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Colorado River Aqueduct

Route Selected for Metropolitan Water District Requires Pumping

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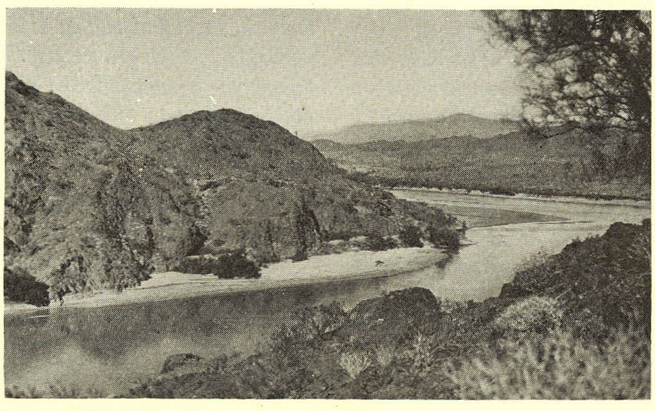
SOUTHERN California, without water, would return to the desert condition from which it has emerged. Its growth has been so great that it is now depleting all of its present available supplies of water. Eighteen years ago Los Angeles completed the Owens River Aqueduct, bringing water from the eastern slopes of the Sierra Nevadas, 250 miles away. That city, within recent months, has voted a $38,800,000 bond issue for extending and enlarging its Owens River Aqueduct to tap the waters of the Mono Basin about 60 miles northwest, and is now engaged in its construction.

The Colorado River being the only available source for additional water, Mr. Weymouth here describes the selection of the most advantageous of the 60 routes examined, and compares six which were intensively studied. Already more than a million dollars have been expended upon investigations and surveys of the desert regions through which the two-hundred-million-dollar aqueduct is to pass; and it has been characterized as the greatest engineering undertaking in America today.

The material from which this paper was prepared was originally presented by Mr. Weymouth before a joint meeting of the Los Angeles sections of the four Founder Societies and first published in the December 1930 issue of "ASCE," the technical publication of the Los Angeles Section of the Society.

THE Metropolitan Water District of Southern California is, in effect, a confederation of cities in the south coastal plain. It was organized in 1928 under the Metropolitan Water District Act of 1927, which authorizes the joining together of non-contiguous municipalities, or water districts, for the purpose of developing a domestic water supply. The district is governed by a Board of Directors composed of at least one director from each city, the voting power being distributed among the member cities on the basis of one vote for each $10,000,000 of assessed valuation, with the provision that no city shall have more than 50 per cent of the voting strength of the board. Each city has the right to appoint an additional director for each $200,000,000 of assessed valuation without, however, increasing its voting power. The enabling act requires that the water be distributed among the member cities in proportion to their assessed valuations, the apportionment to be adjusted from time to time to conform to the growth of the various communities.

There are, at the present time, 11 cities in the district, having an aggregate population of 1,850,000, and an assessed valuation of two and one-third billion dollars. The act provides for the addition of other cities from time to time, and for separations. Three new applications have been recently submitted and formally accepted by the Board of Directors. Ratification by the people of the applicant cities is necessary before these applications become effective. Several other communities have expressed interest in the project. The area, which may be regarded as prospectively a part of the Metropolitan Water District, has a present population of 2,750,000 and this number must be considered in estimating future demands on the water supply.



UPPER PARKER DAM SITE LOOKING UPSTREAM
For a Mile the Colorado Here Flows in a Rock-Bound Channel

PRESENT DEMAND FOR WATER

In 1929–1930 the City of Los Angeles used a total of 268,000 acre-ft. of water. A portion of this was developed from local wells; some of it was derived from surface flows in Owens Valley; and some was pumped from the Owens Valley gravels. No appreciable flows, subject to diversion by the city, went to waste and no water was accumulated in either surface or underground basins. In fact, ground water levels generally went down. In other words, the City of Los Angeles actually took more water from its sources of supply than was put back by nature. This does not mean that the city is actually facing an immediate water famine. There is still water in the underground basins available for emergency use, but the volume of underground water is not inexhaustible, and overdraft upon it cannot continue indefinitely. We are now, admittedly, in the midst of a dry cycle and some relief may ultimately be expected through increased rainfall.

Rainfall records at Los Angeles, for a 50-year period, are shown in Fig. 1. The precipitation has been declining, more or less gradually, since 1916. However, there have been many years with a lower rainfall than 1930, even in the brief period covered by these records. The 1893–1904 drought was more severe than the present one. It would be bold to assume that others, still more severe, will not occur in the future. It appears that Los Angeles is in a dangerous position as to future water supply, and it is evident that more water will be urgently needed by the time Colorado River water can be brought in.

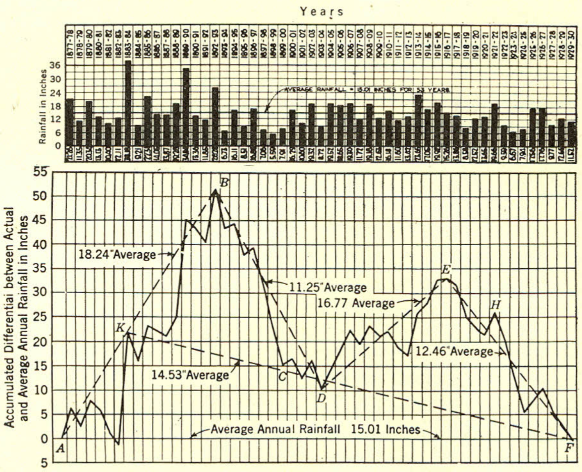


FIG. 1. ANNUAL RAINFALL RECORD, LOS ANGELES
With Accumulated Departures from the Mean

ESTIMATED ULTIMATE DEMAND

The habitable area of the coastal plain is approximately 2,200 square miles, or 1,400,000 acres. The contemplated Colorado River Aqueduct, after allowing for losses, will deliver something less than 1,000,000 acre-ft. per year into local storage reservoirs or, say, 0.70 acre-ft. per acre. The Los Angeles Aqueduct, extended to Mono Basin, can be depended upon for perhaps 0.20 of an acre-ft., bringing the supply up to 0.90. Run-off from the 3,900 square miles of the south coastal plain may be counted upon to supply an additional 0.4 acre-ft. per acre.

Then the total supply, with all prospective importations, amounts to approximately 1.30 acre-ft. per acre. This is a gross figure, and with no allowance for losses in handling and distributing. As an irrigation supply, it is a modest amount, but as a domestic supply it is low, even for sparsely settled sections, and it makes no allowance for the heavy usage in congested and industrial districts. This allowance will probably be slightly increased by sewage reclamation and perhaps more notably by "return flow" from irrigation when a more bountiful primary supply is made available.

A proposed aqueduct capacity of 1,500 sec-ft., or 1,086,000 acre-ft. per year at the point of diversion, was not selected by the above process of reasoning. But these general statements show that, although the region will not be overwhelmed by a surplus of water from the Colorado River Aqueduct, it will nevertheless be placed in a reasonably secure position for a time.

The amount of the proposed Colorado River diversion was arrived at by a study of predicted population curves, based upon past and present population trends and comparisons with the growth curves of other large and progressive communities, such as Chicago and New York.

From 1930 to 1980, the contemplated construction and amortization period, the estimated population increase for "Metropolitan Los Angeles" is 7,500,000. At the point of wholesale delivery, 1 sec-ft. of flow is sufficient for approximately 5,000 people. Therefore, according to these curves, the district will need the entire 1,500 sec-ft. of new water by 1980.

PRELIMINARY SURVEYS COMPLETED

That the Colorado River is the only adequate source of water near at hand, which can be delivered at a reasonable price, is universally conceded. Having decided to go to the Colorado to bring the water into the district, a problem of magnitude is presented, in the solution of which a vast amount of preliminary work has been done. When preliminary work was first started in 1923, the area between San Bernardino and the river was largely unsurveyed and the configuration was not such as to point to any single best line. Accordingly, a general topographic survey was begun, and maps were assembled from which the problem could be studied with facility. As an aid in engineering studies and to assist the public in comprehending the magnitude of the problem, an accurate relief map of the area was prepared. This map is 25 ft. long by 25 ft. in maximum width.

When maps became available, a large number of office locations and preliminary estimates were made. These led to the selection of certain prospective routes for an aqueduct. These routes were run out in the field and studied in detail on the ground by the engineering forces of the district and by a corps of competent geologists, with the result that the problem was narrowed down to one line from each of the several possible diversion points on the river. The locations of these six lines are shown in Fig. 2.

INTENSIVE GEOLOGICAL STUDIES MADE

The San Bernardino and San Jacinto mountains stand as a great barrier between the coastal plain and the desert country lying east of them. The region which the aqueduct must traverse is generally rough and rugged. Mountain masses rise above the general level of the intervening valleys, which are deeply filled with detrital material. These valleys often form enclosed basins which are water bearing. The main fault systems are located along, and to the west of, the San Bernardino and San Jacinto mountains. These systems are generally parallel and extend toward the southeast into Mexico. The most important of these fault lines is that known as the San Andreas, which traverses fully one-half the length of the state. Dr. John P. Buwalda, of the California Institute of Technology, characterizes this as the "most important fault in California, perhaps on the entire earth."

Recent movements of magnitude have occurred at several points along this fault, which any aqueduct from the Colorado River to the Metropolitan Water District must cross. It is considered important that the crossing be made on the surface, and approximately at right angles.

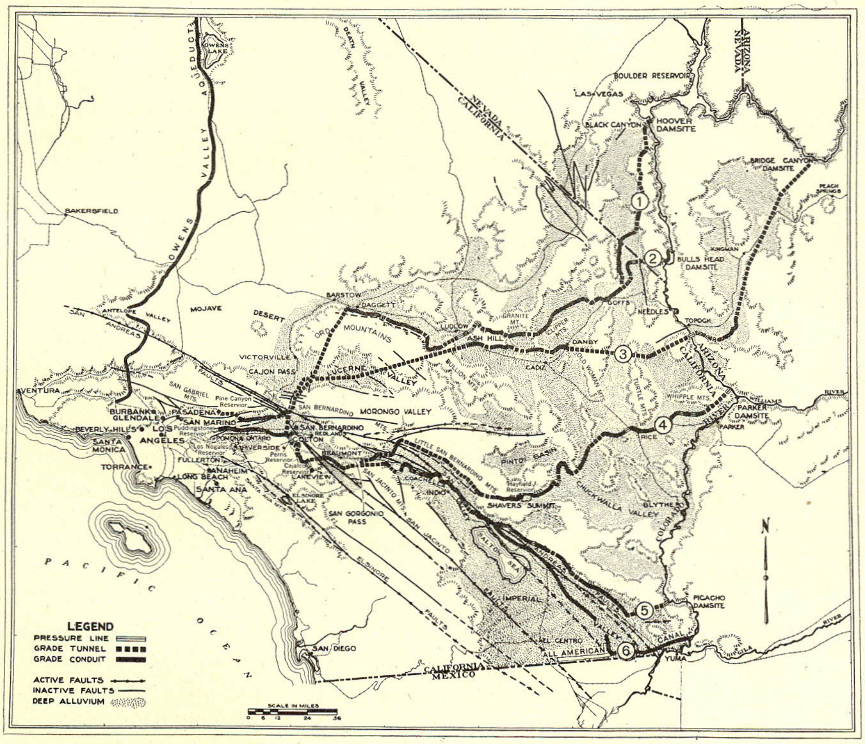


Fig. 2. The Six Routes Considered

THE BLACK CANYON LINE

Returning again to Fig. 2, it will be noted that diversions are possible from the river at Bridge Canyon, Black Canyon, Bulls Head, Upper Parker, and Picacho, or from the All-American Canal. A great number of line studies have been made from each of these points. The reservoir in Black Canyon offers an advantageous point for diversion. The water there is at a higher elevation than at other points farther down the river and, because of the large storage volume, would be of first class quality, entirely free from silt. The best location of a line from Hoover Dam is shown on the map, Fig. 2. This line leaves the reservoir in a short tunnel, after which it follows a contour location to a point near Daggett, where it enters a 50-mile tunnel, passing underneath the western end of the Bullion Mountains, under a portion of the Lucerne Valley, emerging from the San Bernardino Mountains near the city of San Bernardino. From this point it follows a reasonably easy location to Pine Canyon or other suitable reservoir.

The mean elevation of the water behind Hoover Dam in Black Canyon will be 1,167 ft. For convenience in distribution, a terminal elevation of at least 800 ft. is desirable, and 1,000 ft. is preferable. If excessive construction cost is to be avoided, a line as long as that from Black Canyon requires a drop of approximately 1,000 ft. to overcome friction losses. It is, therefore, evident that pumping would be required on a line from Hoover Dam.

If the water were brought through in a straight gravity tunnel, with a low terminal elevation, some flow might be taken from it directly for the areas near sea level. In this event, less pumping would be required than if the entire flow were lifted at the inlet end, but the actual reduction in cost of pumping would be small, because of the higher cost of power at the outfall. Furthermore, the land between the intake and the outlet is all high above any possible direct gravity flow line, and any such line would be wholly in tunnel. It would, moreover, be difficult if not impossible to construct, because it would pass at great depth through several of the deep detritus-filled valleys.

Although the cost of pumping varies with conditions, for the present purpose it may be stated that a sum of $80,000 is sufficient to build and forever maintain and operate the plant required to lift 1,500 sec-ft. one foot. Each time the aqueduct is raised one foot, it may be considered as being penalized by this sum. Within certain limits, lifting will bring the line nearer to the general level of the country and the cost will be reduced. Wherever a pump lift of one foot reduced the estimated construction cost by more than $80,000, the lift was considered to be justified.

Having decided upon a general elevation for the line, its cost then depends upon its slope. If the fall per foot is great, the velocity will be high and the conduit may be small. If the grade is flat, large tunnels and conduits are required and the cost per foot is great. The correct slope was also determined by the value of a foot of pump lift, and additional grade was utilized as long as the reduction in first cost was greater than the endowed value of the increased pump lift.

Taking all of these factors into consideration, a profile for the Black Canyon line was selected, as shown in Fig. 3. This line contemplates a total pumping lift of 1,663 ft. near the point of diversion. The resulting line is in good location, except for possible difficulties in the long 50-mile tunnel between Daggett and San Bernardino. The San Andreas fault is crossed on the surface under favorable conditions. A drop of 564 ft. at the terminus is available for the production of power.

THE BULLS HEAD LINE

As an alternative, it is possible to shorten the Black Canyon line by making the diversion at Bulls Head, about 50 miles farther down the river. This plan necessitates the construction of a diversion and power dam at Bulls Head, the cost of which tends to offset the reduced length of line. The pump lift is higher than at Black Canyon, but this is partly offset by the power produced at the diversion dam. Taken all together, the estimates show this line to be slightly less

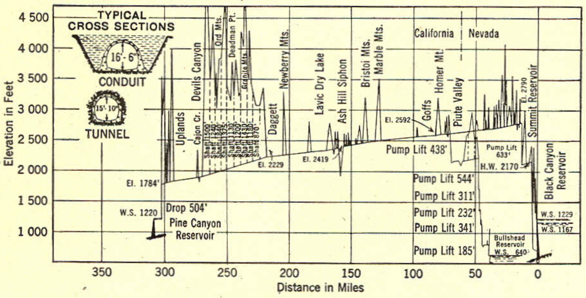


FIG. 3. PROFILE OF TENTATIVE BLACK CANYON LINE
Showing Bulls Head Alternate

economical than the Black Canyon line. A profile of the best Bulls Head line is also shown in Fig. 3. The total lift is 2,051 ft. and the power drop at the outfall is 564 ft., as in the Black Canyon line.

THE PARKER LINE

A diversion at the Parker site, still farther down the river, near Parker, Ariz., is likewise possible. The topography along this line permits of a lower summit elevation so that the total required pump lift is less than for the Black Canyon line, even though the diversion level is lower. The longest tunnel, moreover, will be only 13 miles as compared with 50 miles on the Black Canyon and Bulls Head routes.

For its full length the Parker line is in stable and safe location. After an initial pump lift of 539 ft. to an elevation of 989 ft., the Parker line (with dam) leaves the river in a 12.3-mile tunnel through the Whipple Mountains, of granitic formation and free from important faulting. Beyond this tunnel there is a length of 51 miles of surface conduit which may be of cut-and-cover conduit or open-lined canal. This section is located in granular detrital material, a product of disintegration of the native igneous rocks. It offers stable foundation for any type of lined surface channel. In its proposed location, the conduit through this region will be relatively free from any danger of disturbance by cloudbursts or earth movements.

The above mentioned length of surface conduit leads to a tunnel through the Granite Mountains, which will be mostly in solid rock, although some detrital material will be encountered at the portals. It is not expected that water will be encountered in these detrital approaches. Leaving the Granite Mountains, the aqueduct lies largely on the surface, with a few short tunnels, in stable material, to a point west of Shaver's Summit. In this stretch are located the pumping plants required to lift the water up to its final summit elevation of 1,817 ft.

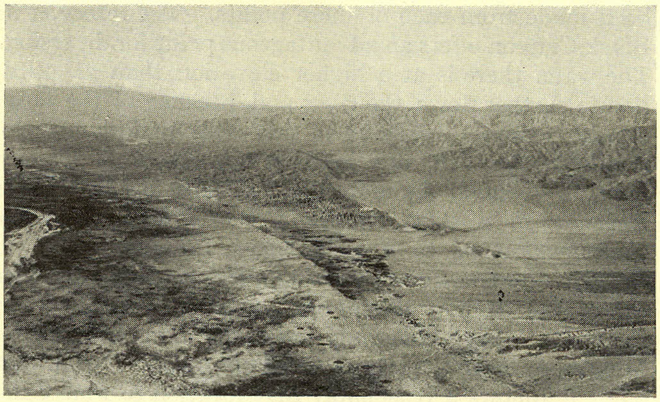
At the base of the last pumping plant, just before reaching the summit, there exists a natural basin of large capacity, the Hayfield Reservoir, which can be developed at a nominal cost and is available for the equalization of flow or as a protection against possible breakage in case the surface conduit leading to it is of open-canal type.

West of Shaver's Summit, the line is located in a series of tunnels along the face of the Little San Bernardino Mountains. The tunnels are in a stable block of ancient rock which shows little if any important faulting.

Emerging from the San Bernardino Mountains, the line crosses the upper end of the Coachella Valley in conduit. The San Andreas fault and its important branches are traversed on the surface under conditions which insure reasonable safety against serious damage in case of movement. The line then passes underneath the San Jacinto Mountains in tunnel, emerging near the mouth of Potrero Canyon in Perris Valley, where the San Jacinto fault line is crossed at the surface. From this point the line may be led to the terminal storage reservoirs by either of several safe and satisfactory routes.

As shown by the map, this line could be shortened by moving the point of diversion downstream. This is impracticable because the river channel below Parker is not permanently fixed and a diversion from it would be precarious. At the proposed diversion, the river is confined between rock walls. The Parker site is favorable for the construction of a combined diversion and power dam. The height to which the water can be raised is limited by encroachment on the city of Needles, Calif., about 58 miles up the river. A dam raising the water 72 ft. to elevation 450 is contemplated. Foundation conditions at the site are excellent for any type of dam, except for the great depth of overburden in the river channel. This difficulty may be offset, in part, by deferring construction until after the river is under control at Hoover Dam.

The diversion may be made by pumping directly



SAN ANDREAS FAULT, NEAR SALTON SEA, FROM THE AIR
Characterized as the Most Important Fault in California if Not on the Entire Earth

from the stream, or a combined diversion and power dam may be constructed. The power producible at the site will pay for the dam. If the dam is not built, it will be necessary to install clarification works at the point of diversion. In this event, a low-head pumping plant will be provided to lift the muddy water into the clarifiers, and only clear water will be delivered to the high-head plant. A profile of the Parker line, as at present projected, is shown in Fig. 4.

THE PICACHO LINE

The lowest practicable point of diversion from the river is at Picacho, about 20 miles north of Yuma, Ariz. It is contemplated that the water would be diverted by pumping directly from the river. This could be accomplished with safety at the selected site, as the river is confined between definite rock walls and has no opportunity to meander. A low diversion dam could be constructed, but its cost would be prohibitive. In any event, it would be necessary to install and operate some type of desilting equipment, as a storage reservoir capable of absorbing all prospective future silt accumulations is not feasible. The water would be pumped from the river through a height of 332 ft. to elevation 516 and delivered into a tunnel leading through the Picacho Mountains to the northern slope of the Imperial Valley. This tunnel would be partly in rock, thought to be of stable character, but toward its western end it would encounter an alluvial formation for a considerable distance.

After emerging from the first tunnel, this line skirts the northern rim of the Imperial and Coachella Valleys for a distance of more than a hundred miles, parallel to and near the San Andreas rift, as shown in Fig. 2. This rift is characterized by numerous side faults. According to Dr. Buwalda, "it appears to be inviting trouble to follow the San Andreas fault closely for long distances."

ALL-AMERICAN CANAL ROUTE

It is possible to eliminate the eastern end of the Picacho route by pumping from the western end of the Coachella branch of the All-American Canal, which, as shown in Fig. 2, follows the San Andreas rift even more closely than the Picacho line and is considered more dangerous.

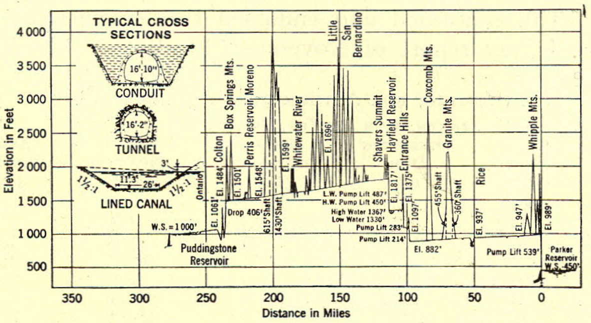


FIG. 4. PROFILE OF ADOPTED PARKER LINE

It is probable that a cooperative project would involve unavoidable operating difficulties, and it would probably be necessary that the All-American Canal and its branches be under full control of the irrigation interests. This would leave the Metropolitan Water District dependent for its supply upon the operation by an outside organization of a long irrigation canal. It would also be difficult to enforce necessary sanitary regulations along the irrigation channel.

Losses in an unlined canal through a sandy region like Imperial Valley would be tremendous. So the only way to make this project feasible, as regards losses, would be for the Metropolitan Water District to line the entire canal at its own expense. The practicability of such an arrangement is questionable.

THE BRIDGE CANYON LINE

Of the lines shown in Fig. 2, the Bridge Canyon line

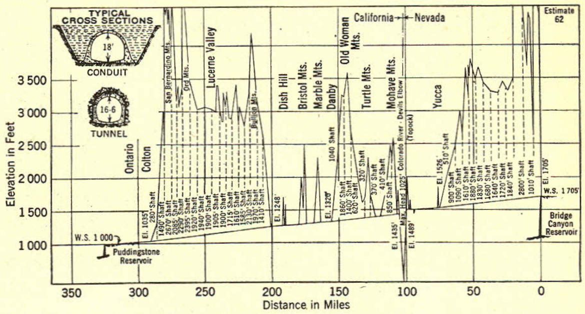


FIG. 5. PROFILE OF BRIDGE CANYON ALL-GRAVITY LINE

is proposed as an all-gravity route, delivering water into Puddingstone or other suitable terminal reservoir. This line requires a dam of from 600 to 900 ft. in height at the lower Bridge Canyon dam site, which site appears satisfactory for a dam of considerable height. The plan, as presented, contemplates the construction of the diversion dam by the district, on the assumption that the power developed will be owned and controlled by it. But it is improbable that such an arrangement could be perfected.

According to this plan, the aqueduct leaves Bridge Canyon in a tunnel 75 miles long under the Grand Wash Cliffs. As this tunnel lies at a great depth below the surface, shafts would be deep and construction of the tunnel expensive. Some of the shafts are located where the alluvial material and detrital valley fillings are of great depth and undoubtedly carry a considerable amount of water.

Emerging from the tunnel, the line passes in conduit to a point west of Topock, where it goes into a steel pressure line 4.9 miles long across the Colorado River, where the maximum head would be 1,025 ft. West of the river, it pierces the Mojave Mountains in tunnel and proceeds along a comparatively safe route, about 45 per cent in surface conduit, to a point near Ludlow, where it passes into a tunnel 89.5 miles long under the Bullion Mountains and beneath the water-filled Lucerne Valley, finally emerging at a point in the vicinity of San Bernardino. The outlet end of the tunnel is at a low elevation and for several miles is in the water-bearing gravels along the northern slope of the Santa Ana Valley. The San Andreas fault system is crossed deep underground by this long tunnel. This line, a profile of which is shown in Fig. 5, traverses a most difficult geological terrain.

The claim that water would ultimately be delivered practically without cost neglects the requirement for paying taxes on district property outside of California. The dam, the reservoir, and 105 miles of aqueduct would be located in Arizona. The cost and the operating expense of this line are much greater than for any of the pumping routes.

QUANTITY AND COST OF TERMINAL STORAGE

Investigations have shown that ample space for terminal storage near the outfall end of the aqueduct is available. There are several promising reservoir combinations from which a development may be chosen. Possibly the most convenient combination would be one including the Los Nogales Reservoir, which lies in the valley west of Pomona. Other promising reservoir combinations involve the use of either the Cajalco site, south of Riverside, or what has been termed the Perris site, near Lake View in the Perris Valley.

Terminal storage, located as near as possible to the delivery end of every long aqueduct, is a most desirable feature. Such storage not only serves to iron out the difference between the seasonal demands for water and the uniform rate of delivery through the aqueduct, but also enables the aqueduct to be shut down whenever necessary for repair or other purpose. The longer the aqueduct the more important does terminal storage become, and this Colorado River system is one of the longest aqueducts ever projected.

Terminal storage, moreover, is even more important for a system used for domestic supply purposes because of its effect in improving the quality of the water delivered for use. Still further, terminal storage is a direct insurance against the possibility of interruption along the entire aqueduct system which lies beyond the reservoirs.

A terminal storage volume equal to 30 days of aqueduct capacity would call for practically 100,000 acre-ft., and this quantity would reasonably serve all other purposes during the early years of the project. Terminal storage of 100,000 acre-ft. can be developed at a total cost of $17,500,000, on the basis of building the necessary dams so that later on they may be raised to provide additional storage as future developments require.

PARKER ROUTE SHOWS LOWEST COSTS

A summary of aqueduct cost estimates along the selected lines, together with certain pertinent physical data, is shown in Table I. Of all the routes studied in detail, the Parker route is clearly the most favorable. The main reasons for this conclusion are summarized as follows:

1. While the Parker route is less expensive in initial cost than any of the others except the Picacho and the All-American routes, it shows a smaller operating cost than either of these because of its lower pump lift, and it will furnish water to the district at less cost per acre-ft. than any other safe and satisfactory route.
2. From the viewpoint of the geology of the country, the Parker route passes through the best terrain, involves less hazardous construction than any other route, and will be the safest line to operate.
3. The Parker route is the only one on which it is practicable to provide intermediate storage. The location of the Hayfield Reservoir gives to it an advantage not enjoyed by any other route.
4. It is located entirely in California and is free from taxation or assessment in any other state. Water may be taken directly from the Colorado without interference with the rights of any other state.
5. The estimated ultimate cost of the Parker route, $220,535,000, is believed to be within the financial capacity of the district and is reasonable in consideration of the value of the service it will render.
6. The advantage of slightly lower initial cost of both the Picacho and the All-American routes is more than outweighed by the generally unfavorable terrain on both of these and the disadvantageous operating conditions of the All-American route.

The foregoing conclusions are also those of the Engineering Board of Review of the Metropolitan Water District. The Board, appointed to review the report of the Chief Engineer and to study the problem as a whole, consisted of: Chairman, Thaddeus Merriman, Chief Engineer of the New York City Board of Water Supply; A. J. Wiley, Consulting Engineer of Boise, Idaho; and Richard R. Lyman, Consulting Engineer of Salt Lake City. Its report, submitted on December 19, 1930, confirmed and endorsed the conclusions set forth in my report of November 14, 1930.

TABLE I. SUMMARY OF COST ESTIMATES, NOT INCLUDING TERMINAL STORAGE, FOR ALTERNATIVE AQUEDUCT LINES

Physical Data	Black Canyon (1)	Bulls Head (2)	Bridge Canyon All Gravity (3)	Parker, with Diversion Dam (4)	Parker, No Dam (Direct Diversion) (4a)	Picacho (5)	All American (6)
Height of diversion dam, feet	0	120	600	72	0	0	0
Initial elevation, feet	1,167	640	1,705	450	378	184	177
Terminal elevation, feet	1,220	1,220	1,000	1,000	1,000	1,000	1,000
Total pump lift, feet	1,662	2,051	0	1,523	1,601	1,997	1,888
Total power drop, feet	564	564	498	406	406	620	406
Pumping, millions of kw-hr. required per year	2,353	3,154	0	2,384	2,533	3,231	2,652
Longest tunnel, miles	51.33	51.33	89.51	12.95	12.95	15.34	12.95
Total length, all tunnels, miles	128.24	105.96	225.64	92.60	93.67	56.71	38.18
Total length, all pipe lines, miles	12.69	24.57	8.69	18.38	18.86	18.43	15.69
Total length of aqueduct, miles	299.40	254.01	315.90	265.36	266.91	234.12	271.44
Deepest shaft, feet	1,840	1,840	2,800	1,430	1,430	1,430	1,430
Total depth of shafts, feet	11,825	12,535	56,575	2,860	2,860	2,620	2,045
Years to construct	6	6	9	6	6	6	6
Cost in Dollars							
Preliminary investigations	$2,500,000	$2,500,000	$2,500,000	$2,500,000	$2,500,000	$2,500,000	$2,500,000
Head works	500,000	13,970,900	68,163,000	13,058,400	3,983,000	3,812,200	3,219,200
Aqueduct	194,529,000	163,051,100	370,977,000	144,423,700	145,942,100	132,836,800	117,334,800
Auxiliary storage	0	0	11,000,000	76,900	76,900	0	2,115,000
First Development (800 sec-ft.):							
Pumping plants	13,047,000	20,867,000	0	24,733,000	26,650,000	35,680,000	29,165,000
Power plants at diversion	0	705,000	11,004,000	516,000	0	0	0
Return power plants	2,286,000	2,306,000	0	1,100,000	1,100,000	5,027,000	2,878,000
Total construction	212,862,000	203,400,000	463,644,000	186,408 000	180,252,000	179,856,000	157,212,000
Total, including interest	239,006,000	227,346,000	557,846,000	206,279,000	199,442,000	199,180,000	174,265,000
Future development (1,500 sec-ft.)	9,724,000	15,768,000	4,284,000	14,256,000	14,112,000	15,552,000	13,320,000
Total capitalized, operation and maintenance	121,617,300	135,940,000	145,918,000	119,454,000	128,635,000	152,642,400	133,146,400
Capitalized return on power sold	0	0	55,095,000	0	0	0	0
Average perpetual cost per acre-ft.	23.35	23.95	39.99	21.60	21.82	23.34	20.30