 or 40 year period, even with a re-regulating reservoir, the power output may be reduced to five-tenths or six-tenths of the capacity of the proposed plant during a long dry period.

This whole matter is further complicated by the proposed seven States compact. It is quite probable that the compact attempts to apportion more water than the actual average undepleted flow of the river. The situation is still further complicated by the fact that the upper States are authorized to take more than an equitable proportion of the flow of the river, for any one or more of a series of dry years, provided they permit a total of 75,000,000 acre-feet to flow down the river in a period of 10 consecutive years.

In any event, the upper basin has, by virtue of its location, first call on the water of the river. The withdrawal of the allotted share of the annual flow during any series of years of low flow may make it impossible to carry out the terms of the compact during the latter part of a low 10-year period. If the low flow continued for a considerable term of years, the proposed storage at Boulder Dam would be inadequate to provide sufficient water for the lower valley through such a period. The power output would also be seriously affected and might be reduced below the estimated minimum previously stated.

A 1,000,000-horsepower hydroelectric plant fully loaded and operating continuously on a 55 per cent load factor would generate annually 3,600,000,000 kilowatt-hours of current. In actual practice this theoretical output might be reduced by approximately 10 per cent.

With the uncertainties of the flow at Boulder Dam it is impossible to estimate closely the average annual output of power which would obtain during a 50-year period.

ECONOMIC FEASIBILITY

The time available for the investigation in preparation of this report has not been sufficient to permit the board to go into all phases of this subject in the detail necessary to fix its findings with the degree of exactness which might otherwise be practicable.

The board believes, however, that it has been able to review the available data with sufficient thoroughness to warrant the conclusions expressed in this report.

In considering the economics of this project the board recognizes the importance, among others, of the following factors:

1. While much land has already been brought under irrigation on the Colorado River delta in Mexico, it is evident that such development has been retarded by the lack of water available from the river during low-water periods. The storage of flood water in the Black Canyon Reservoir and its release during low-water seasons will make more water available in Mexico and will invite immediate expansion in irrigated acreage in that country. With the limited water supply available from the Colorado River, every acre permanently irrigated in Mexico will mean that an acre in the United States can not be irrigated. Such a limitation on lands would result in a corresponding limitation on possible income. It is the opinion of the board that it is of much economic importance in this project that an agreement limiting the amount of water assignable to Mexico should be made prior to the completion of the Boulder Canyon project.

2. The board believes that the growing demand for power in southern California, when considered on a conservative basis, will be sufficient to absorb the probable power output of the proposed hydroelectric plant.

3. As a sound basis for estimating the probable power output of a stream, it is necessary to know the flow of the stream for a long term of years covering periods of low and high flow of sufficient duration to furnish the low, average, and high flows for which the plant must be designed. Any less complete data throw doubt on the estimates, which becomes serious in proportion to the uncertainties in the data and the magnitude of the investment.

When this project was first proposed the cost of steam power in southern California was such as to leave a reasonable margin of profit above the probable cost of hydroelectric power generated at the proposed power plant. With the reduction in costs of power generated by steam, this margin has been greatly reduced.

The operation, maintenance, interest, and sinking fund for the Boulder Canyon project must be paid from the sale of power and of storage services, which latter has been estimated at $1,500,000 per annum by the Secretary of the Interior.

Based on the foregoing and the shortage of power which will occur at low flow, the board is of the opinion that if the Boulder Canyon project is completed and put in operation, carrying as it does the costs of flood-protection works and the all-American canal, it will be impossible to meet operation, maintenance, interest, and a sufficient sinking fund to retire the cost of the project within a 50-year period.

4. It is obvious that the power which can be generated from Boulder Dam is a valuable resource. If the income from storage can be reasonably increased and the capital investment reduced by the cost of the all-American canal, together with a reduction for all or a part of the cost properly chargeable to flood protection, it would be possible to amortize the remaining cost with the income from power

COLORADO RIVER BOARD.

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DENVER, COLO., *November 24, 1928.*

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