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COLORADO RIVER AND ITS UTILIZATION

BY

E. C. LA RUE

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Storage reservoir sites in the Colorado River Basin.

Name of reservoir.	Stream.	Height of dam.[a]	Capacity.
		Feet.	*Acre-feet.*
Flaming Gorge	Green River, Utah and Wyo	255	4,720,000
Browns Park	Green River, Utah	200	2,520,000
Juniper Mountain	Yampa River, Colo	200	1,400,000
Minnie Maud	Green River, Utah	200	4,000,000
Rattlesnake	Green River, Utah	165	1,250,000
Kremmling	Grand River, Colo	230	2,200,000
Green-Grand	Junction of Green and Grand rivers, Utah	270	8,600,000
Durango	Animas River, Colo	100	500,000
Bluff	San Juan River, Utah	264	2,600,000
Colorado-San Juan	Colorado River, Ariz., Utah	244	3,000,000
			30,790,000

[a] The figures in this column indicate the elevation of spillway above average low water.

Information now available indicates that there are in the basin reservoir sites of sufficient capacity and properly located to make it possible to regulate the flow of the lower Colorado as desired. To be effective, however, the reservoir system must include the Green-Grand, Bluff, and other sites on upper Green and Grand rivers, or the Colorado-San Juan reservoir site must be utilized in conjunction with the reservoirs on Green and Grand rivers.

SILT IN COLORADO RIVER.[1]

DETERMINATIONS OF SILT IN COLORADO RIVER AT YUMA, ARIZ.

Prof. C. B. Collingwood, of the University of Arizona Agricultural Experiment Station, determined the content of silt in the water of Colorado River at Yuma for a period of seven months beginning with August, 1892. One pint of water was taken each day and evaporated, and the daily residues for each month were then weighed and analyzed. The results ranged from 1,631 parts per million of suspended matter in January, 1893, to 10,309 parts per million in October, 1892, and averaged 2,577 parts per million.[2]

From January 10, 1900, to January 24, 1901, samples of water were collected daily under the direction of R. H. Forbes, director and chemist, University of Arizona Agricultural Experiment Station, from Colorado River at Yuma, Ariz., and united in sets of six consecutive samples.

The samples were taken from the east side of the Colorado, at Yuma, 1 mile below the entrance of Gila River and 14 miles below Laguna dam. The average of the entire series of 61 determinations of silt is 2,776 parts per million. A fairer average, 2,814 parts per million, for the year 1900 has been obtained, however, by interpolating values of suspended matter for the short periods during which no

[1] Extracts from a discussion, unpublished, prepared by R. B. Dole, chemist, U. S. Geol. Survey.

[2] Cory, H. T., Irrigation and river control in the Colorado delta: Am. Soc. Civil Eng. Trans., vol. 76, p. 1217, 1913. For Prof. Collingwood's article see Arizona Agr. Exper. Sta. Bull. 6.

samples were taken and weighting each figure of the series by the number of days covered by it.

Unfortunately no reliable estimates of daily discharge for 1900 are available, and it is therefore impossible to compute the six-day loads of suspended matter. If the mean annual discharge is assumed to have been 22,800 second-feet and the mean load of suspended matter to have been 2,814 parts per million, the total load of silt during 1900 may be computed as 63,200,000 tons, a quantity in agreement with the estimate, 61,000,000 tons, given by Forbes in discussing his data.[1]

The second annual report of the United States Reclamation Service[2] contains a table of determinations of silt from February 3 to June 16, 1903, inclusive. Daily samples evidently were united in sets of three and the silt was determined in the composite thus obtained. It is not known who made the analyses, no comments on the figures being included in the original text. The load of suspended matter in tons during each sample period has been computed by multiplying together suspended matter in parts per million, the discharge in second-feet, the factor 0.00269, and the number of days in each period. According to this method of computation the total load carried past Yuma from February 13 to June 16, 1903, inclusive, was 58,300,000 tons, and the average content of suspended matter during that period was 8,002 parts per million. The discharge from March to June, 1903, was comparable with that during the same months in 1902 and 1904 but was much less than that during those months in 1905, 1906, and 1907.[3] As the series in 1903 covers only four months and does not include October, which is usually the month of high turbidity, it does not constitute a reliable basis for an estimate of the annual load of silt. It covers the period of spring floods and shows that there were large loads of silt during the last part of March and all of April. Graphic comparison of the content of suspended matter with discharge indicates a fairly regular increase of suspended matter with discharge during March and April. The much greater discharge during May and June, however, was not accompanied by proportionate increase in suspended matter.

During 1904 Prof. Forbes continued his study of silt in Colorado River, apparently taking daily samples and uniting these in composites of three or more consecutive samples, on which he made determinations of the suspended matter by weight. He states[4] that

[1] Forbes, R. H., The river irrigating waters of Arizona: Univ. Arizona Agr. Exper. Sta. Bull. 44, p. 202, 1902.

[2] Lippincott, J. B., Investigations in California [on Colorado River]: U. S. Recl. Service Second Ann. Rept., pp. 153–154, 1904.

[3] McGlashan, H. D., and Dean, H. J., Water resources of California, pt. 3: U. S. Geol. Survey Water-Supply Paper 300, pp. 449–450, 1913.

[4] Forbes, R. H., Irrigating sediments and their effects upon crops: Univ. Arizona Agr. Exper. Sta. Bull. 53, p. 60, 1906.

from January 1 to December 31, 1904, Colorado River carried 840 to 32,630 parts per million of suspended matter, and that the total load of silt during that year was 120,961,000 tons. Neither his individual analyses nor a description of his method of computations is available, but Cory[1] observes that "the investigations were carried out in such detail that it was possible to compute the quantity of solid material from the discharge at the time." It may therefore be assumed that Prof. Forbes calculated the total load of silt by adding together the weighted mean loads corresponding to his sampling periods. As the mean discharge during 1904 was 13,980 second-feet,[2] Forbes's estimate is equivalent to an average content of suspended matter of 8,784 parts per million.

Samples of water were taken daily from the Colorado at Yuma by the Reclamation Service between January 1 and December 31, 1905. The samples, which were taken at the railroad bridge below the mouth of the Gila, were analyzed in composites of three or four under the direction of T. H. Means at Berkeley, Cal. Though the dates indicate that the series is not absolutely complete, the errors due to that source have been practically eliminated by assuming reasonable loads of silt for the omitted days, and the total load of silt in 1905 has been computed as 312,000,000 tons. The average of the entire series of 106 determinations is 9,938 parts per million, which, combined with the mean discharge during 1905, 27,200 second-feet, gives the total load of silt for 1905 as 266,000,000 tons. As an estimate of the load of silt during 1905 this figure is not so nearly correct as the preceding one, but it has been computed for comparison with similar figures for other years. The greatest loads of silt in 1905 were carried between February and June, the maximum daily loads having been carried from March 19 to 24, inclusive; the content of silt during the first half of the year corresponds more regularly with the discharge than the content during the last half but bears no mathematical relation to it for any appreciable length of time. Similar lack of mathematical regularity is shown by comparison of the content of silt with the mean velocity during each sampling period; the most definite deduction that can be made from this comparison is that great loads of silt were not carried while the velocity was less than 3 feet per second; on the other hand, relatively small loads were carried many times while the velocity was between 4 and 5 feet per second.

Since May, 1909, the United States Reclamation Service has made observations of the sediment in Colorado River at Yuma, Ariz. Eight observations were made in 1909, 22 in 1910, 52 in 1911, and

[1] Cory, H. T., Irrigation and river control in the Colorado delta: Am. Soc. Civil Eng. Trans., vol. 76, p. 1217, 1913.

[2] U. S. Geol. Survey Water-Supply Paper 300, p. 450, 1913.

64 in 1912. The annual mean content of silt has been reported[1] as 6,500 parts per million in 1909, 5,000 in 1910, 11,500 in 1911, and 7,560 parts in 1912. From these data and the mean annual discharge, the amount of sediment carried by Colorado River during the years 1909 to 1912, inclusive, has been computed as follows:

Tons of sediment carried annually by Colorado River at Yuma, Ariz., 1909–1912.

Year.	Mean discharge.[a]	Mean content of silt.[b]	Load of silt.[c]
	Second-feet.	*Parts per million.*	*Tons.*
1909	36,200	6,500	232,000,000
1910	19,800	5,000	98,000,000
1911	24,600	11,500	278,000,000
1912	25,400	7,560	189,000,000

[a] McGlashan, H. D., and Dean, H. J., Water resources of California: U. S. Geol. Survey Water-Supply Paper 300, p. 451, 1913.
[b] Determined by the U. S. Reclamation Service.
[c] Tons=Mean annual content of silt in parts per million×mean annual discharge in second-feet×0.985.

The foregoing estimates of the annual loads of silt carried by Colorado River at Yuma just below the mouth of the Gila are summarized as follows:

Summary of estimates of silt carried by Colorado River at Yuma, Ariz.

Year.	Mean discharge.	Average content of suspended matter.	Total load of silt.
	Second-feet.	*Parts per million.*	*Tons.*
1892		2,577	
1900	22,800	2,814	[a] 63,200,000 [b] 61,000,000
1903	15,600	[c] 8,002	
1904	13,980	[d] 8,784	120,961,000
1905	27,200	9,938	[e] 312,000,000 [f] 266,000,000
1909	36,200	6,500	[f] 232,000,000
1910	19,800	5,000	[f] 98,000,000
1911	24,600	11,500	[f] 278,000,000
1912	25,400	7,560	[f] 189,000,000

[a] Estimate by Dole.
[b] Estimate by Forbes.
[c] Feb. 13 to June 16 only.
[d] Calculated from total load of silt.
[e] Sum of daily loads.
[f] Calculated from average content of silt.

These data are complete enough to indicate clearly (1) that the average content of silt varies widely from year to year; (2) that the average discharge varies widely from year to year; (3) that the average annual content of silt is not proportional to the average annual discharge; and therefore (4) that the total annual load of silt is not proportional to the total annual discharge. It has already been shown that the content of silt is not a function of the discharge or the velocity of Colorado River. The annual content of suspended matter

[1] Sellew, F. L., Discussion on irrigation and river control [Colorado River]: Am. Soc. Civil Eng., Trans., vol. 76, p. 1479, 1913.

may be said to vary in round numbers from year to year from 2,400 to 12,000 parts per million and to average 7,000 parts per million. The numerical average of the eight annual estimates of suspended matter in the accompanying table is 6,834. It is of course an open question how much weight should be given to the two low contents in 1892 and 1900.

In view of all the irregularities due to normal conditions it seems that an estimate of the average annual load of silt based on the average annual discharge and the average content of 7,000 parts per million is likely to give a fair idea of the magnitude of this quantity. The average annual discharge from 1895 to 1914, inclusive, is 23,560 second-feet, which, combined with the figure for suspended matter, 7,000 parts per million, gives 162,500,000 tons as a fair estimate for the average annual load of silt carried past Yuma by Colorado River. The probable error of this estimate is such that it may be called roundly 160,000,000 tons. The specific gravity of the silt is given by Forbes[1] as 2.65, which is practically the average specific gravity of the earth's crust[2] and corresponds to a weight of 165 pounds per cubic foot. The weight of dry soil is given by Forbes[1] as 93 pounds per cubic foot. On these bases the average annual load is equivalent to 80,000 acre-feet of dry soil or 45,200 acre-feet of rock. The equivalent as dry soil is a fair estimate of the dry mud or compacted silt on the bottom of a reservoir. This annual deposit in a reservoir 1 mile square is equivalent to a depth of 125 feet. Such complete deposition could not be attained, however, unless absolute stagnation existed for a month, for the finer particles of suspended matter are removed very slowly by sedimentation.

INFLUENCE OF GILA RIVER.

One of the chief sources of the silt in Colorado River at Yuma is the enormous amount of suspended matter discharged by the Gila, which has been characterized by Forbes the muddiest river in the world. The silt in this stream above the head of Florence canal ranged in 1899–1900 from 80 to 94,060 parts per million[1] and averaged 19.23 tons per acre-foot of water. At the Survey gaging station near San Carlos, Ariz., the silt content ranged from 120 to 24,700 parts per million and averaged 3,730 parts per million[3] between April 9, 1905, and January 2, 1906.

[1] Forbes, R. H., Irrigating sediments and their effects upon crops: Univ. Arizona Agr. Exper. Sta. Bull. 53, p. 60, 1906.

[2] Gannett, Henry, and others, Papers on the conservation of water resources: U. S. Geol. Survey Water-Supply Paper 234, p. 80, 1909.

[3] Stabler, Herman, Some stream waters of the western United States, with chapters on sediment carried by the Rio Grande and the industrial application of water analyses: U. S. Geol. Survey Water-Supply Paper 274, p. 41, 1911.

The rise and fall of the Gila between January and May, 1905, are closely followed by the content of suspended matter in the Colorado at Yuma. In June, in spite of the high discharge of the Colorado, its content of silt was small, and the average discharge of the Gila during that month was only 725 second-feet. During July, August, and September the discharge of the Gila was practically nothing and the content of suspended matter at Yuma was small. During October, with a small discharge from Gila River and a somewhat greater discharge from Colorado River, the content of silt increased. The increase of discharge from the Gila in November and December was accompanied by an increased content of silt in the Colorado, but this increase was not proportional because the silt content of the Gila was less in December than in November. A similar but not so close relation may be traced, so far as data are available, between the silt content of the Colorado and the discharge of the Gila during 1903. Comparison of data from 1903 to 1912 indicates that the silt content of the Colorado at Yuma varies chiefly with the discharge of Gila River. If the silt content of the water of Gila River, the discharge of that stream, and the proportion of that discharge to the discharge of the Colorado were all taken into consideration, the influence of the Gila could doubtless be more definitely indicated.

As the data regarding the silt content and the discharge of Gila River are incomplete, it is not safe to attempt to correct the figures for the silt content of the Colorado at Yuma in order to make them applicable to the Colorado at Laguna dam. It is possible that the average silt content above the Gila is less than half that of the stream below; indeed it is less than that at times.

FLUCTUATION OF SILT CONTENT.

The general fluctuations of the silt content of the Colorado at Yuma and their relations to discharge have already been outlined. The discharge of the Colorado usually is greatest in June and least from November to February, with floods in March or April and in September or October. The floods in spring and autumn usually are accompanied by marked increases in silt, but the June flood apparently is not.

SILT BELOW THE JUNCTION OF GREEN AND GRAND RIVERS.

During 1905 and 1906 samples of water were collected daily by the Reclamation Service from Grand River near Kremmling, Colo., and near Palisades, Colo., from Gunnison River, a tributary of the Grand, near Whitewater, Colo., and from Green River, near Green River, Wyo., and near Jensen, Utah. The daily samples were analyzed after being united in sets, usually of 3 to 6 consecutive samples, and the results, with computations of the discharge of silt by Stabler have been published in Water-Supply Paper 274.

The measurements of silt at Jensen, Palisades, and Whitewater represent an area of 43,800 square miles in a total of 70,300 square miles. The observations were not conducted over periods long enough to make estimates of the mean load of silt based on them entirely dependable, but they give some idea of the magnitude of the load. It would be distinctly advisable to make collections during a period of three or four years at these and other points in the basins of both the Grand and the Green in order to obtain data from which thoroughly reliable conclusions regarding the mean silt content of the streams might be drawn.

Samples were collected from Grand River near Palisades, Colo., from March 15 to October 31, 1905, and from April 1 to May 5, 1906, but not during the winter of 1905–6. The average daily content of suspended matter between March 15 and October 31, 1905, computed by weighting the determinations by the number of days that each approximately represents, is 281 parts per million. During the period of 134 days from November 1 to March 14, with low water and ice prevailing much of the time, it is probable that 80 parts per million would represent a generous estimate of the average daily content of suspended matter. If this estimate is included with proper weighting, the average daily content of suspended matter for the year would be 207 parts per million. A similarly computed average, including the determinations made in April, 1906, is 404 parts per million, the difference being caused by the great loads of silt carried during April, 1906. Consequently, if the average daily load of silt is taken as 300 parts per million the estimated annual tonnage may be greatly in error; nevertheless there seems to be no fairer method of estimating this quantity from the data at hand. This figure, combined with the average discharge, 5,320 second-feet, gives a total annual load of 1,570,000 tons of silt.

According to the observations the river carried 1,196,000 tons of silt between April 1 and October 31, 1905, and 871,500 tons between April 1 and May 5, 1906. If the mean daily content of suspended matter is assumed to be 80 parts per million and the mean discharge to be 1,600 second-feet [1] the load between April 1, 1905, and March 31, 1906, may be calculated to have been 1,200,000 tons and that between May 6, 1905, and May 5, 1906, to have been 1,900,000 tons. The discharge was much greater during April, 1906, than during April, 1905, and the mean discharge from April to October in 1906 was greater and that in 1905 was less than the average. Conse-

[1] Estimate by Stabler, Herman, Some stream waters of the western United States, with chapters on sediment carried by the Rio Grande and the industrial application of water analyses: U. S. Geol. Survey Water-Supply Paper 274, p. 46, 1911.

quently it seems fair to estimate the total load of silt carried past Palisades at about 1,600,000 tons a year.

Samples of the water of Green River near Jensen, Utah, were collected regularly from March 24, 1905, to May 11, 1906, inclusive, but as discharge measurements made at that point cover only part of that period it has been possible to compute the daily loads of silt for only part of the series. The weighted average daily content of silt between March 24, 1905, and March 28, 1906, is 1,104 parts per million and that between May 14, 1905, and May 11, 1906, is 1,056 parts per million. According to measurements at Green River, Utah, the discharge between March, 1905, and March, 1906, was much less, and that between May, 1905, and May, 1906, somewhat less than the average; consequently it seems reasonable to estimate the mean annual content of suspended matter at Jensen, Utah, at 1,200 parts per million. Combined with the mean discharge, 5,500 second-feet, this estimate gives the average annual load of silt carried past Jensen by Green River as 6,500,000 tons.

Mean discharge in second-feet of Green River at Green River, Utah, during certain periods.[a]

Period.	Mean discharge March to March, inclusive.	Mean discharge May to May, inclusive.
	Second-feet.	*Second-feet.*
1905-1906	5,530	7,650
1906-1907	9,170	9,040
1907-1908	11,200	9,130
1908-1909	5,250	6,820
1909-1910	11,900	10,600
1910-1911	[b] 6,400	[c] 5,500

[a] Water-Supply Papers 269 and 289.
[b] Discharge for January, February, and March, 1911, estimated.
[c] Discharge January to May, 1911, estimated.

Gunnison River enters Grand River at Grand Junction, Colo., about 15 miles below Palisades, Colo. Determinations were made of the silt content of the water of Gunnison River near Whitewater, Colo., a short distance above Grand Junction, from April to October, 1905. If the average content of suspended matter during the low-water period from November to March is estimated at 80 parts per million the weighted average content of suspended matter for the year may be calculated as 565 parts per million; and if the mean discharge during the winter is assumed to have been 700 second-feet [1] the load of silt carried between April 1, 1905, and March 31, 1906, may be calculated as 2,070,000 tons. The average content of suspended matter, 565 parts per million, combined with the average annual

[1] Based on estimate by Stabler, Herman, op. cit., p. 51.

discharge for 14 years, 2,830 second-feet, gives the average load of silt as 1,600,000 tons a year. The difference between this figure and the former is explainable because the discharge during 1905 was higher than the mean.

The foregoing estimates of total silt load are summarized in the accompanying table:

Mean annual discharge and load of silt of Green, Grand, and Gunnison rivers.

River.	Station.	Annual load of silt.	Drainage area above station.	Mean discharge at station.
		Tons.	*Square miles.*	*Second-feet.*
Grand	Palisades, Colo.	1,600,000	8,550	5,320
Gunnison	Whitewater, Colo.	1,600,000	8,250	2,830
Green	Jensen, Utah	6,500,000	27,000	5,500
		9,700,000	43,800	13,650

The total area of the drainage basins of the Green and the Grand is 70,300 square miles and the mean discharge of both streams is 17,130 second-feet. Because of the nature of the basins below Grand Junction and Jensen the load of silt below the junction of the Green and the Grand would probably be more nearly proportional to the discharge than to the area of the respective basins. On this assumption the total annual load of silt carried by these two streams below their junction would be in round numbers 12,000,000 tons, equivalent to about 6,000 acre-feet of dry soil weighing 93 pounds per cubic foot. This estimate is based on silt determinations covering little more than half the entire basin and extending over a period of less than a year, and it should therefore be considered roughly approximate. In comparison with the load at Yuma, Ariz.—about 160,000,000 tons, equivalent to 80,000 acre-feet of dry soil—it shows that lower Colorado River derives most of its enormous load of silt from the drainage area tributary to Colorado River below the junction of the Green and the Grand, which includes San Juan, Paria, Little Colorado, Virgin, and Gila rivers. How the silt in Gila River affects the Colorado has already been shown. That the Little Colorado also brings in notable loads of silt is indicated by the results of determinations in 1905–6, by which it was found that the weighted average content of suspended matter of Little Colorado River at Woodruff, Ariz., was 7,440 parts per million between April 15, 1905, and April 3, 1906, and individual determinations ranged from 32 to 20,700 parts per million.[1]

[1] Stabler, Herman, op. cit., p. 56.