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FORTIER, S. ; BLANEY, H.F. 1 OF 2

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SILT IN THE COLORADO RIVER AND ITS RELATION TO IRRIGATION

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INTRODUCTION

While silt is the creator of much of the agricultural wealth of the lower Colorado River Basin, it is also the greatest menace to irrigation development and water control. When irrigation water containing silt is applied to fields, the main portion of the silt is deposited near the upper end. From time to time the farmer is compelled to move the deposited silt to lower portions of the field in order to keep the land surface below the level of the irrigation ditch. It is estimated that the annual expense to the farmers of Imperial Valley on account of silt averages $2 per acre. During the next decade vast sums of money are likely to be expended in building structures to control and utilize the waters of the Colorado River, and in the design and location of these structures the silt problem will receive much attention.

This is a preliminary report which does not undertake to offer a complete solution of the silt problem. The data it presents, while basic, do not remove the need for further extensive and thorough investigations of the sources of silt throughout the entire basin, the lessening of soil erosion, the devising of more efficient desilting facilities, and the impounding of silt behind permanent dams.

Many of the data on which this bulletin is based were obtained cooperatively by the Division of Agricultural Engineering of the

Bureau of Public Roads,[1] the California State Department of Public Works, and the Imperial irrigation district.[2] They have been supplemented by the results of investigations carried on independently by the Bureau of Reclamation, the Geological Survey, the Imperial irrigation district, the Division of Agricultural Engineering, and J. E. Peck. Because the interests of the investigating agencies were limited to the lower section of the Colorado River most of the work was done there, but since much of the silt carried into the river's lower reaches is developed in the middle and upper sections, the whole stream has been studied in the preparation of this report.

A strong inducement to enlarge its scope developed as the study progressed. At first, main dependence for a solution of the problem of disposing of the silt carried by the river was placed in the design and construction of suitable structures at the diversion points and in the channels, as well as in the design and installation of equipment that would cheaply and effectively remove silt from artificial waterways, but the results of the experiments soon suggested that the most economical method was to retain the silt behind masonry dams in the main river and its tributaries. Accordingly, this report has a twofold purpose, one being to aid the irrigators of the lower basin in the better control of silt, and the other to pave the way for a more complete control of silt by means of storage reservoirs in the middle and upper sections of the Colorado River system.

SUMMARY AND GENERAL CONCLUSIONS

The Colorado River Basin with its varied physical features is nearly as large as the State of Texas. Those portions which have an annual precipitation of 20 inches or enough to maintain tree growth, are at elevations from 6,000 to 11,000 feet where the soil is too rough and rocky for cultivation, and much of the lower area is too arid or otherwise unfit for profitable farming without irrigation. These limitations, coupled with the cost of providing irrigation water, are likely to confine the reclaimed area to about 7,000,000 acres—less than 5 per cent of the total area. The lower basin, however, possesses exceptional agricultural advantages on account of its mild winter climate, long growing season, and resultant diversity of soil products, as well as exceptional natural facilities for the complete control of the river system by means of impounding reservoirs and the utilization of the water supply for irrigation, power, and other purposes.

The economic remedial measures feasible of application to the control of silt in the Colorado River are as follows: (1) The storage of silt in a large reservoir located near the lower end of the canyon section, supplemented by the storage of silt in smaller reservoirs located on tributary streams; (2) the forming of settling basins and

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[1] The irrigation work of the United States Department of Agriculture was originally conducted under the supervision of the Office of Experiment Stations and designated as "irrigation investigations." Later, under a reorganization of the department, this and other agricultural engineering activities were grouped in a division of agricultural engineering and made a part of the Bureau of Public Roads.

[2] From 1907 to April, 1925, the cooperative investigations were under the general supervision of Samuel Fortier with Clarence E. Tait in direct charge up to the time of his death in April, 1923. Since April, 1925, W. W. McLaughlin, associate chief of the Division of Agricultural Engineering, has supervised the work. Mr. Tait was assisted at various times by Harry F. Blaney, F. D. Bowlus, H. M. Lukens, and F. J. Veihmeyer.

the installation of desilting structures at or near the intakes of diverting canals; and (3) the exercise of efficient control over the growth and maintenance of native grasses and other vegetable covering with the twofold object of providing more forage when needed for domestic animals and lessening the injurious effects of soil erosion and silt formation.

As discussed in this report, the silt transported by the Colorado River consists of finely pulverized rock with a variable proportion of organic matter. Its color and character vary more or less with the watershed and formation from which it is derived. Normally, the specific gravity of this silt is 2.65, but the weight per unit of volume varies within wide limits. After the river emerges from the canyon section and flows on flatter grades, the heavier silt is deposited or transported as bed silt. The suspended silt transported into the lower basin of the Colorado River is fine in texture, and its particles are of fairly uniform size, fully 50 per cent passing a standard sieve of 200 meshes to the inch.

The aggregate quantity of suspended silt in the main tributaries when supplemented by the estimated aggregate quantity in the smaller tributaries, falls far short of equaling the normal load of suspended and bed silt in the Colorado River at Yuma, Ariz., indicating the presence of bed silt in the tributaries and the formation of silt in the canyon section by the action of water and wind.

The finer silt, or that which passes a 200-mesh sieve, may be transported long distances in both natural and artificial channels if the mean velocity of the current exceeds two-thirds of a foot per second, with a fair uniformity of silt content throughout any vertical section, although there is a tendency for the heavier particles to approach or reach the bed. Thus, any velocity that is practical for an irrigation canal will carry in suspension most of the finer silt of the Colorado River.

While great quantities of silt are removed annually from the Imperial Valley canals by mechanical means it is mainly bed silt, the quantity of suspended silt deposited being a small portion of the total quantity carried in suspension. Usually the suspended silt entering the main canal of Imperial Valley is transported throughout the system. The water delivered to the irrigators retains most of this silt content, which is deposited in farm laterals or on the irrigated fields. The estimated average annual cost of silt disposal and control in its various forms in Imperial Valley canals is about $1,000,000.

By properly designed settling basins, sluiceways, and desilting structures at the intakes of diversion canals it is possible to rid the water of half its suspended silt and most of the bed silt.

Formulas held to be applicable to the transportation of silt in the channels of foreign countries, particularly those of India, do not seem to apply to the water channels of the lower basin of the Colorado River.

Determinations of silt content of river water are usually made on a weight basis, which is more practical for research work than a volume basis. "Percentage of silt by weight" is equivalent to the grams of dry silt contained in 100 grams of water, and is derived by weighing the water, then the dry silt, and taking the proportion of the latter to the former. It is believed that the dry sediment in 1 cubic foot of suspended silt as carried by the Colorado River below Laguna Dam would weigh, on an average, about 62.5 pounds. If this estimate is correct the percentage of suspended silt by weight equals the percentage by volume.

The dry weight per cubic foot of Colorado River sediment varies widely. Fine silt deposited in settling basins in Imperial Valley averaged 40 pounds per cubic foot. The average dry weight of silt freshly deposited on irrigated land and in farm laterals does not exceed 50 pounds per cubic foot. The average weight of suspended silt approaches that of water, or 62.5 pounds per cubic foot. The average unit weight of dry silt in a cubic foot of river deposits near Yuma and Laguna Dam was 84.5 pounds. Bed silt in the canals of Imperial Valley averaged 97 pounds per cubic foot.

The average weight of silt deposited in a large reservoir would depend on the thoroughness with which the fine silt was mixed with the coarse. If the two grades were deposited separately in the proportions commonly carried by the stream, the mean weight of dry silt contained in a cubic foot of moist sediment would approach 70 pounds, whereas if mixed the weight would be greater by reason of greater density, but owing to the preponderance of the finer and lighter particles, the average weight would not exceed 85 pounds.

As closely as it can be estimated, the normal quantity of silt annually transported to the lower end of the canyon section is 253,628,000 tons, or 137,000 acre-feet, on the basis of an average weight per cubic foot of 85 pounds. This figure is approximately 37 per cent higher than previous estimates have indicated.

Preventing silt from entering canal systems is a prime factor in the success of irrigation enterprises in that it eliminates the present high annual expenditures for silt disposal and control in the canal system and upon the land, provides a freer passage of water through canals, renders structures serviceable and operative, and protects fields from depositions of fine silt which impairs the texture and productivity of the soil. Means to accomplish these purposes have so far consisted in (1) desilting structures at the intakes of canals; (2) wasteways discharging into settling basins; (3) mechanical removal of silt from canal beds; and (4) distribution of silt over the surface of cultivated fields; but experience has shown these to be temporary, unsatisfactory, or only partially effective.

The most feasible and economical means of solving the silt problem of Imperial Valley is to impound the river silt behind a high dam such as is proposed at Boulder Canyon. Partial resilting of the river undoubtedly will occur for some time below such a dam, but the regulation of the flow will permit the water users to divert the surface waters only, and as the channel scours, the quantity of silt entering diversion channels will become negligible in time.

Thus far no feasible method has been devised to measure bed silt directly, but as accurately as it can be estimated at this time by indirect means, about 20 per cent of the total load of silt in the Colorado River at Yuma, Ariz., is bed silt.

Owing to the magnitude of the normal quantity of silt transported into the lower basin, it would be unwise to attempt to control the river by a relatively low dam located below the canyon section, since a reservoir of 12,000,000 acre-feet capacity would have one-third of its capacity taken by silt in 30 years, if no other reservoirs were built above it during this period.

In order that the capacity of a reservoir formed in Boulder or Black Canyon may not be reduced by the deposition of silt more than two-thirds in 100 years of operation, it will be necessary to impound water to a depth of over 500 feet, if no other reservoirs are built above it. The construction of additional reservoirs and the increased use of water in the upper basin will tend to prolong the life of such a reservoir.

No evidence is at hand to indicate that the life of a storage reservoir may be extended as a result of increasing hydrostatic pressure compacting the silt while deposits deepen. It is the belief of the authors that the hydrostatic pressure on each particle of deposited silt would be balanced and, acting equally in all directions, would have no effect in compacting the deposited material. Hence, so far as this aspect of storage is concerned, the silt deposited on the floor of a shallow reservoir would retain the same consistency as that deposited in a reservoir of much greater depth.

COLORADO RIVER BASIN

In considering the formation and transportation of silt in Colorado River Basin (fig. 1), attention is drawn to certain physical features which cause erosion of surface material covering extensive areas. The aridity of the climate and the consequent lack of vegetation is one of the main causes. Because the territory is sparsely settled, relatively few climatic records have been kept, and in many parts the precipitation is not known accurately. Roughly estimated, 40 per cent of the total area of the basin has a precipitation of less than 10 inches a year, in 50 per cent the precipitation ranges from 10 to 17 inches, and in the remaining 10 per cent it is from 17 to 25 inches and higher in the high mountains. Fully one-half of the basin is either bare or but scantily covered with desert shrubs and grasses. In a more northerly latitude, with lower temperatures and less evaporation, the upper limit of annual precipitation of 10 to 17 inches might support a growth of nonmerchantable timber as well as shrubs and nutritious grasses, but in the lower and warmer portions of the basin much of the rainfall is speedily evaporated, leaving an inadequate supply of moisture for trees and a relatively short growing season for grasses. It is only in those areas where soil has been formed and the yearly precipitation approaches 20 inches or rises above it that a good growth of commercial timber exists.

The greater part of the basin, and more particularly that part below the mouth of the Green River, is subject to sudden violent rainstorms, and resulting floods erode and carry off the unprotected surface soils. Most of these storms deluge small areas and their erosive action is proportionally limited, but occasionally extensive areas receive downpours causing floods in several streams, which transport large quantities of débris.

The depth and aggregate length of the canyons in which the Colorado River and many of its tributaries flow are also extraordinary. From the mouth of Green River in Utah to Fort Mohave in Arizona, a distance of over 650 miles, the river traverses a high plateau which has been deeply trenched by run-off. Likewise, many of the tributaries, as they approach the main channel, flow in deep gulches, the aggregate length of which is greater than the canyon portion of the main river. The gradients of stream channels in the canyons are steep. The water is frequently loaded with sand and flows during its medium and high stages with great turbulence.

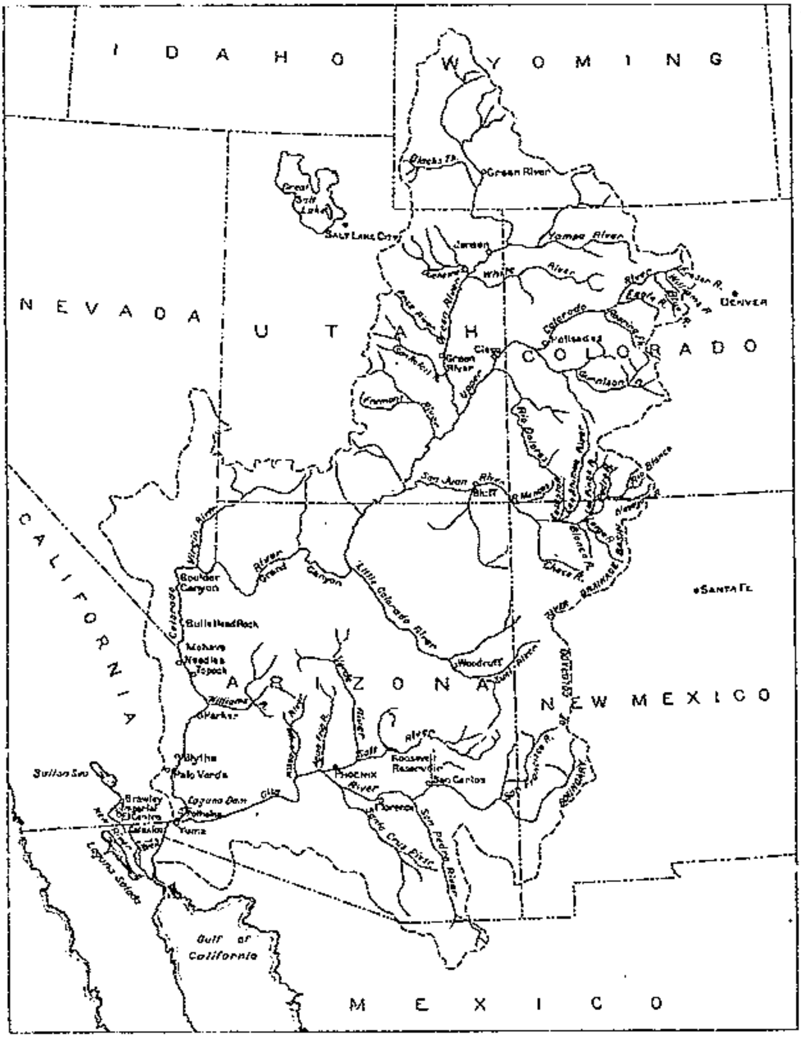

FIG. 1.—The Colorado River Basin

Under such conditions not only is the transported débris soon reduced to powder, but the beds of the canyons are rapidly eroded; also the deposition of silt is not distributed. It is all or nearly all carried to the lower basin.

Wind is also an active agency in supplying silt. Wind-laid material is easily eroded and sand storms are of frequent occurrence throughout the more arid portion of the basin. (*8*) [3] Describing the effect of wind in the Navajo Reservation, Gregory says that

> rocks polished and etched by wind-blown sand, vegetation buried waist deep, and fields of corn with leaves cut into shreds, are everyday sights. Sand storms are frequent and whirling columns of dust reaching high into the air may be counted by the dozens on clear summer days.

Many observers have reached the conclusion that erosion in the Colorado River Basin and throughout the West has been much more widespread and destructive since occupancy by the white race than previously, and they advance much supporting evidence; for example, the fact that in pioneer days numerous narrow mountain valleys were dotted with farm homes and thickly covered with grasses and trees. Through these valleys clear water flowed in shallow beds, whereas in more recent times the shallow streams have been converted into deep and wide arroyos, much of the fertile soil with its vegetable covering has been washed away, and farmsteads that were once well cared for are now abandoned. The extensive observations of Meeker [4] in Colorado, New Mexico, Utah, and Wyoming during the past 25 years are summed up as follows in a letter to Samuel Fortier.

> Prior to the advent of the white man, erosion was a matter of minor importance in the arid southwest. At that time there was generally an excellent grass carpet which retarded run-off and prevented erosion.
>
> Overgrazing by the cattle and sheep industry has depleted, in fact almost exterminated, the grass carpet over large areas, resulting in erosion and denudation.
>
> Rapid restoration of over-grazed areas has taken place during a series of wet years following a series of dry years or where stock have been withdrawn for a number of years.
>
> Deforestation by axe and fire have increased erosion only in limited areas and generally the destruction of forests has been a minor cause of denudation.

Considering the extent of the Colorado River Basin, its agricultural resources are limited. Two elements essential to successful farming—water and soil—are either deficient or ineffectively combined. In the elevated parts of the watershed which have sufficient precipitation to grow crops, the soil with rare exceptions is too shallow, rough, and rocky to be cultivated, and in the lower parts where arable soil has been formed, the natural precipitation is too scanty to support any vegetation other than desert plants. Therefore, the growing of crops depends upon artificial moistening of the soil. The only source of water supply for this purpose is the Colorado River. In 1920, 1,530,000 acres were irrigated in the upper basin and 1,130,000 acres in the lower basin, including the area irrigated in Mexico and the Gila Basin (*5*). The available data are too meager to warrant other than rough estimates as to the ultimate area that can be irrigated in either division of the basin. Estimates made recently by the Bureau of Reclamation limit the area that can be reclaimed by irrigation in the upper basin to 4,080,000 acres, and in the lower basin, including irrigated lands in Mexico and the Gila Basin, to 2,850,000 acres, or 6,930,000 acres for the whole basin. Since 1920 the State engineer of Nevada has reported that an additional area of 80,000 acres is possibly irrigable in that State, of which 50,000 acres are in the upper basin.

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[3] Italic numbers in parentheses refer to "Literature cited," p. 93.
[4] Ralph I. Meeker, special deputy State engineer of Colorado.

Table 1 shows the approximate areas drained by the tributaries of the Colorado River.

TABLE 1.—*Approximate areas drained by tributaries of Colorado River*

Tributary	Drainage area	Proportion of total area	Tributary	Drainage area	Proportion of total area
	Square miles	*Per cent*		*Square miles*	*Per cent*
Green River	44,000	18.03	Gila River	57,000	23.38
Upper Colorado River	26,000	10.65	Other streams	54,000	22.13
San Juan River	26,000	10.65			
Little Colorado River	26,000	10.65	Total	244,000	100.00
Virgin River	11,000	4.51			

For the past 20 years the waters of Salt River have been stored in Roosevelt Reservoir, and the farmers of Salt River Valley who have used the stored water during this period have not been much troubled with silt. It is believed that the silt problem for the 4,250,000 acres yet to be reclaimed by the waters of the Colorado River likewise can be solved effectively and cheaply by the building of storage reservoirs. Nature has provided a superabundance of excellent reservoir sites on the Colorado River system. There are so many sites that most of them have no economic value since the utilization of one is likely to submerge several others equally good. With so many sites from which to make a selection, it will be possible ultimately to control the entire discharge of the river and make use of the stored waters for agricultural, municipal, and industrial purposes.

CHARACTER OF SILT

As discussed in this report, the silt transported by the Colorado River consists of finely pulverized rock with a variable proportion of organic matter. Its color and character vary more or less with the watershed and formation from which it is derived. When violent rainstorms occur on the barren watersheds of the Little Colorado, San Juan, or Gila Rivers, the silt which is carried down by the floods is reddish in color and so fine that when settled it is nearly impervious, whereas the silt deposits from the more elevated areas drained by the Green and Upper Colorado Rivers, the surfaces of which are better protected by trees, shrubs, and grass, are grayish in color though tinged with red, more porous, contain a larger percentage of organic matter, and are less troublesome to the water user.

The only classification of much significance in the present study is that which distinguishes between suspended silt and bed silt, the latter being characterized mainly by its larger and heavier particles. Suspended silt is transported within the water prism of the river or canal, its distribution throughout any cross section being fairly uniform, particularly as regards the finer particles. Bed silt is transported along or near the bed of the river or canal with a rolling motion or in sand waves or dunes. There frequently exists a neutral space in the water prism adjacent to the bed of the channel in which bed silt is temporarily suspended, and suspended silt is entrained in the bed silt. This condition directs attention to the fact that the division of silt into these two classes is neither constant nor permanent, since to a large extent they are interchangeable. As will be pointed out elsewhere, under conditions favorable to such conversions bed silt becomes suspended silt, and the coarser and heavier grains of suspended silt become bed silt. The suspended load is greatly increased in a swiftly flowing turbulent stream, while a smoothly flowing stream of slow or medium velocity tends to decrease it.

In the upper reaches of the Colorado River and its main tributaries where the watersheds are protected by timber, brush, and native grasses, there is little erosion, and the run-off is fairly clear and free from sediment except during flood seasons. In the lower and more arid portions of the basin violent rainstorms erode from unprotected hillsides large quantities of earth and rock material, which are carried by flood waters to tributary channels and thence to the main river. In consequence of this difference in the climatic and physical conditions of the more elevated part of the basin on which snow lodges in winter, and the lower and more barren part, which is subjected to heavy autumnal and winter rains, the percentage of silt transported by melted snow is much less than that transported by rainstorms.

There is no basis upon which to estimate how much dust and sand are carried by the winds which sweep across the arid and barren plains and plateaus and into the canyons of the river system, but the volume is undoubtedly large.

The silt in the lower reaches of the Colorado River is characterized by the uniform fineness of the particles. All silt-laden streams carry fine material, usually mixed, however, with coarse sand, gravel, and occasionally bowlders. This is true of most of the tributaries of Colorado River. During flood periods, large quantities of débris, including bowlders weighing many tons, are rolled, pushed, or carried by walls of water moving rapidly down steep stream channels. The main river not only transports this material but reduces it to fine silt. Through the action of the fast-moving water, sand, gravel, and bowlders alike are ground to a fineness approaching that of Portland cement. In the thousands of samples of water which have been taken from the lower Colorado River and its diversions, little silt has been found which could be classified as coarse sand.

For the purpose of determining the size of silt particles carried in suspension in both the water of the Colorado River and that of the canals of Imperial Valley, samples of water have been taken at different depths from each source and the silt content of each has been separated into grades according to size.

In making sieve analyses, each sample of muddy water was weighed to the nearest tenth of a gram and then poured on sieves 2½ inches in diameter, which had standard graduated meshes. The silt, while passing each sieve, was agitated by a fine stream of water, and the finest silt was collected on filter paper. Each grade of silt was then dried out at 110° C. and weighed to the nearest thousandth of a gram. The results of the mechanical analyses of samples taken in the Colorado River at Yuma (Table 54 of the appendix) indicate that most of the suspended silt was too fine to be retained on a No. 300 sieve, the particles being less than 0.0017 inch in diameter, and none was found coarser than the interstices of a No. 40 sieve; that is, 0.015 inch in diameter. The percentage of silt passing a No. 300 sieve seemed to decrease as the depth increased, while all other grades increased with the depth.

An examination of Tables 49 to 51 of the appendix, giving the results of the mechanical analyses of bed silt as found in the beds of Imperial Valley canals and also in the bed of the river, discloses the fact that bed silt is considerably coarser than suspended silt. Three sets of samples taken at 47-day and 76-day intervals from the bed of Alamo Canal about 1 mile from the intake showed (Table 19) that an average of 7 per cent passed a 200-mesh sieve and as high as 33 per cent was retained on a 60-mesh sieve. At points in canals distant 48 to 104 miles from the intake, the percentage of the coarser silt was less. The finer silt which passed a 200-mesh sieve varied from 10 to 60 per cent, while the coarser silt retained by a 60-mesh sieve varied from 0 to 8.50 per cent. Four samples of bed deposits taken from the channel of the river between Laguna and Parker contained more fine silt than those taken from canals. An average of 40 per cent passed the 200-mesh sieve, and none was retained on a 60-mesh sieve.

Analyses of the chemical ingredients in the water of the Colorado River indicate that the quantity present depends on the stage of the stream flow and the watershed from which the bulk of the water is derived, spring flood water caused by melting snow containing much less than that in floods caused by fall and winter rainstorms throughout the lower basins.

Breazeale (*2*) and others have likewise found that the chemical action of certain salts tends to group or flocculate the finer particles of silt and in this way increase their size and weight, while that of other salts tends to separate or disperse the particles and cause them to be held in suspension. Calcium and magnesium salts flocculate silt, whereas sodium and potassium salts disperse it.

The value to agriculture of the soil-fertilizing ingredients of silt should not be overlooked or minimized. While nitrogen is found in solution in the river water, phosphoric acid, potash, and nitrogen are also found in the silt deposits.

In approximate numbers, Forbes (*6*) found in the silt content of an acre-foot of water of the Colorado River at Yuma, Ariz., from 2 to 44 pounds of phosphoric acid, 15 to 445 pounds of potash, and from 1 to 17 pounds of nitrogen, the variations depending chiefly on the season. Long-continued irrigation with desilted water would doubtless somewhat decrease the productive capacity of the soil, but the nitrogen in solution, amounting to over 40 per cent of the total, would still be of considerable fertilizing value.

Soils vary in weight from less than 30 pounds to over 110 pounds per cubic foot, and silt, being classified as soil, has likewise a wide variation in weight. The results of determinations, as given in Tables 39 to 49 of the Appendix, indicate that the silt which is transported into the lower basin of the Colorado River may range from a minimum of 32 pounds to over 105 pounds per cubic foot, depending on such main factors as size of particles, composition, manner of mixing, consolidation, and more particularly moisture content.

SILT-SAMPLING EQUIPMENT

THE TOPOCK SAMPLER

The device for taking samples of river water hereafter called the "Topock sampler," consisted of a piece of $2\frac{1}{2}$-inch standard pipe $6\frac{7}{16}$ inches long and capped at both ends. To the lower cap were bolted seven iron weights each 3 inches in diameter and 1 inch thick. A $\frac{5}{8}$-inch hole was drilled in the upper cap to admit the sample of water and silt, the sampler being lowered and raised by a rope attached to a bail. (Fig. 2.) The weight of the sampler when empty was 20 pounds and its capacity 505 cubic centimeters.

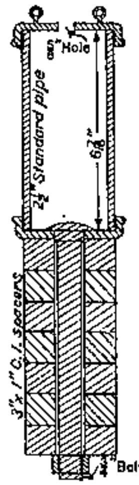

FIG. 2.—Section of silt sampler used by the Bureau of Public Roads at Topock, Ariz.

In taking samples of river water the river at the station was divided into four equal sections, making substations for vertical observations at the horizontal center and quarter points of the channel. At each of the three substations three samples were taken at depths near the top, at the center, and near the bottom. These nine samples constituted a set for any one measurement, the measurements being made at semimonthly intervals beginning August 1, 1917, and ending July 15, 1918.

Each sample of muddy water, containing very nearly 500 cubic centimeters, was weighed to the nearest tenth of a gram and poured on a sieve $2\frac{1}{2}$ inches in diameter, which had 200 standard meshes to the inch. The finer silt, which passed through this sieve, was collected on filter paper, and the coarser silt which was retained was further divided by passing the finer portion through a sieve of 100 meshes to the inch. Thus the silt in each sample was graded as follows: (1) The portion which passed the 200-mesh sieve and that held on the 200-mesh sieve; (2) that held on the 100-mesh sieve. These three silt samples were then thoroughly and separately dried at 110° C. and the weight of each was determined to the nearest thousandth of a gram and expressed as a percentage of the sample.

THE YUMA SAMPLER

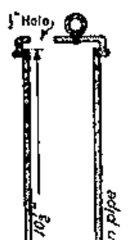

FIG. 3.—Section of silt sampler used by the Bureau of Reclamation at Yuma, Ariz.

The sampler used at Yuma consists of a piece of standard iron pipe 2 inches in internal diameter and $10\frac{1}{2}$ inches long, capped at each end. A $\frac{1}{2}$-inch hole drilled through the upper cap admits the sample of water and silt, and an eyebolt fastened to the same cap (fig. 3) provides a means of attaching a rope or wire. The capacity of the sampler is 575 cubic centimeters.

Samples of river water were taken by the Yuma sampler twice a week at the top, middle, and bottom of each of three stations across the stream, which were approximately at the center and at the quarter points. When the water in the river at the gaging station was 2 to 3 feet deep, the middle sample was not taken. When the water was less than 2 feet deep, only one sample was taken at about half the depth. During periods of high water the sampler was attached to a 125-pound weight and lowered and raised by means of a windlass. At such times, because of the greater depth, it requires about 5 seconds to lower the sampler from the surface of the water to within 6 to 8 inches of the bed where the bottom sample is taken and about 60 seconds to fill the sampler. Each sample of water and silt was poured into a bottle and allowed to settle for 24 hours, after which two-thirds of the clear water was poured off. The remaining mixture was well shaken and poured on filter paper, and the bottle was rinsed with clear water to remove all silt. Before being used, each filter paper was weighed to the nearest hundredth of a gram, and its weight marked on the paper. After receiving its quota of silt, it was allowed to dry thoroughly in air and then weighed. The difference between the weight of the filter paper and that of both paper and silt was the weight of silt.

No doubt the method of taking samples at Yuma is satisfactory, but the laboratory practice of air-drying and not oven-drying the samples is subject to criticism. Experiments made in Imperial Valley show that filter papers are subject to changes in weight as a consequence of atmospheric conditions, even in a dry climate. The error thus caused may be considerable, especially if the amount of silt to be measured is small.

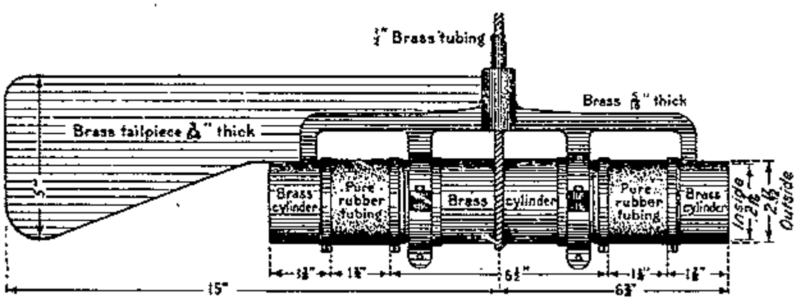

FIG. 4.—Tait-Binckley sampler

What is known as the Tait-Binckley sampler was used in part of the investigations in order to compare the results with those obtained by the use of other samplers. The methods adopted by the Bureau of Public Roads and the Bureau of Reclamation in determining the silt content were likewise compared.

THE TAIT-BINCKLEY SAMPLER

The Tait-Binckley sampler consists of a cylinder 13¾ inches long and $2\frac{7}{16}$ inches in inside diameter mounted horizontally on a brass frame. (Fig. 4.) Attached to the rear of the frame is a 15-inch tailpiece, which serves to keep the axis of the sampler parallel to the stream current. The cylinder is made up of five sectional parts. Each of the two end sections is of brass, 1⅞ inches long and welded to the frame. The middle section, 6½ inches long, is also of brass and, while fastened to the frame, is free to rotate on its longitudinal axis when tension is applied to a rope fastened to the section and wound around it three-quarters of a turn. The three brass sections are connected by two tubes of pure gum rubber.

The sampler is designed to trap 500 cubic centimeters of silt-laden water in a horizontal column under natural conditions at points desired in the vertical section of a stream. It is held in place by a half-inch brass tube screwed to the frame and marked in feet and tenths of feet. For large streams a steel cable and suitable weight is used in place of the brass tube.

The sampler is operated by pulling the rope, which rotates the middle section while the end sections remain stationary. The connecting rubber sections are twisted so that the middle section containing the sample becomes a water-tight compartment.

The main advantages of the Tait-Binckley sampler are as follows: The water is trapped in the natural state; the bearings do not "silt up" in muddy water and stop the operation; and samples may be taken at any point in the stream. The sampler was designed especially for the Bureau of Public Roads for silt investigations in Imperial Valley, by George S. Binckley and C. E. Tait after several existing types of automatic samplers had been tested and found unsatisfactory. It would be better adapted to river work if made of heavier material.

CANAL-BOTTOM SAMPLER

In order to take samples of canal bottom deposits in Imperial Valley canals while the latter were carrying water 10 or more feet in depth, a sampler with a sharp-cutting edge was designed. (Fig. 5.) This consisted of a brass tube 2.7 centimeters in diameter and 15.2 centimeters long. At the bottom was attached a sharp-steel cutting edge to penetrate the hard canal bed. The upper end of this tube was threaded into the bottom of a funnellike enlargement, the shoulders of which prevented the brass tube from sinking into the canal bed beyond the required depth. The upper end of the sampler was a half-inch pipe, jointed together in short sections, the number of sections used depending upon the depth of water in the canal. In taking a sample, the tube was pushed into the bottom deposit as far as the shoulders would permit. The half-inch pipe was then filled with water, and an air-tight cap was screwed on the upper end. When the tube was withdrawn a partial vacuum was formed which held the sample in the tube.

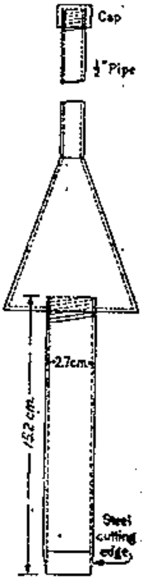

FIG. 5.—Canal-bottom sampler

SILT IN TRIBUTARY STREAMS

In what follows, the physical features of the larger tributaries of the Colorado River are outlined and the results of a few silt determinations given. These were made by the United States Geological Survey, the Bureau of Reclamation, and other agencies previously mentioned. Only silt in suspension was collected in the samples taken, and judging from the low percentage of silt found in most cases as compared with that in the main river in the lower basin, the samples were probably taken near the surface of the stream. Be this as it may, the monthly quantities of suspended silt found in a number of tributaries are small in comparison with the monthly quantities of suspended silt in the lower reaches of the Colorado

River. Similar preliminary silt investigations were made on Salt River, a tributary of Gila River, before its waters were stored in Roosevelt Reservoir, and the results indicated a low percentage of silt (*4*), yet during the past 20 years, the quantity of silt annually deposited in the reservoir has averaged about 5,000 acre-feet.

UPPER STREAMS

GREEN RIVER

Green River and its tributaries drain 44,000 square miles in western Wyoming, northwestern Colorado, and eastern Utah. After flowing nearly 700 miles it joins Upper Colorado River about 43 miles south of its junction with San Rafael River.

As a rule, merchantable timber, with pine, spruce, and fir predominating, covers the higher elevations of the basin in Wyoming and Colorado and also the Duchesne tributary in Utah, from which clear water flows at all times of the year except during spring floods. The forest covering and granitic formations of the higher slopes, coupled with glacial lakes, keep the runoff fairly free of silt. At elevations ranging from 4,000 to 6,000 feet the precipitation is much less than in the higher altitudes, the country is more barren, black sage, salt sage, and rabbit brush forming the chief vegetation, and the abundance of sandstones provides conditions favorable to erosion and the transportation of silt. Some streams, like Price and San Rafael, have clear water near their sources, but their lower tributaries drain barren areas and bring in more or less silt, so that Green River in its lower reaches is seldom clear. With few exceptions, the flood period of Green River and its tributaries occurs in June, when about 31 per cent of the year's normal run-off is discharged. Although the proportion of silt in the river is low, the stream's June discharge is so large that during the month a maximum monthly quantity of silt is carried. On account of erosion caused by October rains, the silt content for that month also is high, but from December 1 to March 1 there is little silt in the river.

UPPER COLORADO RIVER

Upper Colorado River, formerly known as Grand River, has its sources in the high peaks of the Rocky Mountains in north-central Colorado and flows southwesterly 423 miles to its junction with Green River. Its main tributaries are the Frazer, Blue, Eagle, Williams, Roaring Fork, Gunnison, and Dolores Rivers. The drainage area is approximately 26,000 square miles, about half of which is very high and rugged, the elevations ranging from 7,000 to 14,000 feet. The precipitation, which over the more elevated portion varies from 20 to 27 inches, mostly in the form of snow, supports a fine growth of conifers, such as lodgepole pine, yellow pine, spruce, and fir. At the lower elevations, over which the precipitation is lighter, are scattered parks of piñon and cedar, with oak brush, aspen, sagebrush, and native grasses. Over two-fifths of the yearly flow of the Colorado River at Yuma, Ariz., comes from the Upper Colorado and its tributaries. A large part of this annual flow occurs in the spring during the period of melting snow. In April or early in May the run-off begins to increase, and the peak of the discharge is reached late in May or during the first half of June. Usually the spring flood ends during the last week in July. The percentage of silt carried during spring floods is small in both the Upper Colorado and Green Rivers, but owing to the large run-off from both basins the two streams actually carry considerable quantities of silt, accounting very largely, in fact, for the heavy silt load in Colorado River during the spring floods.

SAN JUAN RIVER

The basin of San Juan River includes southwestern Colorado, which is drained by such tributaries as the Los Pinos, Las Animas, La Plata, Piedra, Blanco, Navajo, and Mancos Rivers. It includes also northwestern New Mexico, drained chiefly by the Chaco, Blanco, and Largo tributaries. Little water is added to San Juan River from the extensive Navajo Indian Reservation in Arizona, and the tributaries in southwestern Utah also are small. Although the basin has about the same area as that of the Upper Colorado River, the run-off is much less, the mean for the Upper Colorado being 6,870,000 acre-feet a year while that of the San Juan River is 2,350,000 acre-feet, the greater part being derived from the high slopes of the Needle, San Juan, and La Plata Mountains in southwestern Colorado. From Farmington, N. Mex., where the La Plata and Las Animas Rivers join the main stream, it flows westerly to the mouth of Mancos River in a broad, sandy channel bordered by terraced mesas. From the mouth of the Mancos River to Bluff, Utah, the river bottom narrows, and the bluffs on each side become steeper. From Bluff to its mouth, 133 miles as the water runs, the river flows in a box canyon, 2,500 feet below the surrounding surface, with an average fall of 7 feet to the mile (*17*).

The precipitation is less than 7 inches a year in the lower parts of the basin, about 14 inches at intermediate elevations, and 25 inches or more at the higher elevations. The entire basin, particularly the lower and more arid portion, is subject to violent thunderstorms which erode and transport large quantities of débris.

The headwaters of many of the tributaries in southwestern Colorado are protected by fine growths of pine, spruce, and aspen. Farther south scattered pines and piñons with sagebrush dot the landscape, while the greater part of the basin in New Mexico, Arizona, and Utah has little vegetation to protect the surface from erosion.

Heavy downpours of rain on one or more tributary basins produce floods in the main river which usually transport very large quantities of silt, composed mainly of red sand. A sample of water taken by Pierce (*22*) from the canyon portion of the river during a July flood contained 9 per cent by weight of silt. The percentage of silt carried at times is so high that it produces sand waves in the San Juan River, which Pierce describes as follows:

> The usual length of the sand waves, crest to crest, on the deeper sections of the [San Juan] river is 15 to 20 feet, and the height, trough to crest, is about 3 feet. However, waves of a height of at least 6 feet were observed. The sand waves are not continuous, but follow a rhythmic movement * * * At one moment the stream is running smoothly for a distance of perhaps several hundred yards. Then suddenly a number of waves, usually from 6 to 10, appear. They reach their full size in a few seconds, flow for perhaps two or three minutes, then suddenly disappear.

LITTLE COLORADO RIVER

The drainage basin of this tributary is about as large as that of upper Colorado River or San Juan River, but because of low annual rainfall and the high annual evaporation meager records indicate that it contributes less than 200,000 acre-feet of water a year to Colorado River. This volume is only 2.9 per cent of upper Colorado River's contribution.

About four-fifths of this basin is in northeastern Arizona, the remainder in western New Mexico. It consists chiefly of a plateau over 5,000 feet in elevation, extending from the Continental Divide, in New Mexico, to the headwaters of Gila River in Arizona. Cloudbursts are of frequent occurrence throughout the drainage area, and the floods they produce carry large quantities of silt. However, the run-off is so light that the quantity of silt annually discharged into the Colorado River is small as compared with that transported by San Juan River.

QUANTITY OF SUSPENDED SILT IN THE UPPER STREAMS

During 1905 the United States Geological Survey made determinations, by weight, of the suspended silt in several tributaries of the river. Equal volumes of individual samples were united to form composite samples representing the average for a week or other short period. The results (*25*) were published in terms of milligrams per liter, which have been converted to percentages by weight. Where data were available, the flow of the river at or near the place where the samples were taken has been used in determining the total quantity of silt carried.

Table 2 gives the mean percentages of suspended silt by weight in Green River at Jensen, Utah; upper Colorado River at Palisade, Colo.; and Little Colorado River at Woodruff, Ariz., for various months in 1905. Where possible quantities of silt have also been expressed in tons.

TABLE 2.—*Proportion of silt, by weight, and quantities of suspended silt carried by the Green, upper Colorado, and Little Colorado Rivers during 1905*

Month	Green River, Jensen, Utah: proportion of silt by weight	Upper Colorado River, Palisade, Colo.		Little Colorado River, Woodruff, Ariz.	
		Proportion of silt by weight	Quantity of silt carried	Proportion of silt by weight	Quantity of silt carried
	Mean per cent	*Mean per cent*	*Tons*	*Mean per cent*	*Tons*
March	0.0546	0.0012			
April	.2160	.0163	35,000	1.6300	1,042,000
May	.1259	.0564	617,000	2.0700	101,400
June	.0415	.0165	326,000	.2580	33,300
July	.0091	.0126	64,000	.5462	8,800
August	.0400	.0276	58,000	1.1630	511,000
September	.4749	.0406	60,000	.3230	10,000
October	.0667	.0215	31,000		
November	.0105				
December	.0085				

The Bureau of Reclamation determined the percentage by weight of suspended silt in some of the tributaries of the Colorado River during 1914 and 1915. The method followed consisted in taking about a quart sample of water every few days and determining the percentage of silt which it contained. These experiments have been summarized in Table 3, which gives by months the mean percentage and the quantity of silt in tons when the stream-flow data were available, for Green River near Green River, Utah; upper Colorado River near Cisco, Utah; and San Juan River at Bluff, Utah.

TABLE 3.—*Proportion of silt, by weight, and quantities of suspended silt carried by the Green, upper Colorado, and San Juan Rivers, 1914–15*

Month	Green River near Green River, Utah		Upper Colorado River near Cisco, Utah		San Juan River at Bluff, Utah	
	Proportion of silt by weight	Quantity of silt carried	Proportion of silt by weight	Quantity of silt carried	Proportion of silt by weight	Quantity of silt carried
	Mean per cent	*Tons*	*Mean per cent*	*Tons*	*Mean per cent*	*Tons*
1914						
August	0.045	173,800	[1] 1.803			
September	.132	260,100	.347			
October	.380	1,256,000	.596		0.895	
November	.107	236,000	[1] .033	57,000	.142	182,000
December	.012	15,000	.032	63,000	.130	110,900
1915						
January	.056	70,000	.032	57,000	.103	87,100
February	.030	40,000	.067	128,000	.705	1,237,000
March	.086	225,000	.062	148,000	.782	1,457,000
April	.217	1,300,000	.450	3,540,000	.667	4,339,000
May	.190	1,747,000	.180	2,744,000	.360	2,793,000
June	.158	2,373,000	.090	1,897,000	.398	3,256,000
July	.116	598,000	.057	477,000	.488	2,650,000
August					.380	527,000

[1] For portion of month.

That determinations of the quantity of suspended silt in the Colorado River or any of its tributaries do not represent the total load of silt carried is strikingly exemplified by the accumulation of silt in the Zuni (*28*) reservoir in the channel of the Zuni River, a tributary of the Little Colorado. This reservoir of 10,230 acre-feet capacity is formed by a combination rock-and-earth dam. The stored water is used for irrigation on lands of the Zuni Indian Reservation in western New Mexico. Zuni River is typical of the flashy streams of the Southwest, its bed being dry a considerable portion of the year, but it is subject to sudden and short-lived floods produced by heavy rains which transport large quantities of débris produced by the run-off.

Between the time of closing the gates in the dam in midsummer of 1906 and January of 1920—about 13½ years—the total quantity of silt deposited in the reservoir was 7,433 acre-feet, 72.7 per cent of its original capacity. During this period the total run-off entering the reservoir was 373,252 acre-feet. All of this volume was not stored. A considerable part escaped through the valves when it became necessary to open them to flush out the silt lodged around their inner face and another portion, partially desilted, was allowed to pass over the wasteway. The above data indicate that the average silt content of the river was 2 per cent by volume during this period.

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GILA RIVER

The Gila River Basin is similar in several of its characteristics to the Colorado River Basin, of which it forms the southeastern part. Each has its elevated areas over which the precipitation is sufficient to produce a forest covering from which clear water flows in steep stream beds most of the year. Each has also its extensive deserts sparsely covered with desert plants, while between the two are high tablelands, mesas, and canyons in which the run-off with its load of eroded material is carried to the sea. The Gila Basin in extent is more than 23 per cent of that drained by the entire Colorado River system, but because of its greater aridity its average yearly run-off is little more than 6 per cent of that of the larger stream.

The Gila is distinguished by a lack of regularity in the regimen governing the quantity of water carried and the seasonal or yearly occurrence of its floods. In 1903, the discharge of this tributary into the Colorado River at Yuma was 61,000 acre-feet, while in 1916, as a result of two floods, it was 4,490,000 acre-feet. One or more destructive floods may occur within a few months or several years may elapse without any. Only a scanty run-off leaves the basin during the six-months period from June 1, or earlier, to the close of November, while the months of greatest run-off are, in the order named, March, February, January, and April. An exception to the normally low October run-off occurred in 1916, when a crest flow of 107,870 second-feet entered the Gila from one of its main tributaries.

The principal tributaries of the Gila are San Francisco, Salt, Agua Fria, and Hassayampa Rivers which enter from the north, and San Pedro, and Santa Cruz Rivers, which enter from the south. Each has a large number of tributaries; San Francisco River, for example, with a watershed of 2,895 square miles, has 65 branch streams.

A consideration of silt in Gila River leads back to the rainfall, which usually varies from a few inches a year at the lower elevations to 20 or more inches at the higher. With a few exceptions, the mountains and high tablelands are too low in elevation and the climate too warm for the lodgment of enough snow to cause floods. There is, however, a direct connection between rainfall and silt. The violent rainstorm which usually covers a relatively small area and may affect the flow of only one tributary stream is followed by a sudden and short-lived flood which causes erosion, and erosion in its turn creates silt. The flood may subside before the eroded material is carried far from its source, but such temporary deposits are certain to be picked up by the next flood and carried a short or a long distance depending on its magnitude and duration.

A number of times in each decade a violent rainstorm spreads over a large area, causing floods in several main tributaries which, when combined, create floods in the lower Gila and occasionally in the Colorado itself. During the past 21 years four such floods have occurred; viz, in 1905, 1906, 1916, and 1923. The highest of these was on January 22, 1916, at Yuma, when the estimated discharge on the Colorado was 240,000 second-feet, derived almost wholly from abnormal rainfall on the Gila River Basin. In such storms and floods enormous quantities of eroded material are transported to the Gulf of California or deposited in the beds of the main streams.

Olmstead, in writing of conditions on Blue River and its watershed (*21*), which is typical of the highest and best timbered portions of the Gila Basin, has this to say:

> From an elevation of 9,000 feet in the Datil Mountains, which form the divide between the Gila Basin and that of the Little Colorado, the Blue River descends to an elevation of 3,850 feet at its mouth, a fall of 5,170 feet, or an average of 78 feet to the mile. * * *
>
> About 400 square miles, or 66 per cent, of the watershed is timbered, the density of vegetation being greater about the headwaters and rapidly decreasing toward the mouth of the river, where large areas have only a desert growth. The yellow pine, piñon, juniper, oak, and cottonwood of the upper portions of the watershed give place in the lower to mesquite, yucca, greasewood, bear grass, and cactuses.
>
> The slopes of the Blue River have but little sod. Upon the mesas and mountain slopes well back from the river a fair sod still exists, but the entire watershed has suffered greatly from overgrazing, though in recent years, under the stricter supervision of the Forest Service, less than formerly.
>
> White grama grass, an excellent forage plant, attaining a height of 30 inches, once grew luxuriantly over all the open country, and pine grass covered the woodlands. These grasses defied the encroachment of weeds, but since the sod has been injured and sometimes destroyed by overgrazing and the evils that attend and follow after it, weeds of many kinds have obtained a foothold and taken the place of the native grasses. * * *
>
> Thirty years ago the Blue River flowed through a sodded or cultivated bottom land. * * * To-day [1916] the bottom is a wide wash * * * and represents less than 8 per cent of the original arable area.

QUANTITY OF SUSPENDED SILT

During part of 1895, W. Richins made daily silt determinations of the flow of the Gila River at the Buttes, 12 miles east of Florence, Ariz. (*16*). The samples of water were allowed to settle in glass tubes for several days, when the volume of silt was determined. Several laboratory experiments established the ratio of volume of dry solid matter to volume of mud, which averaged about 1 to 5, and this ratio was used to reduce the daily mud content to solids. The United States Geological Survey made similar silt determinations during part of 1899. The monthly results based on daily records are summarized in Table 4.

TABLE 4.—*Monthly discharge of suspended silt and water in Gila River at the Buttes during a part of 1895 and 1899*

Month	Monthly discharge		
	Water	Mud	Solids
1895	*Acre-feet*	*Acre-feet*	*Acre-feet*
August	97,336	11,076	2,213
September	48,317	7,809	1,579
October	96,966	15,182	3,032
November	65,633	2,273	554
December	46,177	461	89
1899			
January	19,552	----------	30
February	13,273	----------	7
March	7,993	----------	1
April	3,680	----------	1
May	1,107	----------	0
June	31	----------	0
July	73,000	----------	1,854

R. H. Forbes, of the University of Arizona, made some silt determinations of Gila River both on the volume and weight basis in 1899 and 1900 (*6*). Daily samples were taken from the surface water and combined in sets of seven. Sampling during flood periods showed silt ranging from 1.94 per cent by weight to 9.41 per cent, while the percentage on the volume basis varied from 9.2 to 36.4 per cent after settling one day. In Table 5, which gives the results of these tests, the unit "parts per 100,000" has been reduced to per cent by weight.

TABLE 5.—*Proportion of silt by weight in Gila River near head of the Florence Canal, November 28, 1899, to November 5, 1900*

Period	Proportion of silt by weight	Period	Proportion of silt by weight
1899	*Per cent*	1900—Continued	*Per cent*
Nov. 28 to Dec. 4	0.073	Aug. 1 to Aug. 7	7.534
Dec. 5 to Dec. 11	.050	Aug. 8 to Aug. 14	4.380
Dec. 12 to Dec. 18	.030	Aug. 15 to Aug. 21	.159
Dec. 19 to Dec. 25	.058	Aug. 22 to Aug. 28	.075
Dec. 26 to Jan. 1	.078	Sept. 1 to Sept. 7	2.959
		Sept. 8 to Sept. 14	9.406
1900		Sept. 15 to Sept. 21	7.620
Jan. 2 to Jan. 8	.055	Sept. 22 to Sept. 28	1.937
Jan. 11 to Jan. 18	.030	Sept. 29 to Oct. 7	.029
Feb. 1 to Feb. 7	.016	Oct. 8 to Oct. 14	.028
Feb. 8 to Feb. 14	.009	Oct. 15 to Oct. 21	.052
Feb. 15 to Feb 21	.015	Oct. 22 to Oct. 28	.406
Feb. 22 to Feb. 28	.008	Oct. 29 to Nov. 5	.293
Mar. 1 to Mar. 7	.012		

The United States Geological Survey took samples of water from Gila River near San Carlos, Ariz., during part of 1905. The results are given in Table 6.

TABLE 6.—*Mean proportion of suspended silt by weight, monthly discharge, and monthly quantity of silt in Gila River at San Carlos, Ariz., during the last half of 1905*

Month	Mean proportion of silt by weight	Monthly (*11*) discharge	Monthly quantity of silt
1905	*Per cent*	*Acre-feet*	*Tons*
June	0.0971	15,200	20,400
July	.5603	6,100	46,300
August	1.4065	27,100	551,000
September	.3140	32,400	138,800
October	.0432	9,200	5,400
November	.5683	112,000	866,000
December	.1125	53,600	81,700

A few samples of Gila River water were taken by the Bureau of Reclamation 4 miles above Yuma, and the silt content was determined. In Table 7 are given the mean percentage of silt by weight for each period, the discharge, and the quantity of suspended silt for each period, in Gila River near its mouth.

TABLE 7.—*Mean proportion of silt by weight, monthly discharge, and monthly quantity of silt in Gila River 4 miles above Yuma, Ariz., during part of 1914 and 1916*

Period	Mean proportion of silt by weight	Discharge	Quantity of silt
1914	*Per cent*	*Acre-feet*	*Tons*
Aug. 5 to Aug. 20	6.12	23,800	1,983,000
Aug. 20 to Sept. 21	5.08	25,400	1,755,000
Sept. 21 to Oct. 11	4.87	23,800	1,578,000
Oct. 11 to Oct. 15	2.73	1,600	59,000
1916			
Oct. 11 to Oct. 18	.41	20,800	110,000
Oct. 18 to Oct. 30	.74	23,800	240,000
Oct. 30 to Nov. 3	.20	9,900	27,000

A board of Army engineers in reporting on the San Carlos irrigation project, Ariz., in 1914, estimated the percentage of silt in the Gila River at the San Carlos reservoir site and the total quantity of silt that would be annually deposited in the proposed reservoir. According to their report (*11*):

The available data show that at San Carlos, considering all the years in which observations have been made, about 40 per cent of the yearly run-off (of the Gila River) is in the months of July–October and carries about 2½ per cent (by weight) of silt, while the run-off for the remainder of the year carries hardly one-half per cent. This indicates that 1.3 per cent is a liberal figure to be applied to the total yearly run-off. * * *

The volume of silt per year based on a mean annual flow of 346,568 acre-feet in the Gila River and an average percentage of silt of 1.3 per cent is 4,500 acre-feet but it is estimated that about one-sixth would escape, leaving only 3,750 acre-feet, with an average unit weight of 70 pounds per cubic foot, in the reservoir.

As concerns this report, Salt River is the most important tributary of the Gila for the reason that the greater part of its discharge has been stored in Roosevelt Reservoir since 1905, and its silt content determined by surveys of silt deposition in the reservoir.

In 1901 the percentage of silt by volume in Salt River was determined by the United States Geological Survey. From January 1 to April 18 the samples of water were taken at McDowell, Ariz., located on Salt River one-third mile above its junction with Verde River, and from April 18 to December 31 they were taken at what is now the site of Roosevelt Reservoir. The results are given in Table 8 (*4*).

TABLE 8.—*Silt content of Salt River for stated periods throughout 1901, at McDowell and Roosevelt Reservoir sites, Arizona*

Date	Volume of silt	Date	Volume of silt
	Acre-feet		*Acre-feet*
January	9.27	July	83.58
February 1–15	34.42	August	134.16
February 16–28	8.28	September	23.85
March	9.53	October	5.04
April 1–18	.06	November	.65
April 19–May 26	.00	December	.00
May 27–31	28.74		
June	.00	Total for year	337.58

The discharge of Salt River at the reservoir site during 1901 was 477,704 acre-feet, much below the normal; but the silt content was less than 7 per cent of the average quantity annually deposited in the reservoir during the past 20 years. This wide difference may be accounted for in one of two ways: (1) That there was little silt in Salt River in 1901; or (2) that the method followed in determining the silt content included the suspended silt only and excluded the bed silt.

A report made by Cragin [5] to the Bureau of Reclamation, October 15, 1925, states:

The present silt survey (1925) is the last of four since Roosevelt Dam was built, the others being made in 1914, 1916, and 1919. The following is a summary of the silt data:

Year	Silt content	Increase
	Acre-feet	*Acre-feet*
1905	0	0
1914	27,000	27,000
1916	62,000	35,000
1919	62,000	0
1925	101,000	39,000
20-year period	101,000	101,000

The association has just completed a silt survey of the reservoir, showing a total accumulation of silt in the 20 years since the dam was begun of 101,000 acre-feet. This is a reduction in the capacity of the reservoir of less than one-sixteenth of the total, and at that rate it would take 320 years to completely fill the lake. While it would seem at first thought that the present generation need have little concern as to the usefulness of the reservoir being greatly decreased * * * this is not the case. The use of 100,000 acre-feet of water stored in Roosevelt Reservoir has a very high value for power alone. Run through the entire power system of the project, including the Horse Mesa and Mormon Flat plants, this would represent some 35,000,000 k. w. h., or a value of around $250,000. This amount would be available on an average over every three-year period. Therefore from this standpoint alone the loss of power revenue would make decrease in storage capacity at Roosevelt a serious consideration to the present day water user. A note of warning should be sounded in connection with the question of protection of the watershed from overstocking. The amount of erosion and consequently the amount of silt carried in water from the watershed will be greatly increased if stock are allowed to crop the grass close. It is therefore of greatest importance that stock grazing should be strictly limited to an extent that will guard against washing surface soil from the slopes into the streams feeding the reservoir.

SILT IN THE LOWER COLORADO RIVER

SILT IN THE RIVER AT TOPOCK

Silt investigations were carried on by the division of agricultural engineering at Topock, Ariz., from August 1, 1917 to July 31, 1918. Topock is a railroad station on the east bank of the Colorado River 15 miles below Needles and about 206 miles above Yuma. It was considered the best available site near the lower end of the canyon section of the river, affording an opportunity to determine the discharge and the percentage by weight [6] of suspended silt. Some

[5] C. C. Cragin, general superintendent and chief engineer, Salt River Valley Water Users' Association.

[6] In these investigations at Topock, percentages were derived by weighing the silty water, then the dry silt, and taking the proportion of the latter to the former. The relation of weight to volume of silt is discussed later in this report.

uncertainty exists as to where the canyon section ends and the lower basin begins, but if the formation of permanent deltas and irrigable lands exceeding 5,000 acres in extent in the flood plains of the river may be taken as a determining factor, the upper end of Mohave Valley in Mohave County, Ariz., some 32 miles above Topock, may be regarded as the dividing line.

It was assumed that the river after it emerges from the canyon section carries a maximum load of suspended silt and a minimum of bed silt, since little silt, if any, is deposited permanently in the canyon section because of its steep grades, many rapids, narrow and deep channel, and high-water velocities. Furthermore, the silt in the river in the vicinity of Topock is transported more uniformly as regards time and quantity than at other points of the river not in the canyon section because a larger percentage is in suspension. Between Mohave Valley and Yuma the river flows through a succession of valleys bordered by hills and low mountains and separated from each other by relatively low, narrow gorges. As compared with the canyon section, the grade of the river bed is here much flatter and its channel wider, the average grade between Topock and Yuma being 1.5 feet per mile, while that between Topock and the mouth of Green River, nearly 700 miles, is 5 feet per mile. The width of the river channel under normal discharge below Topock varies from a few hundred feet to about half a mile; that of the canyon section varies from about 100 to 1,200 feet, with the exception of a short stretch near the mouth of Virgin River. In general the river is only a few hundred feet wide in the canyon section.

The investigations were made at the gauging station of the United States Geological Survey 1¾ miles below the railroad bridge at Topock. The river channel in the immediate vicinity of the station is

straight above and below gauge. Above the gauge the channel is wide and the bed of loose sand is constantly shifting. At low stages large sand bars form numerous islands between Topock and the gauge. Below the gauge the river enters a steep-walled rock canyon and the channel rapidly narrows from about 800 feet to 400 feet. The bed in the canyon shifts during floods. After floods it probably gradually regains its normal condition, which is maintained until the next rise when it again scours out. The control is indefinite (*9, p. 18*).

During the 12-month period of observations at this station there were no noteworthy abnormal occurrences in either the drainage area or the river which materially affected the run-off. The drainage area above Topock is 171,000 square miles, and no excessive rainstorms or floods occurred to cause wide departures from the normal regimen of the main river. The discharge at Yuma for the 12-month period was approximately 16 per cent below the average of 24 years. The quantity of suspended silt transported during this period as measured at Yuma was 38 per cent below the average of 18 years.

The flow of the Colorado River was measured at Topock by the United States Geological Survey from August 1, 1917, to July 31, 1918, and the maximum, minimum, mean,, and total monthly discharges expressed in acre-feet for this 12-month period are given in Table 9. In this table are also given the average monthly percentages of suspended silt by weight derived from Table 60, and in the last columns the total monthly quantity of dry silt in the river, expressed in tons, as well as the amount of fine and coarse silt.

Table 9.—*Monthly discharge and silt content of Colorado River, near Topock, Ariz., August, 1917, to July, 1918, inclusive*

Month	Discharge			Run-off (*9, p. 19; 10, p. 15*)	Suspended silt					
	Maximum	Minimum	Mean		No. 200 sieve		Total	No. 200 sieve		Total
					Passing	Retained		Passing	Retained	
	Sec.-ft.	*Sec.-ft.*	*Sec.-ft.*	*Acre-feet*	*P. ct.*	*P. ct.*	*P. ct.*	*Tons*	*Tons*	*Tons*
August	34,400	12,700	19,400	1,190,000	0.780	0.332	1.112	12,635,200	5,378,000	18,013,200
September	15,600	9,450	12,000	714,000	.246	1.785	2.031	2,391,000	17,349,000	19,740,000
October			9,570	588,000	.308	1.129	1.407	2,945,500	9,036,700	11,982,200
November			9,100	541,000	.148	1.315	1.463	1,689,900	9,084,100	10,774,000
December			8,830	543,000	.178	.630	.808	1,315,700	4,656,700	5,972,400
January			8,590	528,000	.120	.259	.379	862,500	1,861,500	2,724,000
February	11,800	6,400	8,300	461,000	.101	.037	.138	633,800	232,200	866,000
March	40,100	10,000	16,100	990,000	.945	.240	1.185	12,735,200	3,234,300	15,969,500
April	23,300	11,000	17,000	1,010,000	.349	.359	.708	4,798,300	4,935,700	9,734,000
May	55,100	14,100	38,200	2,350,000	.304	.171	.475	9,724,800	5,470,200	15,195,000
June	92,000	32,200	66,300	3,950,000	.260	.531	.791	13,980,000	28,551,500	42,531,500
July	87,500	24,000	45,100	2,770,000	1.137	.249	1.386	42,872,400	9,389,000	52,261,400
Yearly total				15,635,000				105,084,300	99,778,500	205,763,200
Percentage								51.5	48.5	100

SILT IN THE RIVER AT YUMA

Silt determination [7] have been made for the waters of the Colorado River at Yuma by the Bureau of Reclamation since 1909. Prior to July 1, 1911, samples were taken at somewhat irregular periods, but since that date sets of nine samples each have usually been taken twice a week. The cross section of the river from which samples are taken is 600 feet below the old Southern Pacific Railroad bridge at Yuma, the work being done from a car suspended from the cable of a current meter gauging station.

The drainage area of the river at Yuma is nearly 42 per cent larger than at Topock mainly because the lower watershed includes that of the Gila River, which joins the Colorado 1½ miles above Yuma; and there is also the drainage area of Williams River which joins the main river 41 miles below Topock. However, the Gila River contributes only about 6 per cent of the average yearly run-off of the Colorado River.

Between Topock and Yuma the river is further influenced by diversions for three irrigation projects, viz., the Colorado River Indian Reservation, the Palo Verde, and the Yuma.

The average percentages as determined by the Bureau of Reclamation for each month of each year from 1910 to 1925, inclusive, are given in Table 10.

[7] Data furnished by Porter J. Preston, superintendent of the Yuma Project.

TABLE 10.—*Monthly mean proportion of silt, by weight, in Colorado River at Yuma for 1910–1925, inclusive, stated in percentages*

Year	Jan.	Feb.	Mar.	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
1910				[1] 0.50		0.56	0.40	[1] 0.24	[1] 0.00		[1] 0.35	[1] 0.38
1911	[1] 0.08	[1] 1.00	[1] 1.06	[1] .84	[1] 0.86	[1] .72	1.68	1.27	.81	2.37	.53	.22
1912	.10	.23	.79	1.13	.90	.52	.71	.78	.85	.46	1.10	[1] .24
1913	[1] .14	.13	.30	1.15	.73	[1] .65	.41	[1] .61	1.70	1.09	.30	.39
1914	.45	1.06	1.49	1.03	.70	.55	1.35	1.54	.96	1.42	.81	.60
1915	1.26	1.01	.94	1.21	1.20	.80	.55	1.14	.59	.65	.42	.30
1916	1.53	1.59	1.62	1.10	.98	.69	.65	1.95	.87	2.08	.68	.31
1917	.48	.31	.49	1.03	.98	.54	.40	.68	.30	.20	.14	.13
1918	.15	.15	.96	.39	.54	.53	1.01	.68	.63	.48	.34	.28
1919	.15	.32	.58	.93	.50	.54	1.67	2.24	1.03	.72	.54	1.22
1920	.60	[1] .35	1.23	1.02	.94	.66	.66	.92	[1] 1.11	.24	.30	.20
1921	.22	.18	.52	.34	.80	.50	.67	2.12	1.71	.43	.32	.56
1922	.66	.57	1.11	1.00	1.11	.60	.48	1.37	1.61	.16	.21	.26
1923	.18	.18	.35	.74	.72	.62	.80	1.07	2.77	1.29	1.23	.50
1924	1.03	.43	.42	1.00	.88	.75	.05	.48	.57	.75	.35	.26
1925	.18	.31	.48	.69	.53	.62	.74	.80	2.81	1.83	.73	.42

[1] Less than four sets of nine samples taken during month.

The data given for the years 1912 to 1916, do not always agree with those already published in the Transactions of the American Society of Civil Engineers, because the latter (*12*, *24*) appear to have been taken from a theoretical silt-discharge curve, while data given in Table 10 are monthly averages of actual observations. Plotting the results of semiweekly sampling at Yuma shows that there is very little basis for the assumption that the relation between percentages of silt by weight and river discharge is more or less constant and that a silt-discharge curve is feasible.

In Table 11 are given the average yearly percentage by weight of suspended silt in Colorado River at Yuma, the discharge of the river to the nearest thousand acre-feet, and the computed weight of silt in tons for each of the years 1911 to 1925, inclusive. To these items has been added a like summary of the silt determinations made by the United States Geological Survey at the same station during the years 1903 and 1905, and by R. H. Forbes for 1904. The silt content for these 18 years averages 183,759,000 tons a year. This average is used in this report to represent the normal load of suspended silt in the river at Yuma.

TABLE 11.—*Amount of suspended silt in Colorado River at Yuma, Ariz., for 18 years*

Year	Average yearly proportion of silt by weight	Discharge	Suspended silt	Year	Average yearly proportion of silt by weight	Discharge	Suspended silt
	Per cent	*Acre-feet*	*Tons*		*Per cent*	*Acre-feet*	*Tons*
1903		11,328,000	[1] 110,746,000	1919	0.87	10,747,000	127,275,000
1904		10,118,000	[2] 120,981,000	1920	.78	21,444,000	227,087,000
1905		19,712,000	[1] 308,728,000	1921	.70	19,428,000	185,125,000
1911	1.01	17,831,000	245,152,000	1922	.71	17,014,000	164,438,000
1912	.67	18,400,000	167,870,000	1923	.95	17,848,000	230,808,000
1913	.60	11,708,000	110,532,000	1924	.63	11,348,000	97,319,000
1914	1.00	20,655,000	281,166,000	1925	.85	12,452,000	144,077,000
1915	.93	14,641,000	185,350,000				
1916	1.18	23,140,000	371,692,000	Total			3,307,665,000
1917	.49	20,598,000	137,301,000	Mean			183,750,000
1918	.51	13,158,000	91,348,000				

[1] Computed from monthly discharges. [2] (7, p. 60.)

The detailed results of determinations made at Yuma by the Bureau of Reclamation from July 30, 1917, to July 29, 1918, are shown in Table 61 of the appendix to establish a comparison with similar results obtained at Topock during the same period. It should be noted, however, that at Yuma the suspended silt was not separated into grades, only the total percentage being given.

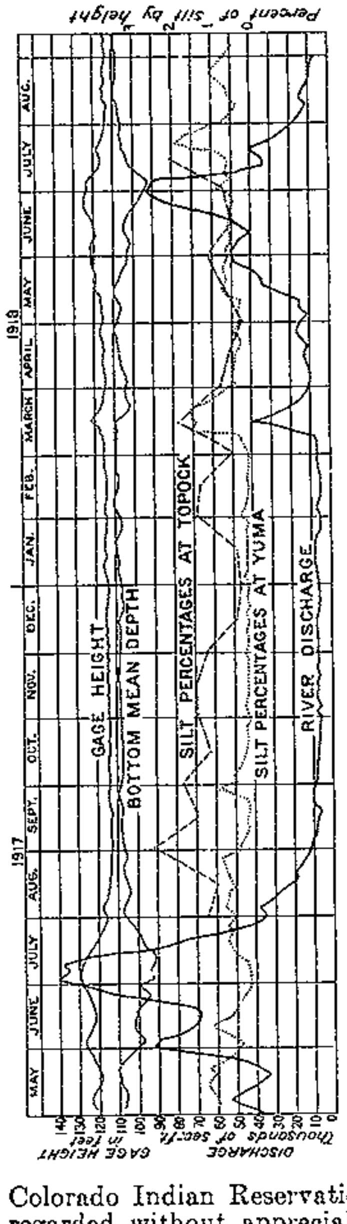

FIG. 6.—Gauge heights, semiweekly mean depths, discharge, and percentage of silt in Colorado River at Yuma, and percentages of silt at Topock in 1917–18

(NOTE.—One hundred feet added to gauge heights to avoid minus readings.)

COMPARISON OF SILT LOAD AT TOPOCK WITH THAT AT YUMA

A comparison of the quantity of suspended silt in the Colorado River at Topock with that at Yuma, during the same 12-month period, lends support to the belief that as the river emerges from the canyon section it is carrying what may be regarded as its greatest load of suspended silt, and that in its course through the lower basin part of the suspended load is dropped and becomes bed silt. A relatively small part of the suspended silt which drops to the bed of the river channel between Topock and Yuma is deposited permanently. The results of other investigations discussed later lead to the conclusion that when conditions are favorable for such transportation, the greater part of the bed silt is carried farther and farther downstream.

Curves in Figure 6 show the gauge heights, mean depth, discharge, and percentage of silt by weight at Yuma. The semimonthly percentage of silt by weight at Topock is also indicated. The rise and fall of the bed of the river at Yuma as a result of scouring is clearly shown.

The quantity of water diverted at Bulls Head, Ariz., for Mohave Valley lands and that diverted at Parker, Ariz., for those of the Colorado Indian Reservation were so small that they may be disregarded without appreciable error in estimating the outflow and inflow of Colorado River between Topock and Yuma during the 12-month period ended July 31, 1918. The intake of the Palo Verde (Blythe) irrigation project is about 100 miles below Topock. During the 12-month period under consideration, about 160,000 acre-feet of water was diverted for the irrigation of lands in this project, while the diversion at Laguna for the Yuma project was 457,254 acre-feet.

The only inflows were from Williams River and Gila River. The flow of the former from August 1, 1917, to July 31, 1918, was estimated to be 64,000 acre-feet, and measurements made by the Bureau of Reclamation on the latter showed a discharge for the 12-month period of 356,600 acre-feet. During this same period Colorado River carried past Topock 15,635,000 acre-feet, while at Yuma it carried 13,919,000 acre-feet. That this condition of flow is not confined to the period under consideration is shown by the fact that the average annual flow of the river at Topock from 1917 to 1925 is 16,588,000 acre-feet, while that at Yuma for the same period is 15,319,000 acre-feet.

A comparison of the quantity of suspended silt at Topock and Yuma for the 12-month period ended July 31, 1918, is given in Table 12, which shows that for the period the total quantity at Topock was 205,763,200 tons, while that at Yuma was 113,943,000 tons, or 44.6 per cent less. If it be assumed for the sake of argument that there was no deposition of silt between the two points, then the larger quantity of silt might be looked for at Yuma, as a result of the influx of silt from Williams and Gila Rivers and the desilting effected at the intakes of the diversion canals.

TABLE 12.—*Average monthly proportions of suspended silt by weight and monthly quantities of silt at Topock, Ariz., and Yuma, Ariz., for the 12-month period ended July 31, 1918*

Year and month	Topock			Yuma		
	Proportion of silt by weight	Monthly discharge	Suspended silt	Proportion of silt by weight [1]	Monthly discharge (*9*, p. *21*; *10*, p. *17*)	Suspended silt
1917	*Per cent*	*Acre-feet*	*Tons*	*Per cent*	*Acre-feet*	*Tons*
August	1.112	1,190,000	18,017,200	0.68	1,440,000	13,329,000
September	2.031	714,000	19,740,000	.30	536,000	2,180,000
October	1.497	588,000	11,982,200	.20	405,000	1,830,000
November	1.463	541,000	10,774,000	.14	422,000	804,000
December	.808	543,000	5,972,400	.13	420,000	743,000
1918						
January	.370	528,000	2,724,000	.15	405,000	827,000
February	.138	401,000	866,000	.15	323,000	660,000
March	1.185	990,000	15,969,500	.96	1,010,000	13,199,000
April	.708	1,010,000	9,734,000	.39	768,000	4,077,000
May	.475	2,350,000	15,195,000	.54	1,790,000	13,168,000
June	.772	3,950,000	42,531,500	.53	3,680,000	26,550,000
July	1.386	2,770,000	52,261,400	1.01	2,660,000	36,571,000
Total			205,763,200			113,943,000

[1] Average of U. S. Bureau of Reclamation measurements, taken from Table 10.

THE SILT PROBLEM OF THE LOWER BASIN

For hundreds of miles the Colorado River flows in canyons which at most places are several thousand feet deep, and this part of its system has been appropriately termed the canyon section. At an air-line distance of about 220 miles from its mouth, or 360 miles measured along the stream, the river emerges from the deeper canyons, the grade of its bed becomes flatter, and alluvial soil has been formed in the flood plain of the river in past geologic times in several valleys of variable extent above the upper margin of the main delta. In this report reference to the "lower basin"[8] means that part of the river system and deltaic formations located below the canyon section.

Owing to the high transporting power of the river in the canyon section, practically no silt is permanently deposited there. All the water-borne sediment and débris carried into the upper reaches of the main river and tributaries sooner or later pass through the Grand Canyon on their way to the lower portion of the basin and the Gulf of California.

If Colorado River carried no silt there would be no delta and no rich farming lands. Where bountiful crops are now produced, high waves would roll over an arm of the Pacific Ocean or dash against a barren shore. On the other hand, many of the ways in which the silt injuriously affects the agriculture of the lower basin are so obvious as to require no more than brief mention in this bulletin.

A high bed in the lower reach of the river renders control of the river expensive and hazardous. For ages the Colorado meandered over the delta without human interference. When one channel became too high for the passage of water, a new one was formed at a lower elevation until it in turn became clogged with silt. This natural process continued until about a quarter of a century ago when an attempt was made not only to utilize for irrigation purposes a part of the river's flow, but also, in a measure, to control its course to the gulf. Since then, although $7,500,000[9] has been expended in building control levees much of the wealth created by the diverted water has been repeatedly menaced and damaged by the failure of structures to hold the river in check. From June, 1905, to February, 1907, practically no control could be exercised at the diversion points. The cost of closing the breaks during this period and restoring the river to its old channel was more than $2,000,000 (*5*).

The Bureau of Reclamation has expended a large amount of money in building headworks to prevent the heavier silt from entering the Yuma irrigation system, but it has not been feasible to prevent the finer sediment from being transported to the ditches and fields of the farmers. The Imperial irrigation district also has spent money for a similar purpose, but the skimming and sluicing processes so successfully carried out on the Federal project could not be put in effect during the low stages of the river because the district is the lowest water user. On account of the scarcity of water, the lower intake gates must remain open, thereby affording an opportunity for all the suspended as well as the bed silt to enter the canal system. The authors are indebted to M. J. Dowd, general superintendent of the Imperial irrigation district, for the following tabulation giving the sums expended by the district in 1923 and 1924 in removing silt at the intake and throughout the canal system:

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[8] The lower basin of the Colorado River, as defined in the Colorado River compact, includes "those parts of the States of Arizona, California, Nevada, New Mexico, and Utah within and from which waters naturally drain into the Colorado River system below Lees Ferry, and also all parts of said States located without the drainage area of the Colorado River system which are now or shall hereafter be beneficially served by waters diverted from the system below Lees Ferry."

[9] Unpublished report to the United States Bureau of Reclamation by F. E. Weymouth, 1924.

	1923	1924
Intake	$36, 965	$33, 343
Main canals	105, 547	100, 331
Secondary canals and waste ditches	436, 990	394, 463
New River and Salton Sea	-------	30, 995
Total	579, 502	559, 132

Unfortunately the problem is not disposed of by the removal of part of the silt from the main and secondary channels. Much of the suspended load is carried through the system and deposited in farm ditches and on irrigated fields. Mr. Dowd says:

The irrigation district delivers water to the high corner of each 160-acre tract from which point the owner at his expense conducts it to his farm. The amount and frequency of cleaning supply and head ditches which a farmer must do, varies with the location and elevation of the farm. There are many cases in which the farmer must clean his supply ditch after each irrigation and his head ditches three or four times a year. In a considerable number of other cases, the supply ditch has to be cleaned from one to three times a year and the head ditches a similar number of times.

In passing over the land the water drops most of its silt, the main portion being deposited at the head of each field, thereby building up this part. In three years time, on an average, the head of each field or strip near the opening of the head ditch must be lowered by moving the deposited silt to other parts of the field. The first time this is done it is not, as a rule, necessary to move the silt far, but at each removal it must be moved farther at a corresponding greater cost. To-day (1925) a large number of farmers are moving silt an eighth of a mile.

In addition, the silt in the water increases the difficulties of raising certain kinds of crops. In the case of alfalfa grown on the harder type of soil with little fall to the land, the silt depositing in a thin film seals the ground surface, thus increasing the length of time the water stands on the land after an irrigation, and during the hot summer this results often in the scalding of the alfalfa. In the case of lettuce and cantaloupes which are furrow-irrigated, it is a common occurrence for a farmer to run water in a furrow for several days trying to "sub" the moisture to the top of the hill and often before this is accomplished it is necessary to shut off the water, break up the film of deposited silt on the bottom and sides of the furrow, and then turn the water on again.

It is estimated that the annual expense to the farmers of Imperial Valley caused by silt averages $2 an acre. Applying this cost to the acreage irrigated in 1924, and adding thereto the cost of canal cleaning, brings that year's cost of silt disposal and control in its various forms above $1,333,000.

Another problem has developed recently. Waste and drainage waters from Alamo and New Rivers, upon merging with the still and salty waters of Salton Sea, immediately precipitate their silt load, forming deltas which obstruct the natural flow and cause the water to back up and flood the near-by farming lands. In 1924 the Imperial district spent about $31,000 in dredging at New River outlet.

SILT INVESTIGATIONS IN IMPERIAL VALLEY

The delta of the Colorado River—in past geologic times a part of the Gulf of California—was formed by the alluvial deposits of the river which diked off the upper end of the gulf. The area extends from the present head of the gulf in a northwesterly direction about 140 miles, and is from 10 to 40 miles wide. Except at the southeast, the delta is surrounded by mountains. The northwestern part of the delta is known as Coachella Valley and the central part as Imperial Valley. Separating these two valleys is the somewhat variable expanse of Salton Sea.

From the notes and reports of explorers and the traditions of the Indian tribes in the vicinity, Lake Cahuilla, as Salton Sea was formerly called, has been subject for centuries to sudden enlargements resulting from excessive floods in the Colorado River, followed by long periods of recession to a dry basin caused by evaporation. The largest flood entering this basin within recorded times occurred in 1905 and 1906, when the intakes of the Imperial Canal system were washed away and little or no control could be exercised to prevent the entire discharge of the river from entering the lake. When control was regained in February, 1907, Salton Sea was 45 miles long and 17 miles wide. The water surface at that time was 198 feet below sea level, but by 1925 it had dropped to 250 feet.

More than one-third the area of the delta lies in Mexico. In this portion are found many old river channels, the chief of which are the Alamo and Pescadero. The channel heading in Volcano Lake and made by the overflow of the Colorado River into Salton Sea from 1905 to 1907 is called the New River. The permanent outlet to Volcano Lake, however, is Hardy River, the course of which is southeasterly, whereas that of New River is northwesterly.

When the California Development Co., later merged in the Imperial irrigation district, undertook in 1900 to construct a canal system to irrigate lands in Imperial Valley and delta lands in Mexico, it was found that a canal on United States territory would be difficult and costly to construct because of an intervening range of sand hills, some 15 miles in width, which terminated several miles below the Mexican line. Accordingly, it was decided to build the main canal in Mexican territory and to utilize in part the old natural channel called Alamo River. A temporary wooden intake known as the Chaffey gate was built on the right bank of the river 500 feet north of the international line, and 14 miles of canal was excavated to connect the intake with Alamo River. From this point the main canal was located and built in this old channel, by straightening the sharp bends and deepening and strengthening the channel where necessary.

The present Imperial Valley enterprise is located in Imperial County, Calif., and in Lower California, Mexico, and covers about 1,000,000 acres of land, all of which, however, is not irrigable. In the Imperial irrigation district in California there are 605,000 acres, of which 515,000 acres are considered irrigable. The area irrigated varies somewhat each year. The maximum recorded was in 1920, when 603,440 acres in the United States and Mexico were supplied with water. In 1925, the Imperial irrigation district operated 137 miles of canals in Mexico, 1,669 miles of irrigation canals and laterals in the United States, and many miles of drainage canals.

Water for the irrigation of the valley is diverted from the California side of the Colorado River at Rockwood heading, about 8 miles below Yuma. There is no permanent diversion dam, and a temporary one must be constructed for low-water periods.

The main Imperial canal, known as the Alamo, has a maximum capacity of 7,100 second-feet and in some dry periods carries the entire flow of the Colorado River. The Alamo Canal passes from the United States into Mexico shortly after leaving the intake and follows mainly the old Alamo River channel for about 46 miles. Before reentering the United States, it is divided into several canals which supply the east, central, and west portions of Imperial irrigation district.

SILT AT THE INTAKES

Principally because of the deposition of silt, the location of the intake on the river has been changed from time to time, and new structures have been installed. In 1906, Hanlon heading was built at Andrade or Pilot Knob, near the right bank and about 2,000 feet north of the boundary line; and 2,000 feet of fore bay connected the intake with the river. The heading consists of seven openings, each 10 feet wide, controlled by gates. Rockwood heading (pl. 1), the present intake was constructed in 1918 at a point on the river 7,000 feet above the Mexican boundary. This is a concrete structure over 700 feet long. Its face is parallel to the river bank, and there are 75 openings, 8 feet center to center, controlled by flashboards. The sills of 48 gates are 106.7 feet above sea level, and those of the remainder are 8.1 feet lower, the purpose of this arrangement being to divert the water by skimming the surface and thus prevent the heavier sediment from entering the canal system. The new intake is connected with the old Hanlon heading by a channel 6,000 feet long, and the old fore bay has been abandoned. The distance from Yuma to the Rockwood intake is 8 miles. Depending on the volume and mean flow, it takes from one and one-half to six hours for the water to traverse this distance.

In order to determine the grade and percentage of suspended silt by weight at the Hanlon and Rockwood intakes of the Imperial irrigation district and to compare the amount of silt found there with suspended silt passing Yuma in the Colorado River, investigations were carried on from time to time between 1917 and 1920, the results of which are summarized in Tables 64 to 69, inclusive, of the Appendix.

The general conclusions that may be drawn from these results are as follows:

(1) Prior to October, 1918, when operation of the Rockwood intake was begun, there was but a slight difference (less than 10 per cent) between the quantity of suspended silt entering the Alamo Canal and that in the river at Yuma.

(2) With the Rockwood intake in operation the quantity of suspended silt entering the Alamo Canal decreased at times by as much as 47 per cent and also increased at other times in a greater ratio depending, seemingly, on the stage of the river and manner in which the intake flashboards were operated.

(3) About 90 per cent of the suspended silt entering the Alamo Canal passed a 200-mesh sieve, and only one-third of 1 per cent was retained on a 60-mesh sieve.

(4) The finer suspended silt, or that which passed a 200-mesh sieve, was fairly evenly distributed throughout any vertical section of the canal, but the small quantity of heavier silt present tended to gravitate toward the bottom.

(5) Although not measured, large quantities of bed silt entered the Alamo Canal when the lower flashboards of the intake were removed.

The studies of the silt problems of Imperial Valley by the division of agricultural engineering began in 1907, and were continued at various intervals thereafter. Some of the investigations were conducted cooperatively with the Imperial irrigation district, while others were made independently. Valuable assistance was given in this work by J. E. Peck, R. S. Carberry, and many other members of the Imperial irrigation district staff.

DISTRIBUTION OF SUSPENDED SILT IN CANAL SYSTEM

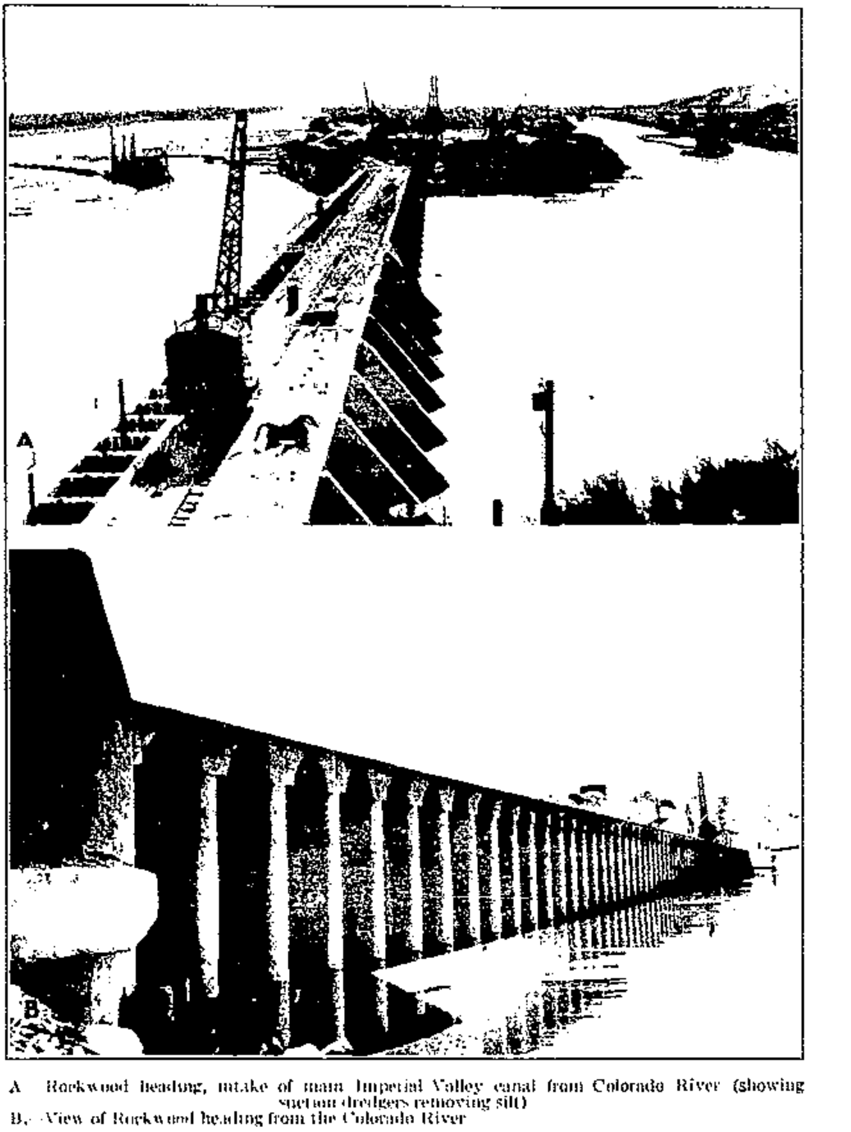
The investigations started in 1907 sought to determine the amount and distribution of the silt in the canal system. The eight sampling stations shown in Table 13 were selected from among all those comprising the system. The first six were on a continuous 80-mile run of water. The several mutual water companies owning the distributing canals and the California Development Co. owning the main canal rendered valuable aid by arranging for their zanjeros to take the water samples at the stations. The equipment for taking samples was placed in a small locker at each station and consisted of a 2-gallon demijohn to contain the water as it accumulated throughout the month, a 1-quart bucket with bail and rope to raise the water from the canal, a half-pint cup to measure the amount of water to be saved each day, and a funnel. The samples were dipped from the turbulent water below the gates where no silt was being deposited. Presumably the solids were well mixed in this agitated water. The bucket was shaken to keep the silt in suspension when the measure was filled. The daily samples of equal amount were put into the same demijohn to give a composite for each calendar month. At the end of each month the full demijohns were collected and empty ones left in their places.

The monthly composites were taken to the office of Imperial Water Co. No. 1, where they were placed in tubes to settle for 30 days, a period adopted as the standard for comparative purposes. The sediment after 30 days was found to be quite small, and this period facilitated the work with only a few tubes, because a new set of samples was ready every 30 days. The demijohns were shaken violently to mix the silt and sand thoroughly with the water when the tubes were being filled. The first tubes used were one-quarter inch inside diameter, but later tubes of three-quarter inch inside diameter were used, and these were found more convenient if not more accurate. The tubes were of specially drawn glass, 42 inches long, and were selected for even bore. The bottom of each was corked and sealed with paraffin. A scratch on the tube 1 meter above the top of the cork marked the height to which the tube was filled. After the mud had settled for 30 days the height of the mud column was read in centimeters, which gave the percentage by volume directly. The results are given in Table 13.

TABLE 13.—*Proportion of silt by volume in water from Imperial Valley canals,*[1] *October, 1907, to September, 1908, inclusive*

Station	Canal	Distance from Colorado River	Proportion of silt by volume				
			October	November	December	January	February
		Miles	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*
Hanlon heading	Alamo	½	1.9	1.0	0.5	0.3	1.3
Sharps heading	do	45	1.6	2.0	1.1	.2	.8
Ten-foot drop	Central main	51	1.0	.8	.9	.3	1.0
Dahlia heading	do	58	1.3	1.1	1.0	.3	.7
Imperial Water Co. No. 4 headgate	Brawley	75	1.1	1.0	.6	.3	.5
Lateral gate near Brawley	Brawley main extension.	80			.6	.3	.3
Imperial Water Co. No. 5 headgate	Holt	53	1.5	1.1	1.0	.3	.7
Lateral gate near El Centro	Dahlia	65	.3	.9	.6	.2	.5

[1] The silt in the samples was allowed to settle 30 days before being measured.



A Rockwood heading, intake of main Imperial Valley canal from Colorado River (showing suction dredgers removing silt)
B.—View of Rockwood heading from the Colorado River

TABLE 13.—*Proportion of silt by volume in water from Imperial Valley canals October, 1907, to September, 1908, inclusive*—Continued

Station	Proportion of silt by volume							
	March	April	May	June	July	August	September	Mean
	Per cent	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*
Hanlon heading	2.2	1.6	1.2	1.1	0.9	3.8	3.7	1.6
Sharps heading	1.8	1.0	.8	.6	.4	3.6	3.3	1.4
Ten-foot drop	4.6	1.0	.5	.5	.5	4.5	1.3	1.4
Dahlia heading	1.4	.8	.6	.6	.4	3.6	3.4	1.3
Imperial Water Co., No. 4 headgate	1.7	.6	.6	.6	.4	4.0	1.5	1.1
Lateral gate near Brawley	1.6	--------	.5	.7	.4	8.1	1.6	--------
Imperial Water Co., No. 5 headgate	1.2	.6	.6	.5	.4	5.0	3.2	1.3
Lateral gate near El Centro	1.4	1.0	.5	.6	.4	1.5	4.0	1.0

Water did not flow continuously through the lateral gate near Brawley. The figures that appear suspiciously high such as the amounts for Sharps heading in November, Ten-foot drop in March, and lateral gate near Brawley in August may be incorrect on account of one or more of three causes: Error, temporary natural sluicing, or dredging above the stations at the time, probably the latter. No record of dredging during the period was obtained. It is quite possible for these extremes to occur without gross error being involved.

It will be noted that no great change in the amount of silt took place throughout the length of the canal. The Hanlon samples from near the intake show the highest average, and the lateral-gate samples taken near El Centro, 65 miles from the river, show the lowest average amounts, but the measurements made at the stations throughout the middle part of the system are not materially different. The deposits in the tubes indicated the difference to be due mainly to a greater amount of sand toward the intake without much difference in the finer silts. This sand was the first to settle and occupied the bottom of the tubes. Although great quantities of silt are cleaned out of the canals each year this would be a small proportion of the amount carried by the water running for 365 days. The great portion of the silt entering the canal reaches the lands irrigated.

DISTRIBUTION OF SUSPENDED SILT IN 1914

For the purpose of determining the silt content at the intake and at several division points of the canal system of Imperial Valley, the receiver of the California Development Co. (subsequently the Imperial irrigation district) authorized the taking of water samples daily throughout 1914, at Hanlon heading, the intake of the main canal which is called the Alamo; at Allison heading, 45 miles below the intake; and at No. 5 heading, 53 miles below the intake. The work was in charge of J. E. Peck. The maximum, minimum, and mean percentages of suspended silt by weight for each month at the three designated points of the canal system are given in Table 14.

It should be noted that the Colorado River at Yuma carried a high content of silt during 1914, the average for the year being 1 per cent of suspended silt by weight, while Alamo Canal at its head, for the same period, had an average of 0.9 per cent, 90 per cent of that in the river.

Considering the averages for the year, it will be noted that the load of suspended silt varies but little in its passage through 53 miles of main and secondary canals.

TABLE 14.—*Proportions of silt by weight at three stations in the main Imperial Valley canal system in 1914*

Month	Hanlon heading			Allison heading			No. 5 heading		
	Maximum	Minimum	Mean	Maximum	Minimum	Mean	Maximum	Minimum	Mean
	Per cent	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*
January	1.7688	0.2600	0.8231	1.7798	0.2210	0.4882	1.7588	0.1598	0.3903
February	1.7402	.4144	.8047	1.5284	.4312	.8344	1.5820	.4358	.7816
March	2.0848	.8870	1.3093	2.2114	.9412	1.3398	2.1304	.9060	1.3722
April	1.1080	.5202	.7944	1.0180	.5250	.7839	1.0932	.0609	.8351
May	.8064	.3088	.0350	.9632	.2470	.5715	.7220	.1518	.5192
June	.5562	.2194	.3231	.2616	.1100	.1738	.2544	.1126	.1899
July	2.4302	.3600	1.0070	1.8892	.0920	.5509	1.2858	.1704	.5443
August	2.3080	.8554	1.3071	2.0356	.7690	1.2496	1.8172	.0984	1.1480
September	1.7880	.2044	.8076	1.7912	.3508	.7485	1.8792	.3494	1.0182
October	2.5880	.2750	1.1045	2.1786	.3404	1.0481	2.5740	.3540	1.1506
November	1.2032	.3130	.5922	1.3272	.3300	.6032	1.3140	.2940	.6510
December	3.0460	.2644	1.1888	2.9502	.2402	.7374	2.8830	.2290	.6408
Average			.9040			.7062			.7706

DISTRIBUTION OF SUSPENDED SILT IN 1917 AND 1918

Two years later an agreement was entered into between the Bureau of Public Roads and the Imperial irrigation district providing for the resumption of the investigations on a somewhat broader scale. In order to determine the distribution of suspended silt throughout the canal system, 18 stations, the locations of which are indicated in Figure 7, were selected.

At each station the equipment consisted of a water sampler, a glass funnel for holding the filter paper, a cover for the funnel, a cup for catching the filtered water, and a week's supply of weighted filters in envelopes. (Pl. 2, A.) The sampler consisted of a narrow-necked bottle, with the neck ground off to give a capacity of 500 cubic centimeters, to which was attached a leaden sinker, a bail, and a rope. The filters and their envelopes were dated chronologically in advance and placed in order in the locker. The following procedure was observed each day by the zanjero at the sampling station: Any water in the drain cup under the funnel was emptied. The filter used on the preceding day was removed from the funnel, folded, and placed in its envelope, which was sealed and left on the locker shelf. The filter for the date was placed in the funnel. The sampler was filled from the turbulent water below the gates and the water poured through the filter. The first water passing the filter, if slightly colored, was poured a second time through the filter. The funnel was covered to prevent dust from settling on the filter, and the moist filter was left to dry until the following day. The dried silt clings to the filters tenaciously and can be removed only by scraping, but the sand when dry has a tendency to drop off. The sampler used was found well adapted to the needs of the work. The small neck of the bottle made it easy to take a full, accurate, and uniform sample each day. The paper effected a ready filtering, which was necessary to avoid delaying the zanjero. The entire equipment was found to be very satisfactory.

In 1916 a few tests were made to determine whether or not the exact point of sampling at a canal structure affected the result. It was expected that samples from water violently agitated, as for instance, below the gates, would show more silt than those from the sur-

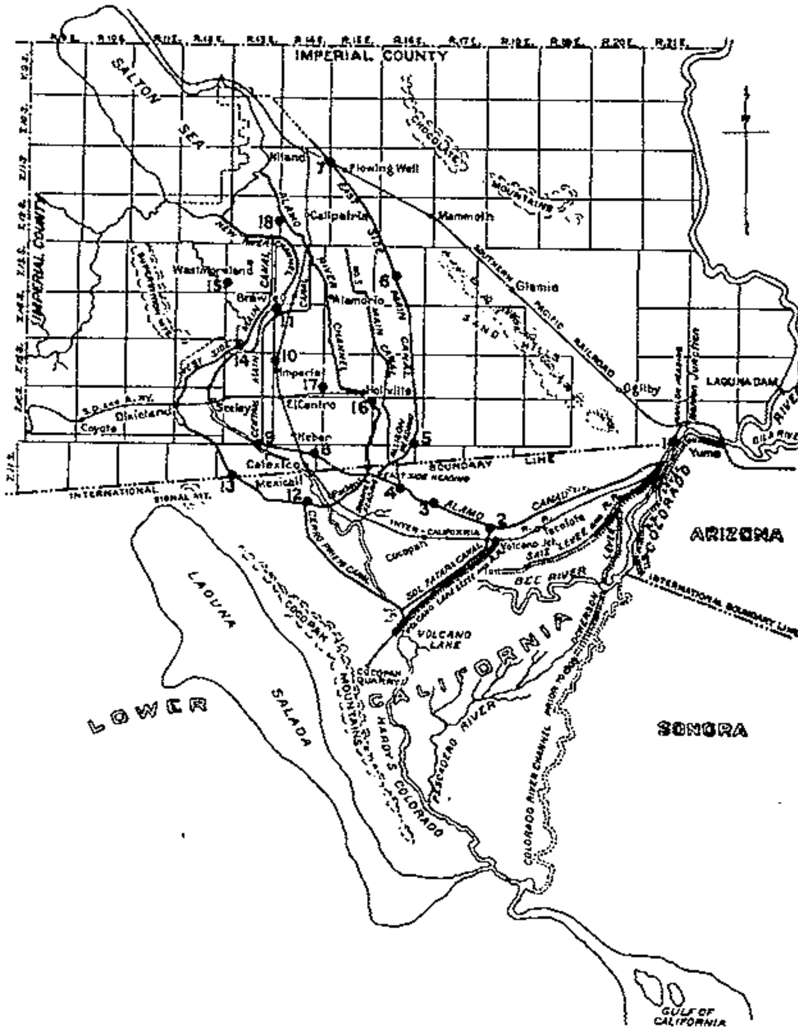


FIG. 7.—Map of Imperial Valley, showing locations of sampling stations

face, and less than those from the bottom in quiet water. Table 15 gives the results of two of these tests. No marked differences are shown, but more accurate results might have been obtained had calculations been made on the weight basis.

TABLE 15.—*Results of tests on point of sampling in canals*

Date	Place	Point of sampling	Volume of silt after settling 30 days
			Per cent
Feb. 1, 1916	Dahlia heading	Bottom of structure in overpour	4.0
Do	do	Below gates in rough water	4.0
Do	do	50 feet below gates in quiet water	3.0
Feb. 2, 1916	Sharps heading	Above gates in quiet water	4.0
Do	do	In overpour	3.9
Do	do	Below gates in rough water	4.0

Table 16 was the outcome of tests made to ascertain whether the manner of handling the 500-cubic-centimeter bottle sampler had any effect on the results. The percentage of total silt is slightly greater in the samples obtained when moving the sampler up and down than in those obtained when holding it in one place, except for the one bottom sample.

TABLE 16.—*Results of tests on use of 500 cubic centimeter bottle silt sampler*

Date	Place	Point of sampling	Proportion of silt by weight: Sieve No. 200, Passing	Proportion of silt by weight: Sieve No. 200, Retained	Proportion of silt by weight: Total	Average
			Per cent	*Per cent*	*Per cent*	*Per cent*
June 19, 1918	Dahlia heading	Surface of canal at meter bridge.	0.324	0.013	0.337	0.313
Do	do	do	.287	.002	.289	
Do	do	Same, moving sampler up and down.	.360	.015	.375	.375
June 20, 1918	Central main canal.	Meter bridge at boundary, surface.	.234	.037	.271	.306
Do	do	Same, mid depth	.251	.036	.287	
Do	do	Same, bottom	.308	.053	.361	
Do	do	Same, up and down	.296	.052	.348	.342
Do	do	do	.301	.035	.336	

The two main operations in the laboratory consisted of (1) weighing and preparing the filters for sending out to the stations and (2) weighing the used filters and calculating the results after collecting the filters from the field. Whatman's No. 2 filters, 32 centimeters in diameter, were used. The filters were folded twice and weighed to the nearest centigram on a balance of high accuracy. It was found that the weight of the filters varied with the amount of moisture in the atmosphere, that they were not uniform in weight, and that the heavier papers absorbed the most moisture. Most weighed 6 or 7 grams, but some 4 and 10 grams. From each bunch of papers, two papers of extreme weight (one heavy, the other light) were selected, weighed, and their average weights used as checks in making corrections for effect of moisture. Each couple of check papers were marked with their weights and numbers 1 and 2, 3 and 4, etc. The date of weighing was recorded on the filters and the numbers of the check papers on the envelopes. One set of check papers was a month's supply of filters at all the stations. After collecting the used filters from the field the number of the station and date of the sample were marked on each. About 75 filters were all that could be handled advantageously at one time, and these were chosen so that only one set of check papers would be weighed with them. All were dried in an electric oven at 110° C. for one hour. The temperature of the oven was governed automatically. After the papers had been spread out in a desiccator and cooled for 30 minutes, they were weighed, and the final weights were recorded on the filters below the original weights. A curve was plotted with weights of the two check papers against the differences in weights, from which the correction for any given weight of filter was read at once.

This greatly facilitated the making of the corrections. The essential data for each filter were recorded on a card, and the cards were filed in chronological order by stations.

The monthly average percentages are given in Table 17. For the 12-month period from July 1, 1917, to June 30, 1918, the suspended silt in the Colorado River at Yuma averaged 0.39 per cent, while the average in the Alamo Canal at Hanlon heading was 0.26 per cent, or about 67 per cent of that in the river. These figures, if considered with those for 1914, account for the large quantity of silt entering the Imperial canal system in 1914, as compared with that which entered from July 1, 1917, to June 30, 1918. However, before any definite conclusions are based on this comparison the fact should be considered that during 1918 a channel about 6,000 feet long and several hundred feet wide was built to connect the new Rockwood heading with Hanlon gate. This reduced the velocity above Hanlon heading materially, and undoubtedly some of the suspended silt became bed silt before reaching this sampling station.

Samples obtained at station 2, farther down the Alamo Canal, may be more representative of suspended silt entering the system. The average for the 12-month period at this point was 0.35 per cent, or 90 per cent of the silt in the river at Yuma, this being the same ratio found in 1914.

Table 17.—*Average monthly proportions of suspended silt by weight at sampling stations on Imperial Valley canals, July, 1917, to June, 1918, inclusive*

Station				July	August	September	October	November	December	January	February	March	April	May	June	Mean
No.	Distance from river	Canal	Location													
	Miles			*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*
1	1	Alamo	Hanlon heading	0.232	0.574	0.145	0.371	0.111	0.080	0.088	0.083	0.609	0.286	0.266	0.267	0.259
2	27	do	Cudahy check	.363	.680	.406	.409	.128	.155	.131	.139	.664	.405	.402	.365	.354
3	35	do	Alamo Mocho	.237	.622	.279	.377	.146	.124	.114	.118	.594	.375	.372	.310	.306
4	41	do	Lawrence heading	.260	.692	.357	.363	.185	.239	.119	.123	.531	.355	.293	.276	.316
5	48	East side main	Check No. 1	.175	.605	.352	.315	.112	.121	.139	.153	.697	.356	.319	.299	.304
6	71	do	Myrtle check	.188	.679	.336	.360	.149	.099	.140	.162	.651	.381	.318	.287	.313
7	86	do	Junction lateral	.237	.598	.262	.325	.121	.091	.132	------	.551	.231	.336	.312	.291
8	52	Central	Ten-foot drop	.273	.676	.344	.417	.147	.083	.100	.125	.629	.436	.305	.310	.320
9	50	Dahlia	Heading	.323	.667	.427	.420	.141	.116	.123	.151	.635	.547	.486	.479	.376
10	69	do	Lateral No. 12	.276	.623	.351	.401	.114	.100	.090	.081	.473	.338	.270	.168	.274
11	76	Brawley main	No. 4 delivery	.273	.657	.415	.281	.137	.075	.095	.111	.618	.433	.342	.343	.315
12	56	West side main	Wisteria check	.112	.120	.165	.105	.029	.075	.128	.038	.200	.340	.247	.132	.141
13	[1] 65	do	International boundary	.181	.119	.186	.162	.052	.054	.081	.060	.204	.291	.213	.172	.148
14	[1] 91	do	No. 8 delivery	.231	.175	.221	.244	.157	.095	.085	.146	.205	.258	.145	.130	.175
15	[1] 104	Trifolium	No. 6 heading	.282	.408	.259	.225	.097	.069	.070	.115	.230	.296	.277	.203	.211
16	53	No. 5 main	Imperial Water Co. No. 5 delivery.	.264	.570	.295	.312	.114	.087	.111	.138	.806	.307	.302	.317	.312
17	60	Rositas	Heading	.302	.515	.335	.567	.229	.224	.189	.188	.682	.408	.476	.411	.377
18	83	North end	do	.355	.350	.404	.854	.362	------	------	.266	.393	.466	.601	.486	------

[1] Twelve miles farther, via Cerro Prieto Canal.

By referring to Table 17 and to Figure 7, it will be seen that the stations cover the main canals of the Imperial Valley system. Stations 1, 2, 3, and 4 are on the Alamo Canal, through which all the water for the valley flows. Station 1 is near the intake, while stations 2, 3, and 4 are in Mexico. Before entering the United States, the water is divided so as to cover the eastern, central, and western portions of the valley. Stations 5, 6, and 7 are on east side main canal and the distance of station 7 from the intake is about 86 miles. Stations 8, 9, 10, and 11 are on the central main system, station 11 being about 76 miles from the intake. Stations 12, 13, 14, and 15 are on the west side canal system, and station 15 is about 104 miles from the intake.

For portions of the season the west side canal received water by the way of Volcano Lake, and this accounts in some instances for the lower percentage of silt found in this portion of the system. Stations 17 and 18 obtain water diverted from the Alamo River; hence they are not directly comparable with other stations.

The percentages of silt appearing in Table 17 for the other 17 stations on the system below station 1 show amounts varying both above and below this station, and in general they show no appreciable reduction, thereby indicating that while great quantities of silt are annually removed from the canals by mechanical means, the amount deposited in them is a very small portion of the total amount carried in suspension, and that most of the suspended silt entering the canals passes on to the irrigated lands. Frequently a lower station shows an increase in percentage over an upper station, indicating scouring instead of deposition, the influence of dredging, or possibly that diversions to laterals take the clearer water at the top of the trunk canal, leaving undiverted the more heavily silt-laden water at the bottom. This may be the result also of evaporation or seepage losses.

These facts may be more clearly illustrated by tracing the percentage of silt in different portions of the valley for July, 1917. Starting at station 1, at the intake, there is 0.232 per cent. A maximum percentage of 0.363 for the month appears at station 2 which is 27 miles farther down on the Alamo Canal. Station 7, at the lower end of the east side main canal, 86 miles from the intake, has 0.237 per cent of silt. Following down the central main canal, a percentage of 0.273 is found at station 11, near the lower end, which is 76 miles from source; while at station 15, the lower end of the west side main canal, the percentage is 0.282. December's record indicates that although the percentage of suspended silt entering the system at station 1 was small, enough scouring occurred before station 2 was reached to increase the amount of silt about 94 per cent; then the load varied throughout the lower stations, depending mainly on whether the channels were scouring or silting.

AMOUNT OF SILT CARRIED TO IRRIGATED LANDS

By far the greater part of the total silt in suspension in the irrigation canals of Imperial Valley is fine material that passes the 300-mesh sieve, which is the finest screen obtainable. The silt is finer than Portland cement. In all cases this material was found to be equally distributed throughout the vertical section for all velocities under which tests were made, including mean velocities of less than two-thirds foot per second in small ditches. In other words, any velocity that is practical for an irrigation canal will carry in suspension the greater part of the silt transported by the waters of Colorado River, and most of it, therefore, passes on to the irrigated land. The amount of suspended silt deposited in the canals is a very small proportion of the total amount in suspension, notwithstanding the fact that large quantities of bed silt are removed each year.

The manner in which the silt is distributed on the land depends upon the kind of crops, the method of irrigation, and the slope of the field. If the grade is fairly flat, a large portion will be deposited near the point of diversion from the supply ditch or on the upper part of the field, while on the steeper slopes it will be distributed more uniformly.

Station 10, mentioned in Table 17, was on one of the smaller laterals. Tests indicated that about 90 per cent of the silt carried in suspension reached the fields irrigated. On the average, this would amount to about 0.25 per cent of silt by weight at this station for the year. At this rate an acre-foot of water applied would carry 3.4 tons of dry silt to the land.

It is difficult to calculate the depth of silt deposited on an irrigated field, as in most cases the distribution is not uniform and the weight of dry silt in a cubic foot of deposited sediment varies considerably. Samples carefully taken indicated that 1 cubic foot of silt deposit, still moist but dry enough to crack, contained 46 pounds of dry silt. On this basis and assuming 3 acre-feet of water per acre containing 0.274 per cent of silt, as at station 10, Table 17, applied per year, about one-eighth (0.122) inch of moist silt would be deposited uniformly over a field.

In the latter part of September, 1916, tests were made to determine the amount and distribution of silt carried to the land by one irrigation. Four typical tracts were selected in various parts of the valley. Samples of water were taken at the upper, middle, and lower ends of the flooded borders. The percentage of silt by volume was obtained by shaking the sample well, placing it in a glass tube 100 centimeters long and 2 centimeters in diameter, and allowing it to settle 68 days.

Tract 1 was 2 miles south of El Centro. The irrigation border was 1,000 feet long. The percentage of silt at the upper end was 2.7, at the middle 1.5, and at the lower end 0.55.

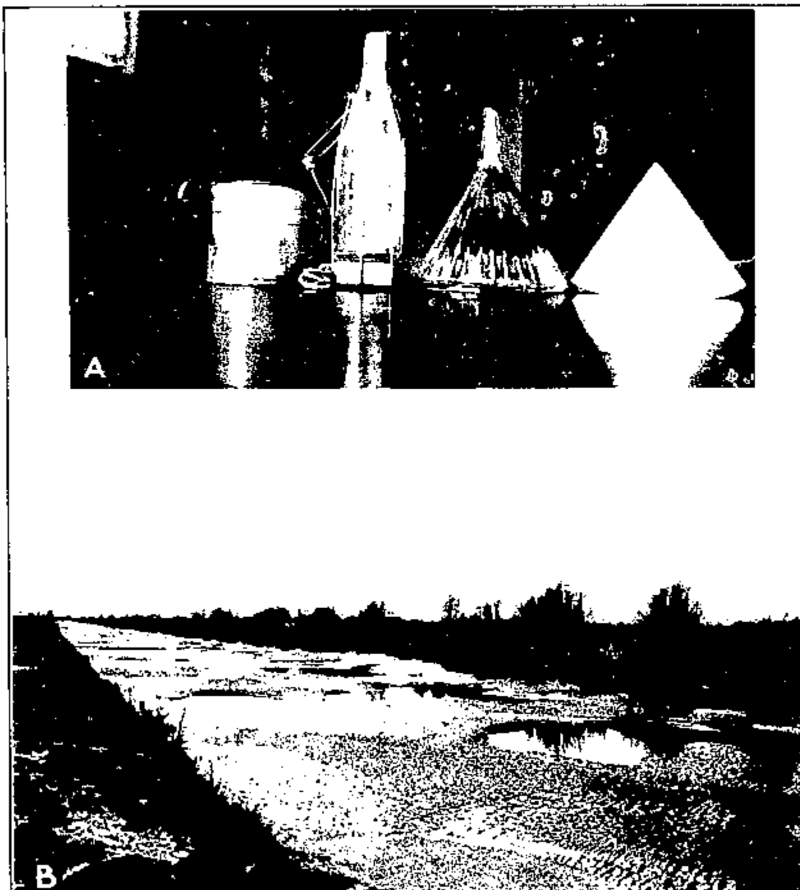
Tract 2 was at Bonds Corner, in the southeast portion of the district. The border was 4,290 feet long and had a slope of about 8 feet to the mile. The percentage of silt by volume at the upper end was 3.45, at the middle 2.6, and at the lower end 2.25.

Tract 3 was near Meloland. The border tested had a length of 1,080 feet. At the upper end the percentage of silt by volume was 5.35, at the quarter point 4.8, at the middle 4.5, and at the lower end 4.

Tract 4 was situated several miles west of El Centro. The border had a length of 1,320 feet. The percentage of silt by volume at the upper end of the border was 2, at the middle 1, and at the lower end 0.4.

Although all the samples were taken within a few days of each other, there is a wide variation in the percentage of silt carried to the lands. This is because the water, in some instances, was diverted

PLATE 2



A.—Apparatus used in taking silt samples, 1917–18
B.—View of east side main canal, showing bed silt

from small laterals at some distance from the main canal, and the slower velocities had permitted some of the silt to deposit before it could reach the land.

A greater portion of the silt was found at the upper ends of the borders in tracts 1 and 4 than in tracts 2 and 3. This difference was caused by the flatter slopes of tracts 1 and 4, and the retarding action of the crops, which slowed down the velocity and caused the silt to deposit more rapidly.

Assuming that the amount of silt found in the water at the various points in the fields settles there with the same volumes as indicated in the glass tubes, the depth of deposit in inches is shown in Table 18 for a 4-inch irrigation and for a 3-acre-foot average annual use of water.

TABLE 18.—*Depth of wet silt deposited by irrigation water at three points of a field*

Tract No.	Single irrigation			Total for year		
	Upper end	Middle	Lower end	Upper end	Middle	Lower end
	Inch	*Inch*	*Inch*	*Inches*	*Inches*	*Inches*
1	0.11	0.06	0.02	0.97	0.54	0.20
2	.14	.10	.09	1.24	.94	.81
3	.21	.18	.16	1.93	1.62	1.44
4	.08	.04	.02	.72	.36	.14

MOVEMENT OF BED SILT

In order to determine the character of silt in canal beds both at the head of the main canal and in the lower reaches of the system, samples of bottom deposits were taken and analyzed by J. E. Peck. The results are given in Table 19.

TABLE 19.—*Mechanical analyses of material deposited on Imperial Canal bottoms*

Distance from river	Location	Date	Dry weight per cubic foot	Specific gravity	Proportion of silt passing and retained on sieve with specified number of meshes per inch						
					Passing 10, retained on 20	Passing 20, retained on 40	Passing 40, retained on 60	Passing 60, retained on 80	Passing 80, retained on 100	Passing 100, retained on 200	Passing 200
Miles		1917	*Lbs.*		*Per ct.*	*Per ct.*	*Per ct.*	*Per ct.*	*Per ct.*	*Per ct.*	*Per ct.*
1	Hanlon heading, Alamo Canal	Mar. 14	--------	2.719	0.00	0.05	1.22	33.07	23.50	34.41	7.71
		May 1	102.77	2.695	.00	.26	5.03	48.59	16.90	17.07	12.15
		July 15	--------	2.654	18.09	20.88	33.13	20.58	1.34	4.26	1.72
48	Check No. 1, East Side Canal	July 16	103.26	-------	.00	.60	.90	3.30	20.00	50.50	24.70
71	Myrtle check, East Side Canal	July 18	101.70	2.641	.00	3.10	8.50	40.50	22.10	16.50	9.30
86	Junction lateral, East Side Canal	July 19	99.02	2.619	.00	.00	2.20	9.10	4.10	23.00	61.60
59	Heading, Dahlia Canal	July 16	--------	2.802	.00	.00	.30	.00	.50	54.80	44.40
69	Lateral No. 12, Dahlia Canal	July 17	93.22	2.631	.50	.35	.00	.20	.65	78.30	20.00
76	No. 4 delivery, Brawley main	do	--------	2.670	.00	.00	1.60	4.80	12.70	50.10	30.80
104	No. 6 heading, Trifolium Canal	July 19	--------	2.651	.00	.00	.70	4.70	7.70	60.90	26.00
53	No. 5 heading, No. 5 main	July 17	102.13	2.660	.00	.00	.00	11.10	44.90	32.50	11.50

As shown by mechanical analysis, the character of the bed silt as regards size of particles, in the bed of the Alamo Canal, varies with the discharge of the Colorado River. Thus, during February and

March, 1917, the mean flow of the river was 9,065 second-feet, and the sieve analysis for March 14 of that year showed only 0.05 per cent of the recently deposited silt in the bed of the Alamo Canal coarse enough to be retained on a No. 40 sieve, very little on a No. 60 sieve, and 42.1 per cent passing a No. 100 sieve. On July 15, 1917, 11 days after the passing of the peak of the spring flood carrying 143,000 second-feet, the recent deposits in the bed of Alamo Canal were much coarser in grain. At that time 18.1 per cent was retained on a No. 20 sieve, 20.9 per cent passed the No. 20 but was retained on the No. 40 sieve, 33.1 per cent passed the No. 40 and was retained on the No. 60 sieve, while 7.3 per cent passed a No. 80 sieve. These results indicate that bed silt is transported and that the high waters bring in most of the heavier silt.

Some appreciable time would, of course, be necessary for the heavier silt to travel down to the lower reaches of the canal system. If this fact is kept in mind and the July 15 analysis of the Hanlon heading samples is disregarded, no great difference will be apparent between the character of the bed silt near the intake and that in the lower parts of the system.

TRANSPORTATION OF SILT

It is obvious that much of the coarser inorganic material, usually termed "débris," eroded during flood periods and carried by water into the main and tributary channels of the Colorado River, differs from the silt present in its lower reaches. The coarse sand, gravel, cobbles, and bowlders contained in such débris undergo a long-continued grinding process in their passage through the canyons of the lower tributaries and the main river. This natural rock-grinding mill is so efficient that the texture of only a small proportion of the output is large enough to be classified as medium sand.

It is equally obvious that the greater part of the fine sediment eroded by melting snow and rain and carried into the river system by spring floods and summer rains undergoes little change in the course of its passage to the Gulf of California.

Since this report deals mainly with silt in the lower basin of the river, only meager data have been given to indicate the character and quantity of débris transported by the various tributaries. Each has its peculiar débris problem, which should be treated separately. The building of storage reservoirs and the more complete utilization of the waters of a tributary stream for irrigation, power, and other purposes will necessitate thorough studies of this nature to prevent mistakes in planning such development.

The suspended silt in the Colorado River as it flowed past Topock, Ariz., was somewhat arbitrarily divided into two grades as to fineness of particles. That which passed through a sieve of 200 meshes to the inch was regarded as the finer silt and that retained on this sieve the coarser. More than half the total load of suspended silt at Topock was of the finer grade. This classification was also adopted in many other silt measurements, although occasionally when necessity arose for a more complete grading, other standard sieves were used.

Repeated efforts were made to coordinate the movement of silt in the lower Colorado River and in diverting channels with the laws and formula held to be applicable to the movement of silt in other streams, but while there was agreement in some features there was disagreement in others, so that on the whole few satisfactory conclusions could be drawn, largely because of the character of the silt and the chemical activity of certain salts in the waters of the river. The preponderance of fine silt held in suspension, and the fact that in its movement downward or parallel to the grade of the channel it seems to obey physical laws different from those governing bed silt, led to the conclusion that any formula applicable to one kind would not apply to the other. Furthermore, it is not generally feasible to apply two sets of laws or formulas to the same portion of a channel, since silt suspended at one time and place may become bed silt elsewhere at another time. Conversely, more or less bed silt may become suspended silt.

It was not difficult to trace the relation between the movement of the finer silt and the velocity of the current. All velocities in excess of about two-thirds foot per second transported the finer silt, not only in the river but also in the canals. The chief difficulty arose in determining the velocities and other hydraulic elements that would cause the transportation of bed silt and the heavier grade of suspended silt.

KENNEDY'S SILT THEORY

One of the best-known and most widely used formulas in foreign countries for calculating the transportation of silt is that developed by R. G. Kennedy while executive engineer, superintending engineer, and chief engineer of the irrigation branch of the public works department of the government of the Punjab, India. Mr. Kennedy's investigations of silt in Indian rivers and canals began in 1890 and continued for some 16 years. The results were published from time to time in both India and Great Britain (*13*). In Hydraulic Diagrams (second edition), he says:

> If the bed sand of any canal system is analyzed, it is found that it becomes finer and finer as one goes down the canal, near the head being coarser than that in the river, and in the lower reaches much finer, at any rate in the low supply season, when the clear water has been at work picking up the canal bed sand left in the flood season, and carrying it forward at varying rates. The same action is found to take place in rivers, the sand on the bed of the river near the hills being much coarser than well out on the plains, and still more so compared with that near the delta.
>
> The finer grades of sand enter the canal in the flood season in such immense quantities, that annual clearances of branches and distributaries would be impossible, because of the long closures necessary, and the cost; and it therefore becomes essential to grade all channels so as to carry this sand down to and into the water-courses, from which it can be easily cleared out by the cultivators themselves, at such seasons and during the closure rotations which are most convenient to themselves. The purpose of the silt data here given is therefore to obtain this desideratum, viz, that each channel shall be so designed as to its section and slope, that it shall be able to carry forward its full quota of sand silt, without either deposit or erosion.

Between 1890 and 1894 experiments were made on 30 channels varying in bed width from 8 to 91 feet and in depth from 2.2 to 7.3 feet, to determine the mean velocities necessary for channels of various sections and discharges so that each should carry its full share of sand-silt, that is, be fully charged. All of the channels selected were in permanent regimen and varied from 26 to 1,700 second-feet in capacity. Their beds were self-silted and each had the option of picking up more sand from the bed or dropping the overcharge. On each was observed the bed width, depth, and mean velocity, and on tabulating these it was seen that the width had no effect on the velocity, but that the depth had. Hence, depth and mean velocity were plotted as coordinates, and the resulting relation was found to be

$$V_o = 0.84\ d^{0.64}$$

where V_o is the critical or nonsilting mean velocity in feet per second, and d is the depth in feet. The general equation for Kennedy's formula is

$$V_o = Cd^m$$

where C increases from a value of 0.82 for light sandy silt to more than 1 for coarse silt, and m decreases in value with an increase in the size of the particles.

Kennedy's formula expressed in metric units becomes

$$V_o = 0.55\ d^{0.64}$$

The engineers who investigated the silt problem in the waters of the Nile River in Egypt modified Kennedy's formula so that it became in metric units

$$V_o = 0.36\ d^{0.64}$$

At a still later period when the formula was applied to the silt-laden streams of Siam, the modification adopted was

$$V_o = 0.35\ d^{0.66}$$

In the earlier silt investigations of Imperial Valley, experiments were conducted from time to time with the object of applying Kennedy's formula to the canals of the valley. These were not successful, and the officials in charge suffered keen disappointment over their failure. The silt problem of the valley is now better understood, and without seeking to disparage the excellent work done by Kennedy and of the value to the world of his silt theory, truthfully it can be stated that it is of no practical value to the farmers and canal operators of Imperial Valley. Kennedy's purpose was to transport the entire silt load through the canal system and dump it into the field ditches and on the fields of the Hindu farmers. The farmers of Imperial Valley not only own the irrigated land, but they also own, maintain, and operate the canal system. They have learned from costly experience that it is much cheaper and easier to dispose of as much as possible of the inflowing load of silt at or near the intake than to take care of it after it reaches the farms. Silt at the intake of the main canal can be removed by means of a suction dredge; silt in the main canal by a drag-line dredge; and silt in the secondary canals and laterals by an ordinary dredge, at a lower cost to the water users than is required to dispose of like quantities in farm ditches and on cropped lands. In other words, the landowners of Imperial Valley are seeking relief from the present burdensome silt nuisance in a manner directly opposed to that recommended by Kennedy to the Government of the Punjab for the canals of that territory.

From the data at hand it is believed that the character of the silt in some of the Colorado's tributaries bears a closer resemblance to that present in some of the rivers of India than that in the lower reaches of the Colorado, and the purpose and essential elements of Kennedy's theory are here given so that it may not be overlooked in future investigations on other parts of the river system.

THE SILT LOAD IN IMPERIAL VALLEY CANALS

Experiments indicate that the flowing water in all the main and secondary canals of the Imperial Valley have sufficient velocity to keep in suspension the finer silt or that which passes a 200-mesh sieve, and that the distribution of this part of the silt load is practically uniform over the system and in any canal section. The usual percentage by weight of this suspended load varies from 0.05 to 1 per cent and depends primarily on the quantity of this kind of silt entering the canal system. It has been shown, under the heading Silt Investigations in Imperial Valley (pp. 29 to 42), that for two years the proportion of suspended silt in the main canal was 90 per cent of the suspended silt content found in the Colorado River at Yuma. Assuming that this ratio holds true over a period of years and that a cubic foot of suspended silt contains 62½ pounds of dry material, Table 20 has been prepared to show the annual load of suspended silt entering the Imperial Valley Canal system from 1912 to 1925, inclusive.

TABLE 20.—*Estimated suspended silt load entering Imperial Valley Canal system 1912 to 1925, inclusive*

Year	Total water diverted at Imperial heading from Colorado River	Proportion of silt by weight (estimated)	Suspended silt	Year	Total water diverted at Imperial heading from Colorado River	Proportion of silt by weight (estimated)	Suspended silt
	Acre-feet	*Per cent*	*Acre-feet*		*Acre-feet*	*Per cent*	*Acre-feet*
1912	1,433,800	0.60	8,600	1920	3,006,000	0.70	21,700
1913	1,607,300	.62	10,300	1921	2,535,000	.63	16,000
1914	1,863,500	.90	16,800	1922	2,800,300	.64	18,500
1915	1,912,900	.84	16,100	1923	3,275,400	.86	28,200
1916	2,230,200	1.06	23,700	1924	3,078,300	.57	17,500
1917	2,412,500	.44	10,600	1925	3,158,700	.77	24,300
1918	2,876,800	.46	13,200				
1919	2,854,200	.78	22,300	Mean			17,700

The results show that the maximum suspended load during the period was 28,200 acre-feet, the minimum 8,600 acre-feet, and the average 17,700 acre-feet. Silt measurements at various stations during 1907–08 ,1914, and 1917–18 show that the suspended silt content of the water is about the same throughout the main canal system. Thus, very little of the suspended silt load is deposited in the main canals but passes on to the secondary canals, irrigated land, and wasteways. The water reaching the irrigated lands contains about 85 per cent of its original suspended silt content. In addition to the suspended silt load entering the Imperial Canal intake there is a large quantity of bed silt.

The normal annual silt load in the Colorado River at Yuma is 253,528,000 tons, of which 20 per cent is estimated to be bed silt. It is evident from the character of the material periodically removed from the beds of canals, as determined by mechanical analyses, that the material deposited in the canals is composed chiefly of bed silt or sand, as it is commonly termed. Judging, too, from the large quantities of such material annually removed from the canal system of Imperial Valley, correspondingly large quantities of bed silt must enter the system and be transported in the canals in diminishing quantities as the distance from the intake increases.

To describe bed silt as sand which rolls along the stream bed, would be misleading. It would be more nearly correct to state that bed silt moves down stream in several ways and combinations of ways, one of which is by rolling along the bed. If the paths of individual particles could be traced it would probably appear that few had not at one time been bed silt and at another time suspended silt. As to whether a particle journeys the greater part of the way as bed silt or in a state of suspension depends on its relative size and the velocity of the water near the bed. If the velocity is rapid enough to lift the particle from the bed, it will be carried forward in suspension for a time at least. If the vertical components of the current fail to raise a particle some other mode of transportation is followed. Usually the bed of a channel which is carrying a heavy load of silt assumes the form of a series of steps rising with a gradual slope and dropping on the downstream side with a steeper slope. As the current scours the long upstream slope and deposits the scourings on the steeper downstream slope, each step or wave moves forward in a manner somewhat similar to sand dunes under the action of air currents. When some of these waves reach a certain height, they begin to cut away rapidly on the downward slope and move forward in a mass. The sudden displacement of such masses causes boils and waves in the canal. A view of the east side main canal (pl. 2, B) taken February 28, 1925, shows the choppy appearance of the bed of the canal when bed silt is transported in the manner described.

It follows from what has been stated that the total silt load in a stream or canal may be divided into three general classifications in accordance with the method of transportation of each: (1) The suspended load, (2) the traction load carried by the vertical components of the upward currents rising from the bottom, and (3) the load which is carried along on the bottom by rolling or by short skips, forming either plane beds or dunes. The finer silt is naturally separated and forms the first group, while the heavier and coarser particles of sand form the other two groups. With this classification in mind, it may be stated that with very few exceptions the canals of Imperial Valley are "silting up." Water, with its load of silt, is diverted from the Colorado River, but as its velocity in the river is greater than in the canals, deposition begins at the intake and continues throughout the entire system so long as the velocity is decreasing and there is heavy silt to drop. A canal that is "silting up" is always dropping the largest particles first. With diminishing velocities all the so-called sand may be dropped. On the other hand, if sufficient velocity is maintained to transport some load of sand, and the canal has a self-silted bed, it can either pick up or deposit sand and hence will always be at its capacity for any given velocity. Close observation of the silt in water samples taken from near the surface of canals disclosed that many particles were of odd shapes. Some were smooth and flat, others angular and flat, while still others were light in weight, the lightest being composed of vegetable matter. The size of these particles prevented their passage through a 200-mesh sieve; although since they were carried in suspension they belong to the finer grade, and would have been so classed if the silt had been graded by the method of elutriation instead of sieving.

SOME RELATIONS BETWEEN VELOCITY AND DISTRIBUTION OF SILT IN CANAL CROSS SECTIONS

Many experiments were made on canals of various dimensions and capacities in Imperial Valley with the object of determining for different seasons in 1917 and 1918, the distribution of the two grades of silt (passing and retained on a No. 200 sieve) throughout the canal cross sections, and to throw some light on the relation of the velocity of water and the movement of particles belonging to each grade. The method adopted was to divide each canal at the place of measurement into a number of vertical sections by horizontal stations. From each station samples of water were taken at various depths with the Tait-Binckley sampler (fig. 4), and at each place and time of sampling, current meter measurements were made to determine the velocity of the water, the two operations being carried on by two operators simultaneously. The samples at the lowest depth were taken as close to the bottom as possible, but extreme care was necessary so as not to disturb the bed of the canal. Each sample was separated into two grades—that which passed a No. 200 sieve and that which was retained on it, by methods previously described. Then the percentage by weight of dry silt was determined. Many tests were made, but only the data obtained from each of four typical canals appear in Tables 21 to 24, inclusive.

TABLE 21.—*Distribution of silt in cross section of Central main canal at a point west of the Southern Pacific Railroad crossing, September 11, 1917*

[The canal is 40 feet wide and its middle depth is 5 feet]

Distance between station and bank	Total depth	Depth to sample	Velocity	Proportion of silt by weight		
				Sieve No. 200		Total
				Passing	Retained	
Feet	*Feet*	*Feet*	*Feet per second*	*Per cent*	*Per cent*	*Per cent*
0	3.8					
2	4.4	0.5	1.54	0.180	0.013	0.193
		2.0	1.30	.174	.030	.204
		3.5	1.44	.165	.027	.192
		4.3	.66	.157	.039	.196
6	5.3	0.5	2.57	.181	.022	.203
		2.0	2.81	.186	.054	.240
		3.5	2.27	.184	.059	.243
		5.0	1.79	.170	.106	.276
10	5.8	.5	3.01	.185	.016	.201
		2.0	3.30	.127	.086	.213
		3.5	3.11	.190	.065	.255
		5.0	3.01	.186	.137	.323
14	5.1	.5	3.50	.173	.017	.190
		2.0	3.65	.188	.028	.216
		3.5	3.35	.175	.080	.255
		5.0	2.67	.194	.205	.399
18	5.0	.5	3.65	.174	.079	.253
		2.0	3.70	.159	(1)	(1)
		3.5	3.26	.169	.071	.240
		4.9	2.28	.207	(1)	(1)
22	4.7	.5	3.55	.170	.026	.196
		2.0	3.60	.173	.130	.303
		3.5	3.21	.169	.086	.255
		4.6	2.38	.202	.239	.441
26	4.8	.5	3.35	.165	.018	.183
		2.0	3.50	.174	.035	.209
		3.5	3.16	.181	.085	.266
		4.7	2.19	.202	.529	.731
30	4.8	.5	2.82	.169	.011	.180
		2.0	3.26	.193	.063	.256
		3.5	3.01	.177	.088	.265
		4.7	2.58	.181	.414	.595
34	5.2	.5	2.63	.164	.061	.225
		2.0	2.92	.179	.053	.232
		3.5	2.48	.156	.143	.299
		5.0	1.90	.137	.176	.313
38	4.4	.5	2.28	.168	.051	.219
		2.0	2.34	.176	.107	.283
		3.5	2.04	.147	.118	.265
		4.3	1.07	.165	.308	.473
40	4.8					

[1] Percentage retained on the 200-mesh sieve not recorded.

TABLE 22.—*Distribution of silt in cross section of Dahlia Canal, 800 feet below heading, September 18, 1917*

[The canal is 15 feet wide, 1.2 feet deep at the center, and has a gradient of 0.63 feet per 1,000 feet]

Distance between station and bank	Total depth	Depth to sample	Velocity	Proportion of silt by weight: Sieve No. 200, Passing	Proportion of silt by weight: Sieve No. 200, Retained	Proportion of silt by weight: Total
Feet	*Feet*	*Feet*	*Feet per second*	*Per cent*	*Per cent*	*Per cent*
0	1.5					
1.5	1.6	0.2	1.84	0.069	0.011	0.080
		.96	1.30	.082	.053	.135
		1.40	1.05	.089	.211	.300
4.5	1.2	.20	1.74	.081	.013	.094
		.72	1.98	.093	.133	.226
		1.00	1.54	.089	.500	.589
7.5	1.2	.20	2.13	.088	.015	.103
		.72	2.06	.098	.091	.189
		1.00	1.59	.123	.728	.851
10.5	1.2	.20	1.64	.069	.007	.076
		.72	1.98	.105	.111	.216
		1.00	1.69	.093	.402	.495
13.5	1.0	.20	1.44	.080	.012	.092
		.60	1.49	.081	.045	.126
		.80	1.34	.094	.308	.402
15	1.0					

TABLE 23.—*Distribution of silt in cross section of Elder Canal, March 28, 1918*

[The canal is 10 feet wide, 3.5 feet deep at the center, and has a gradient of 0.725 feet per 1,000 feet]

Distance between station and bank	Total depth	Depth to sample	Velocity	Proportion of silt by weight: Sieve No. 200, Passing	Proportion of silt by weight: Sieve No. 200, Retained	Proportion of silt by weight: Total
Feet	*Feet*	*Feet*	*Feet per second*	*Per cent*	*Per cent*	*Per cent*
0	3.0					
1	3.1	0.2	1.70	0.637	0.002	0.639
		1.0	2.96	.648	.002	.650
		2.0	1.99	.652	.003	.655
		2.5	1.82	.651	.003	.654
		2.9	1.16	.657	.005	.662
3	3.4	.2	2.38	.646	.002	.648
		1.0	3.40	.648	.005	.653
		2.0	2.79	.651	.003	.654
		2.5	2.53	.652	.003	.655
		3.2	1.97	.653	.008	.661
5	3.6	.2	2.79	.631	.008	.639
		1.0	3.45	.637	.002	.639
		2.0	3.01	.648	.003	.651
		2.5	2.60	.666	.004	.670
		3.0	2.55	.658	.003	.661
		3.3	2.23	.655	.003	.658
7	3.3	.2	2.86	(1)	.002	(1)
		1.0	3.50	.644	.004	.648
		2.0	3.03	.651	.002	.653
		2.5	2.67	.680	.002	.682
		3.1	1.99	.641	.002	.643
9	3.1	.2	2.21	.661	.003	.664
		1.0	3.10	.655	.003	.658
		2.0	2.70	.666	.002	.668
		2.5	2.18	.653	.002	.655
		2.9	1.43	.659	.003	.662
10	2.9					

[1] Percentage passing 200-mesh sieve not recorded.

TABLE 24.—*Distribution of silt in cross section of Rositas Canal, 150 feet below heading, March 29, 1918*

[The canal is 22.5 feet wide, 2.2 feet deep at the center, and has a gradient of 0.4 feet per 1,000 feet]

Distance between station and bank	Total depth	Depth to sample	Velocity	Proportion of silt by weight		
				Sieve No. 200		Total
				Passing	Retained	
Feet	*Feet*	*Feet*	*Feet per second*	*Per cent*	*Per cent*	*Per cent*
0	1.5					
2.25	3.2	0.2	1.58	0.589	0.002	0.591
		1.0	1.53	.586	.012	.598
		1.5	.99	.589	.011	.600
		2.0	.75	.591	.047	.638
6.75	2.5	.2	1.75	.573	.006	.579
		1.0	2.18	.589	.006	.595
		1.5	1.84	.573	.018	.591
		2.0	1.60	.584	.028	.612
		2.3	1.11	.577	.322	.899
11.25	2.2	.2	1.84	.575	.005	.580
		1.0	2.30	.578	.008	.586
		1.5	2.01	.579	.015	.594
		2.0	1.50	.568	(1)	(1)
15.76	2.2	.2	1.89	.565	.001	.566
		1.0	2.35	.574	.003	.577
		1.5	2.16	.580	.008	.588
		2.0	1.53	.571	.061	.632
20.25	2.2	.2	1.55	.573	.002	.575
		1.0	2.25	.576	.004	.580
		1.5	1.94	.576	.006	.582
		2.0	1.43	.583	.084	.667
22.50	2.2					

[1] Percentage retained on 200-mesh sieve not recorded.

The results shown in Tables 21 to 24 inclusive indicate that there is very little if any difference in the amount of fine silt (passing No. 200 sieve) at different points along any horizontal in the cross section of a canal and that the amount carried by water at higher velocities at the middle of the stream is not appreciably greater than that carried by the water of slower velocities near the banks at the same elevation. In the upper sections of a canal this is generally true of the total amount of silt carried, which includes the coarser material (that retained on No. 200 sieve). In most cases the fine silt was fairly evenly distributed throughout the entire section considering that on the larger canals several hours were required to take a complete set of samples; but the distribution of coarse silt was quite uneven in any vertical of a stream.

The experiments further indicate that neither the depth nor the velocity in the same canal has an appreciable effect upon the percentage of fine silt carried, once the material is in suspension. On the other hand, the percentage of coarser silt or sand increases as the bottom of the canal is approached. The effect of the velocity, however, is not so apparent.

RELATION OF VELOCITY AND DEPTH TO THE QUANTITY AND SIZE OF SILT TRANSPORTED

Since the experiments to determine the distribution of silt in the cross section of canals indicated that the total percentage of silt carried in any particular vertical of the channel increased with the

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depth, the subsequent experiments were confined to obtaining more data on the vertical distribution and the size of particles. By the use of sieves ranging from 10 to 300 meshes per inch, the silt samples were graded for fineness, but no silt particles were found coarse enough to be retained on a No. 40 sieve. Silt and velocity measurements were made at more points in the vertical than in the previous experiments, and most of the tests were made in the center vertical of the canal. Samples were taken with the Tait-Binckley sampler at depths ranging from the water surface to as near the bottom as was possible, without disturbing the bed of the canal. Many experiments were made. A few of the typical examples are shown in Tables 25 to 28.

TABLE 25.—*Proportion of silt in each of 13 grades at various depths in Briar Canal at Boundary, May 5, 1919*

[Samples were taken from the center vertical, which had a depth of 3.7 feet and a mean velocity of 2.42 feet per second]

Depth at which sample was taken	Proportion of silt by weight passing and retained on sieve with specified number of meshes per inch													
	Passing 60, retained on 80	Passing 80, retained on 100	Passing 100, retained on 120	Passing 120, retained on 140	Passing 140, retained on 160	Passing 160, retained on 180	Passing 180 retained on 200	Passing 200, retained on 220	Passing 220, retained on 240	Passing 240, retained on 260	Passing 260, retained on 280	Passing 280, retained on 300	Passing 300	Total
Feet	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*
Top	0.000	0.001	0.001	0.003	0.003	0.007	0.007	0.003	0.005	0.027	0.013	0.020	0.720	0.810
2.0	.002	.005	.007	.015	.009	.019	.008	.007	.016	.038	.017	.020	.740	.903
2.5	.003	.007	.012	.017	.012	.023	.010	.012	.010	.041	.022	.020	.735	.924
3.0	.005	.010	.015	.027	.014	.026	.012	.008	.004	.046	.020	.025	.740	.952
3.5	.009	.010	.028	.029	.015	.037	.011	.012	.013	.045	.027	.031	.724	.991

TABLE 26.—*Proportion of silt in each of five grades at various depths in the Ash Canal at Boundary, June 25, 1920*

[Samples were taken from the center vertical, which had a depth of 3.2 feet and a mean velocity of 3.22 feet per second. The canal was 20 feet wide and the discharge was 190.7 second-feet]

Depth at which sample was taken	Velocity at point	Proportion of silt, by weight, passing and retained on sieve, with specified number of meshes per inch					
		Passing 40, retained on 60	Passing 60, retained on 100	Passing 100, retained on 200	Passing 200, retained on 300	Passing 300	Total
	Feet per second	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*
Top	3.55	0.000	0.000	0.000	0.028	0.232	0.260
1 foot	4.31	.000	.001	.014	.045	.249	.309
2 feet	4.36	.000	.001	.022	.053	.258	.334
2.5 feet	4.11	.000	.012	.048	.065	.257	.382
3 feet	3.40	.001	.025	.063	.116	.268	.473
3.1 feet	2.77	.005	.061	.064	.100	.273	.503

TABLE 27.—*Proportion of silt of each of five grades at various depths in the Birch Canal one-half mile east of Calexico, Calif., June 30, 1920*

[The samples were taken from the center vertical, which had a depth of 1.8 feet and a mean velocity of 2.21 feet per second. The canal was 5 feet wide, and the discharge was 19.14 second-feet]

Depth at which sample was taken	Velocity at point	Proportion of silt, by weight, passing and retained on sieve, with specified number of meshes per inch					
		Passing 40, retained on 60	Passing 60, retained on 100	Passing 100, retained on 200	Passing 200, retained on 300	Passing 300	Total
	Feet per second	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*
Top	1.393	0	0.000	0.003	0.017	0.334	0.354
0.5 foot	2.177	0	.000	.003	.026	.342	.371
1 foot	2.422	0	.002	.010	.028	.347	.387
1.5 feet	1.981	0	.008	.045	.075	.400	.528
1.7 feet	1.393	0	.096	.134	.099	.414	.743

TABLE 28.—*Proportion of silt in each of five grades at various depths of Alamo Canal near Hanlon heading, July 26, 1920*

[The samples were taken 120 feet from the east bank of the canal, which was 180 feet wide and 10 feet deep and had a discharge of 5,749 second-feet and mean velocity of 4.1 feet per second]

Depth at which sample was taken	Velocity at point	Proportion of silt, by weight, passing and retained on sieve, with specified number of meshes per inch					
		Passing 40, retained on 60	Passing 60, retained on 100	Passing 100, retained on 200	Passing 200, retained on 300	Passing 300	Total
	Feet per second	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*
Top	4.00	0.000	0.005	0.011	0.033	0.298	0.347
2 feet	4.38	.001	.005	.017	.037	.295	.355
3 feet	4.42	.001	.009	.016	.040	.293	.359
4 feet	4.62	.001	.010	.018	.033	.301	.363
5 feet	4.38	.004	.046	.047	.054	.318	.469
6 feet	4.38	.003	.029	.032	.048	.305	.417
7 feet	4.16	.001	.007	.029	.035	.297	.369
8 feet	4.02	.003	.014	.035	.040	.301	.393
8.5 feet		.002	.015	.049	.053	.321	.440
9 feet	4.00	.002	.014	.036	.047	.272	.371
9.5 feet	3.31	.003	.025	.057	.078	.284	.447
9.8 feet		.004	.026	.079	.075	.302	.486

The results in the preceding tables indicate that the percentage of silt in suspension increases from top to bottom, also that the coarser the particles the greater their proportion becomes as the bottom of the channel is approached; the finer they are the more equal their distribution in the vertical. Specific gravity of the silt material as well as degree of fineness influences its distribution, but variation in specific gravity was found to be small. At most ordinary canal velocities material coarse enough to be retained on a No. 60 sieve was confined to approximately the lower tenth of the depth of the water, while that fine enough to pass a No. 100 sieve would, in small percentages, reach to the surface of the water. The greater part of the total amount of silt in suspension in the irrigation canals was fine material that passed the No. 300 sieve. This material was usually found to be fairly equally distributed throughout the vertical for all velocities in which tests were made, including in some instances mean velocities of less than two-thirds foot per second in small laterals. In other words, any velocity that is practical for an irrigation canal will carry in suspension the greater part of the silt transported by the waters of Colorado River. Although it requires very little velocity to transport the silts of the Colorado the material in suspension usually settles rapidly when the water is brought to rest, as in a reservoir, settling basin, or tube. This is undoubtedly greatly influenced by the chemical composition of the water which produces flocculation (*2*).

QUANTITY OF SILT TRANSPORTED BY COLORADO RIVER

From a practical standpoint, the quantity of silt transported is of more importance than the manner in which it is transported. Some of the data previously presented are reviewed in the following paragraphs with the object of forming an approximate estimate of the normal quantity of silt which is transported annually into the lower basin of the Colorado River, and a like estimate of the normal quantity of bed silt annually transported in the river at Yuma.

It will be recalled that the quantity of suspended silt during a 12-month period ended July 31, 1918 (see Table 12), in the river at Topock was, in round numbers, 205,763,000 tons. During the same period the quantity of suspended silt in the river at Yuma, 206 miles downstream, was 113,943,000 tons. The methods used in taking the samples and determining the silt content were practically the same at both points. The diversions for irrigation during the period about equal the quantities of inflow water derived from the Williams River, Gila River, and other sources. The flow of the river at Topock was 1,716,000 acre-feet more than at Yuma. While a small part of this difference may be due to evaporation, it is believed the major part is due to infiltration in the porous material forming the bed of the channel and flood plain. That this condition is not confined to the period under consideration is shown by the fact that the average annual flow of the river at Topock for eight years ended September 30, 1925, is 1,269,000 acre-feet more than at Yuma. It is likewise true that the greater silt load found at Topock can not be accounted for in any large measure by the greater discharge.

At first glance, one would be led to conclude that the normal silt load in the Colorado River at Yuma, including suspended and bed silt, would be greater than it is at Topock, inasmuch as the Gila River dumps its load into the main channel a few miles above Yuma and desilting processes are applied to most of the water diverted into the canals above Yuma. On the other hand, reasoning from the data available, it would appear that the greater load of suspended silt found at Topock can be rightly attributed to the steeper grades, higher velocities, and churning effects of the canyon section, and that after the river emerges from deep-walled canyons and flows on flatter grades with much less disturbance, the heavier silt is temporarily deposited and transported as bed silt or rests on the bed of the channel until a flood carries it farther downstream.

Judging from the manner in which silt is transported by water in motion, it is believed that some bed silt in addition to suspended silt is carried past Topock, but with the data at hand there is no means of ascertaining its relative quantity. There is also known to be permanent silt deposition between Topock and the mouth of the Gila River, but the quantity can not be computed. If these two unknown quantities were equal, they would counterbalance each other, and the total load of suspended silt at Topock would be approximately equal to the total load of suspended and bed silt at the mouth of the Gila River.

The Gila River contributes about 6 per cent of the normal flow of the Colorado River, and the results of silt measurements show that it carries about double the percentage of silt in the main river at Yuma. Accordingly, there would be about 12 per cent less silt in the Colorado immediately above its junction with the Gila than at Yuma. Reducing the normal suspended silt load of 183,759,000 tons at Yuma by this amount gives 161,708,000 tons as the normal load of suspended silt exclusive of that contributed by the Gila River.

Furthermore, since the quantity of suspended silt in the river during the period under consideration was below normal, it is necessary to increase the quantity of silt found at Topock during the period August 1, 1917, to July 31, 1918, from 205,763,000 tons a year to 253,628,000 tons a year, to bring it to normal.

Comparing this load with that at Yuma exclusive of the Gila would indicate that 36 per cent of the silt load at Topock either passed Yuma as bed silt or was temporarily deposited in the river channel or flood plains above Yuma.

The estimate just set out eliminates from consideration the silt carried by Gila River for the reason that the Gila's silt will not contribute to the sedimentation of any reservoir built above Topock, which is the matter of principal concern in the present discussion.

No practical method was found for measuring the total amount of bed silt moving in the river channel, but minimum and maximum cross sections at Yuma gauging station shown in Figure 8 indicated a scour of about 1,600 acre-feet per mile during the flood of 1916. Further indications that large quantities of bed silt are shifting is shown (fig. 6) by the rise and fall of the river bed at Yuma. The All-American Canal Board (*1*) estimated that there were 12,000 acre-feet of bed silt in a total silt load of 102,000 acre-feet at Yuma or about 12 per cent bed silt. This was based on movement of bed silt in Imperial Valley main canal. Silt measurements at Topock from August, 1917, to June, 1918, inclusive, show that 37 per cent of the suspended silt was coarser than a No. 100 sieve, and because of the decreased relative quantity of this grade of suspended silt found at Yuma it is believed that more than one-half passes the latter point as bed silt.

A consideration of all the available data on this subject leads to the general conclusion that of the total normal load of silt passing Yuma 80 per cent is suspended silt and 20 per cent bed silt.

DESILTING PROCESSES

Desilting the waters of the Colorado River may be said to begin on tributary basins and in tributary streams. The so-called cloudburst, an intensive rainfall covering relatively small areas and usually lasting only an hour or two, is a common occurrence throughout the greater part of the Colorado River Basin. As a result, small streams are suddenly swollen to a high flood stage, and while flowing bankfull at a high velocity, pick up and transport large quantities of débris. However, as a general rule the flood subsides nearly as quickly as it rises, and the débris is deposited to await a similar flood or one of longer duration.

It has likewise been pointed out that the two classes of silt herein considered—suspended silt and bed silt—are to a large extent interchangeable and consequently do not remain constant under changing hydraulic conditions. Where water is confined to narrow, rough channels and flows at a rapid rate, the ratio of suspended silt to bed silt is greatly increased, but when water flows at a low velocity in broad, shallow channels, temporary or permanent desilting results from the dropping of the heavier particles. By this process and under conditions prevalent in the lower basin, the lighter silt is

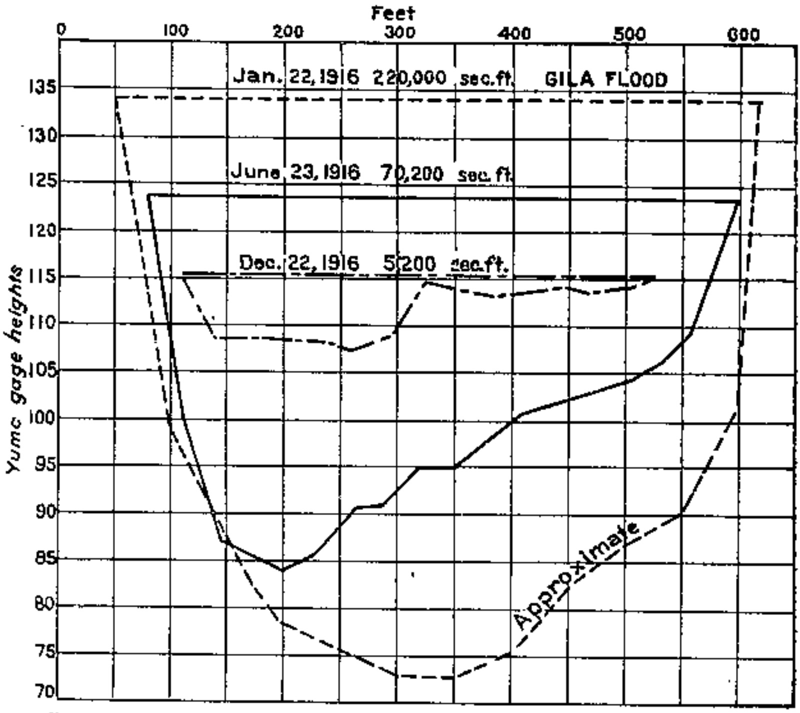


FIG. 8.—Maximum and minimum cross sections. Colorado River at Yuma, Ariz., 1916
(NOTE.—One hundred feet added to gauge heights to avoid minus readings)

separated from the heavier and carried in suspension to the gulf, deposited on irrigated land, or is carried off in wasteways. Of the total load of silt in the waters diverted from the river to supply the needs of Imperial Valley irrigators, exclusive of waste waters, about 85 per cent is deposited on the land irrigated or in farm ditches having less than a mean velocity of two-thirds foot per second.

With the exception of the earlier structures, all the intakes built for the purpose of diverting water from the Colorado River in the lower basin are provided with some kind of desilting equipment designed to prevent the heavier silt from entering and being distributed within the diverting channel. The intakes of Imperial irrigation district are described in another part of this report; those described below are at Potholes, Calif. (Laguna), and near Parker, Ariz.

DESILTING AT POTHOLES, CALIF.

The intake at Potholes, Calif., is located on the Colorado River about 12 miles above Yuma. A diversion weir, known as Laguna Dam, raises the water about 10 feet. It is diverted thence into a canal system which conveys water to the irrigable lands on the California side of the river, crossing the river at Yuma through an inverted siphon, and serving the lands in the Yuma Valley and on the Yuma Mesa below the town of Yuma, which comprise what is known as the Yuma project. This project, one of many Federal irrigation systems built, operated, and maintained by the Bureau of Reclamation under the terms of the reclamation act of June 17, 1902, comprises an irrigable area of about 110,000 acres in Yuma County, Ariz., and Imperial County, Calif. The 95,000 acres of irrigable land on the Arizona side is made up of 50,000 acres of river-bottom lands, protected by levees and supplied by gravity canals, and 45,000 acres of mesa lands, to which water is to be pumped through an average height of 80 feet.

A distinctive feature of the Laguna Dam and its accessories is the effective manner in which the larger and heavier particles of silt are prevented from entering the intake of the project main canal. To accomplish this exclusion the heading on the California side has a sluiceway channel in solid granite rock around the end of the dam, regulated at the downstream end with three Stoney roller gates, and an overflow skimming structure consisting of 35 regulator gates, controlled by means of horizontal flashboards. The sluiceway channel is 128 feet wide at the top, 116 feet at the bottom, and 18 feet deep. At the downstream end it contracts to a rectangular cross section 116 feet wide, which is divided into three sluice-gate openings, each 33 feet 4 inches wide, by two piers 8 feet in width, each opening being regulated by a Stoney roller gate. The channel of the stream extends about 650 feet above the sluiceway.

Generally the sluice gates are closed when water is being supplied to the main canal. The sluiceway channel thus acts as a settling basin, the slow velocities during this period encouraging the deposition of silt. About once a week or every other week, depending upon conditions, the sluice gates are opened so that the deposited material may be scoured out. The flow of water over the canal gates may also be regulated by the sluice gates.

The head gate for the main canal is a simple structure with 35 openings, each 7½ feet in the clear, between concrete piers. (Pl. 3, A.) On these piers rests a concrete footbridge from which the flow of water is regulated by the use of flashboards. The water is skimmed off the top and drops into the canal over these flashboards, so that only a surface stream about a foot deep, which is relatively free from silt, is admitted. Experiments indicate that an average of 50 per cent of the silt is removed from the canal water. This desilting process keeps out of the canal practically all of the bed load of the river, together with the coarser particles of the suspended load.

The capacity of the main canal is about 1,600 second-feet. The full capacity of the California sluiceway is about 15,000 second-feet, or about four times the ordinary low-stage flow of the river, and the sluiceway has a scouring velocity around 10 feet per second. When the sluice gates are closed and the water is entering the main canal the velocity in the settling basin formed in the sluiceway channel is generally less than 1 foot per second, which permits most of the heavier silt to deposit. When the sluice gates (pl. 3, B) are opened the diversion of water into the canal ceases, and the canal is empty for about a day, while the sand and silt which have been deposited in the desilting channel are washed through the sluice gates back into the river below Laguna Dam.

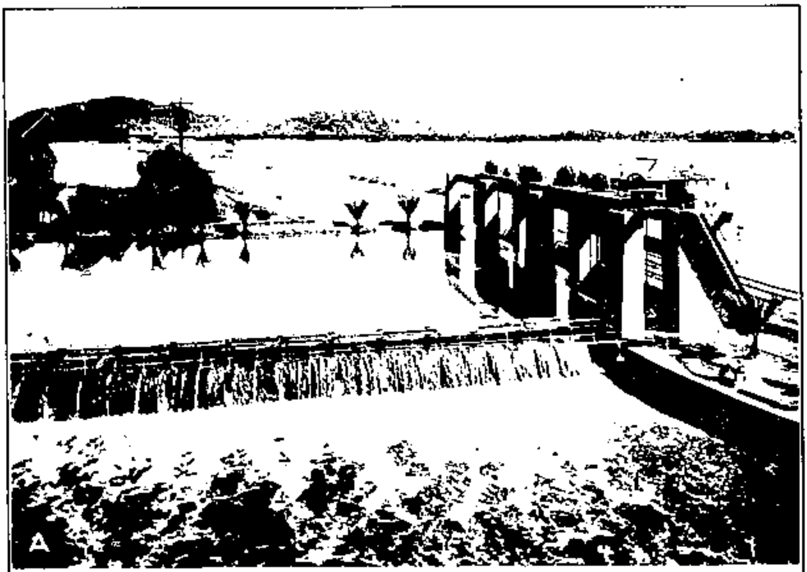
Experiments were carried on to determine the effect of desilting and sluicing at Laguna Dam on the suspended silt and flow of water in the Colorado River at Yuma, 12 miles below. The summarized results are given in Table 29.

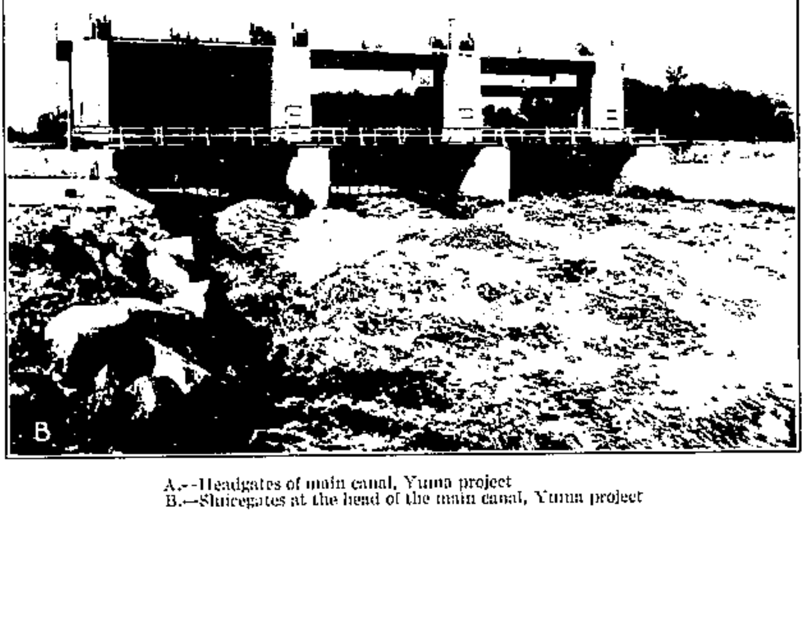
TABLE 29.—*Effect of sluicing at Laguna Dam on silt content and discharge of Colorado River at Yuma, October 7, 1916, to January 13, 1917*

Date	Sluice gates opened at Laguna Dam	Measurements of Colorado River at Yuma				
		Time of measurement	Discharge	Area	Velocity	Proportion of silt by weight
	Hour	*Hour*	*Second-feet*	*Square feet*	*Feet per second*	*Per cent*
Oct. 7, 1916	12 m.	1 p. m.	7,900	2,503	3.16	0.40
		5 p. m.	12,300	2,715	4.53	.67
Nov. 3, 1916	9 a. m.	9.30 a. m.	15,800	2,748	5.75	1.33
		1 p. m.	21,000	3,105	6.77	1.40
		4 p. m.	18,200	2,901	6.27	1.39
Nov. 10, 1916	9 a. m.	9.30 a. m.	13,100	2,375	5.52	.73
		1 p. m.	17,800	2,681	6.64	1.11
		3.30 p. m.	15,300	2,477	6.18	1.22
Jan. 12, 1917	9 p. m.	2 p. m.	6,400	1,542	4.15	.20
Jan. 13, 1917		9 a. m.	8,600	1,606	5.35	.38

These results and observations indicate that sluicing operations at the Potholes intake materially affect both the silt content and discharge of the Colorado River at Yuma. In four hours on October 7, 1916, there was an increase at Yuma of 0.27 in the percentage of silt and 4,400 second-feet in the discharge of the river. In the first three and one-half hours on November 3, 1916, the silt content at Yuma increased 0.07 per cent, while the discharge increased 5,200 second feet. On November 10, the first three and one-half hours of sluicing at Laguna Dam resulted in an increase of silt content at Yuma of 0.38 per cent and an increase in discharge of 4,700 second-feet.

The purpose of another set of experiments was to determine the relationship at any given time of the silt content in the Colorado River above the Laguna Dam and that in the sluiceway, as well as in the intake of the main canal. The percentage of silt at various depths in a vertical section of the Colorado River in midstream above the Laguna Dam is given in Table 30, while Table 31 gives the proportion of silt at each of three sections in the sluiceway—section D, 150 feet above canal intake; section X, at the upper end of the canal intake; and section Y, at gate No. 10 of canal intake.





A.—Headgates of main canal, Yuma project
B.—Sluicegates at the head of the main canal, Yuma project

TABLE 30.—*Proportion of silt in the middle of Colorado River above Laguna Dam, August 2, 1918*

Location	Depth	Proportion of silt, by weight		
		Sieve No. 200		Total
		Passing	Retained	
	Feet	*Per cent*	*Per cent*	*Per cent*
Surface	0	0.438	0.001	0.439
	1.5	.534	.041	.575
	2.0	.664	.133	.797
Bottom	2.6	.647	.270	.917

TABLE 31.—*Proportion of silt, by weight, in sluiceway, Laguna Dam, August 2, 1918*

Section D			Section X			Section Y			
Depth	One-third point	Two-thirds point	One-fourth point	One-half point	Three-fourths point	Depth	West side	Depth	Center
Feet	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Feet*	*Per cent*	*Feet*	*Per cent*
Surface	0.056	0.038	0.048	0.034	0.028	Surface	0.025	Surface	0.024
4	.100	.100	.108	.080	.064	2	.100	3	.052
8	.500	.351	.540	.673	.650	4	.198	6	.212
						6	.615		

While Table 30 shows some silt in the river coarse enough to be retained on a No. 200 sieve, no silt of this grade was found in samples taken in the sluiceway or canal. The heavier silt is doubtless deposited soon after leaving the river and is carried back into the river below the dam during sluicing periods.

The average velocity in the center section of the river at the time of making the tests was about 3.5 feet per second; in the sluiceway, 0.9 foot per second; and in the canal 2.5 feet per second.

The average silt content in the river above the dam was 0.682 per cent, while that in the channel leading from the river to the sluiceway averaged 0.062 per cent at the surface and 0.683 at the 8-foot depth, the measurements in the connecting channel being made about 300 feet above the canal intake.

Samples taken in the main canal below the intake indicated that the percentage of silt throughout the vertical section was more uniform than in the sluiceway. The average was 0.252 per cent, or about 37 per cent of the amount in the river, indicating that about 63 per cent of the silt had been removed from the water.

The percentage of silt carried near the surface of the river is 0.439, 0.062 in the connecting channel and only 0.025 in front of the intake gate. This indicates that the silt is deposited rapidly after leaving the main river channel. Upon reaching the intake gate the surface water has been desilted about 94 per cent. Although water entering the main canal consists of surface water about a foot in depth, the percentage of silt found in the canal is about ten times that in the surface water admitted.

Additional tests indicated that when water was admitted into the head of the main canal of the Yuma project irrigation system by allowing a relatively thin sheet of surface water to flow over the flashboards of the gates, much more silt was found in the canal than was present in the top stratum of water above the flashboards. To find the explanation of the disagreement, a large number of water samples were taken, and a series of tests were made, upon which the following conclusions were based:

(1) Flashboards which can readily be removed and replaced are not silt-tight. Silt passes around the ends and between the edges, especially near the bottom of the gate where the water pressure and silt content are greatest.

(2) Because the silt lodged against the upper side of the flashboards is of the finer grade (passing a No. 200 sieve), upward currents and eddies tend to transport it over the tops of the flashboards.

(3) When 800 second-feet of water is entering the canal over the flashboards, the velocity of upward currents near the upstream face of the flashboards averages about 2 feet per second.

(4) When the flashboards are placed in front of the buttress walls the quantity of silt passing is materially reduced.

EFFICIENCY OF DESILTING OPERATIONS AT HEADING

In 1918 the division of agricultural engineering made experiments on the efficiency of desilting operations at Laguna Dam. Top and bottom samples were taken in both the river and the canal. The river samples were taken in about the center of the main stream before the water enters the channel leading to the sluiceway and overpour gates. The samples in the canal were taken in the center below the intake. The results are summarized in Table 32. The amount of desiltation ranged from 33 to 72 per cent and averaged about 57 per cent.

TABLE 32.—*Amount of desiltation at Potholes headgates in August and October, 1918*

Date	Average proportion of silt (by weight)		Proportion of desiltation	
	Colorado River	Main canal	Actual	Comparative
	Per cent	*Per cent*	*Per cent*	*Per cent*
Aug. 1	0.502	0.320	0.182	36
Aug. 2	.682	.252	.430	63
Oct. 8	.250	.071	.179	72
Oct. 9	.242	.080	.162	67
Oct. 10	.233	.008	.135	58
Oct. 12	.275	.077	.198	72
Oct. 17	.468	.314	.154	33

The desilting efficiency of the headworks at Laguna Dam was determined for the Bureau of Reclamation by Raymond A. Hill, who carried on experiments and collected data at intervals during several years. These data have not been published, but Table 33 summarizes the results he obtained, by comparing, for each experiment, the silt content of the water in the river above the Laguna Dam with that in the main canal at its head. The amount of desiltation ranged from 18 to 70 per cent, with an average of 50 per cent.

TABLE 33.—*Comparison between silt content in Colorado River at Laguna Dam and in project main canal*

Average proportion of silt (by weight)		Proportion of desiltation		Average proportion of silt (by weight)		Proportion of desiltation	
Colorado River	Main canal	Actual	Comparative	Colorado River	Main canal	Actual	Comparative
Per cent	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*
0.53	0.41	0.12	22.7	0.54	0.21	0.33	61.2
.30	.09	.21	70.0	.59	.25	.34	57.7
.48	.21	.27	56.5	.50	.27	.23	46.1
.45	.37	.08	18.0	.33	.11	.22	66.7
1.55	.97	.58	37.4	.21	.10	.11	52.3
1.17	.76	.41	35.1	.34	.12	.22	64.7
.93	.51	.42	45.2	.40	.21	.25	54.5
.84	.40	.44	52.4	.48	.16	.32	66.7
.77	.49	.28	36.4	.43	.25	.18	41.9
.72	.40	.32	44.5	.44	.35	.09	20.4
.63	.30	.33	52.5	.44	.22	.22	50.0
.57	.19	.38	66.7	.32	.16	.16	50.0
.52	.23	.29	55.8	.31	.15	.16	51.7
.50	.18	.32	64.0	.30	.12	.18	60.0

DESILTING AT PARKER, ARIZ.

The irrigation project of the Colorado River Indian Reservation is mainly in Yuma County, Ariz., with a small part in Riverside County, Calif. The irrigable lands, estimated to contain 110,000 acres, extend from Parker to Ehrenberg, Ariz., a distance of 37 miles. At

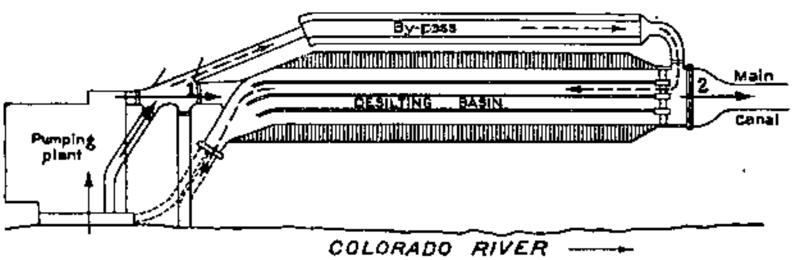


FIG. 9.—Desilting basin used at Parker project, Colorado River Indian Reservation, Ariz. Gates 1 and 2 are closed when by-pass is in use

present an area of about 6,000 acres is irrigated by pumping 7 to 14 feet from a sump into which water enters from the Colorado River through gates controlled by flashboards. A settling basin is near the pump house. (Fig. 9.) The pumped water from 1921 to 1925, the quantity of which varied from 15,000 to 26,000 acre-feet a year, was desilted in the basins. These basins were sluiced out about once a week. It is claimed that 50 per cent of the suspended silt in the river has been removed by this process before the water enters the main canal.

From 1900 to 1918 water was diverted from the Colorado River into the Alamo Canal, which is the intake of the Imperial irrigation district, without the installation of any special structure designed to desilt the admitted waters. The results of silt measurements at the head of the Alamo Canal showed fully 90 per cent as much suspended silt as was found in the river at Yuma.

One of the purposes of Rockwood heading, which was completed in 1918, was to admit the surface waters of the river and prevent the heavier silt from entering the Imperial Valley canal system. However, this is not always possible on account of the scarcity of water at the extreme low stages of the river. During these periods the lower intake gates must remain open, and practically the entire flow of the river is diverted into the main canal, thereby affording an opportunity for all the suspended silt as well as a large amount of bed silt to enter the canal system.

Notwithstanding the lack of continuity in the desilting process, that it was effective to some extent in checking the entrance of suspended silt is shown by the following figures.

On October 14, 1918, there was 0.39 per cent of suspended silt in the Colorado River at Yuma, and on the same date the mean proportion of silt passing through the gates of the Rockwood heading was 0.292 per cent. On February 13, 1919, the percentage of silt in the river above Rockwood heading was 0.143, while that at the heading averaged 0.138. Before the installation of Rockwood heading the average proportion of silt in the Alamo Canal for the year 1914 and again in 1917 and 1918, when compared with the amount of silt in the river at Yuma, indicated that the canal was desilted one-tenth.

While the utility and economy of the desilting appliances at the intakes of the irrigation systems of the lower basin are generally conceded, they have solved only a part of the silt problem. The finer and what the farmer considers the most injurious silt is transported through the entire canal systems and deposited on the irrigated fields. Accordingly, desilting appliances are being regarded more and more as temporary expedients, and the users of water from the lower Colorado River are hopefully anticipating the time when the entire silt load of the stream will be deposited in one or more large reservoirs. In the opinion of the authors, such reservoirs offer the only satisfactory solution of the silt problem, but foresight and good judgment will have to be exercised in the selection of the reservoir sites and the construction of dams.

Some may contend that the abandonment of present river intakes of the Imperial Valley irrigation system and the diversion of all water from Laguna Dam would solve the silt problem so far as this district is concerned. The silt at Laguna Dam, however, would in all probability have to be removed by sluicing operations, and these would necessitate shutdowns of the system during periods of maximum water demand, which would cause serious damage to irrigators; besides, desilting processes as thus far perfected, would not exclude the finer silt.

While a dam and reservoir such as are proposed at Boulder Canyon will effectively desilt the Colorado River at that point, it should be kept in mind that perhaps for many years the clear water after leaving the reservoir will pick up a new load of silt from the bed of the river. The resilting of the river water below the Elephant Butte Reservoir on the Rio Grande in New Mexico is a good example of what may take place. During the past 12 years the floods from the upper Rio Grande Basin have been retained in this reservoir. The water leaves the reservoir practically clear, but within 50 miles it is again turbid, and at El Paso the river carries considerable suspended silt despite the fact that the flow has been regulated.

On the supposition that a high dam of this type is urgently needed and will be built in the near future at the lower end of the canyon section, a question of far-reaching importance arises as to how soon the efficiency of the reservoir created will be greatly reduced by the deposition of silt. To answer this question, it is necessary to convert the normal load of silt in the river from the basis of weight to that of volume. It has been shown that 253,628,000 tons is a fair estimate of the total normal silt load carried by the river through the canyon section. It has also been shown that the weight of dry silt contained in a cubic foot of Colorado River sediment varies greatly. This finer silt deposited on irrigated land weighs less than 50 pounds per cubic foot, while the weight of this silt in the beds of irrigation and river channels approaches 100 pounds per cubic foot. In the case of silt deposited in a reservoir, the finer grades may be mixed with the coarser but since there is a preponderance of fine silt, the combined weight per unit of volume may be expected to be considerably less than that of bed silt. In estimating the weight of silt deposited in a reservoir located near the lower end of the canyon section of the river, 85 pounds of dry silt per cubic foot of sediment would seem to be a fair average, on the assumption that it is mixed. On this basis there would be an average of 137,000 acre-feet of wet sediment deposited annually.

Some of the estimates made by others of the amount of silt transported by the Colorado River are shown in Table 34.

TABLE 34.—*Some previous estimates of amount of silt transported annually by the Colorado River*

Reference	Location	Period	Dry weight of silt per cubic foot	Annual silt load	Remarks
			Pounds	*Acre-feet*	
Dole and La Rue, Water Supply Paper 395, United States Geological Survey *(15)*.	Yuma	1895–1914	93	80,000	Compact deposits of suspended silt in reservoir.
Mead, Schlecht, and Grunsky. Report of All-American Canal Board *(1)*.	do	1909–1918	100	97,330	Suspended silt.
Mead, Schlecht, and Grunsky. Report *(1)*.		Average.	100	102,000	Compact deposits of suspended and bed silt in reservoir.
Weymouth. Unpublished report United States Bureau of Reclamation.	do	1909–1922	86	105,000	Suspended silt.
Bureau of Reclamation (1922) Senate Document No. 142 *(5)*.	do	Average.	85	113,000	Do.
Bureau of Reclamation (1922) Senate Document No. 142 *(5)*.	Boulder Canyon.	do		88,000	Do.

Attention is drawn to the fact that the estimate made in this report is 137,000 acre-feet, whereas the previous estimates made by others range from 80,000 to 113,000 acre-feet annually. In this connection it is to be understood that the present estimate includes both suspended and bed silt, whereas, with one known exception, the earlier estimates do not include bed silt. They are based on the suspended-silt records at Yuma, which have been converted from a weight to a volume basis by using dry weights of silt ranging from 85 to 100 pounds per cubic foot. These weights are too high for suspended silt, although they may be correct for a mixture of bed and suspended silt as deposited in a reservoir.

Measurements of suspended silt in the Colorado River at Topock and Yuma indicate that most of the heavier suspended silt in the river near the end of the canyon section is deposited before reaching Yuma, and undoubtedly a large portion passes this point as bed silt.

The following estimate of the total silt load in the river above its junction with the Gila River is based on the silt measurements at Yuma and is made as a check. It will be shown in the Appendix under the heading of "Relation of volume and weight of silt" that in the lower reaches of the river 62.5 pounds would be a fair average weight of a cubic foot of suspended silt (not including bed silt) after being thoroughly dried. On this basis the normal suspended silt load of 161,708,000 tons at Yuma, exclusive of that from the Gila River, would be equal to 119,000 acre-feet. Assuming that this represents 80 per cent of the total load and that the additional bed silt has a dry weight of 100 pounds per cubic foot, there would be a bed load of 19,000 acre-feet, which when added to the suspended load, gives a total silt load of 138,000 acre-feet in the river at Yuma exclusive of the Gila.

After giving the matter careful thought, the authors consider that 137,000 acre-feet is a fair estimate of the average amount of silt which would be deposited annually in a reservoir located near the lower end of the canyon section of the river. On this basis, in 100 years the silt would occupy a space in the reservoir equivalent to 13,700,000 acre-feet. However, the construction of additional reservoirs, together with a more regulated flow and the increased use of water in the upper basin, will prolong the life of such a reservoir.

The quantity of silt transported through the canyon section is believed to be about 37 per cent larger than previous estimates have indicated. Should this larger estimate be found to be approximately accurate, it would be a waste of money to attempt to store silt, prevent floods, and provide water for both power and irrigation by the impounding of a relatively small quantity of water. The building of a dam on the Colorado River near Topock to store some 10,000,000 acre-feet of water has been advocated, but if the quantity of silt annually deposited in this proposed reservoir is 137,000 acre-feet, it would not be long until its effectiveness for flood control and water storage purposes would be seriously impaired.

If it be true that the Colorado River transports so large a normal load of silt to the lower basin, the necessity for providing an artificial lake of the largest practical dimensions, in which the water may be desilted and the silt stored, becomes of first importance. The proposed Boulder or Black Canyon Dam if built to a height of 550 feet above mean low water in the river, would store approximately 26,000,000 acre-feet of water. In view of the larger quantity of silt to be stored, earnest consideration should be given to raising rather than lowering the height of this proposed structure, for the principal reason that water can be stored in the upper levels of such a reservoir at a cost not exceeding 75 cents per acre-foot of storage.

The subject of removal of silt from proposed reservoirs on the Colorado River was not investigated, but it deserves consideration. In order to determine proper means for preserving the required capacity of the San Carlos Reservoir (to be created by Coolidge Dam) on the Gila River, a United States Army board made an extensive study of various methods of desilting. The conclusion reached was that "the most promising method, indeed the only practicable method is dredging," but it was estimated that dredging would cost 5 cents per cubic yard or about $80 per acre-foot. Such a cost would be prohibitive on the Colorado River where there are many reservoir sites in which additional storage capacity could be furnished at a much lower cost.

APPENDIX

RELATION OF VOLUME AND WEIGHT OF SILT

The earlier silt investigations carried on by the division of agricultural engineering were based on volume. The method generally followed was to pour each sample of river water into a glass tube and allow it to settle until the top part was clear. Then the clear water was decanted and the balance transferred to a smaller tube graduated in cubic centimeters, enough water being added to cover the silt to a depth of about 7 inches. The usual time of settling in the graduated tube was one week. Owing to the difficulty and cost of obtaining glass tubes, relatively few of the samples were allowed to settle for 30 days or longer.

Such silt determinations, made on southwestern rivers (*18, 19, 20*) from May, 1899, to June, 1902, gave basis for the conclusion that 100 units of volume of silt as measured in the tubes at the end of one week would shrink to 90 units at the end of a month and to about 75 units at the end of a year. For a few samples the relation between percentages of weight and volume at the end of one year was also determined. The mean of these determinations for the Brazos River in Texas indicates that the volume percentage is approximately three times the weight percentage. The results of these investigations likewise indicated that there is no definite relation between the proportion of silt in the water and the discharge of the stream, and that the time required to settle silt in still water depends mainly upon the character of the silt, its degree of fineness, the chemical content of the water, and the watershed from which it is derived.

When, in 1907, the division of agricultural engineering began to investigate silt in the canals of Imperial Valley the determinations were made on a volume basis, but the methods and equipment used differed somewhat from those of previous years. These studies have been described in detail in the section on Silt Investigations in Imperial Valley (p. 29). Of the eight stations at which samples were taken, at only one—No. 4, Dahlia heading—was a comparison made between the volume and weight of silt. The results given in Table 35 show the monthly silt average by percentages of volume and weight and their ratio. In these determinations the monthly ratio of volume percentage to weight percentage ranged from 1.4 to 4.5, the mean for the year being 3.25.

TABLE 35.—*Relation between monthly silt proportions by volume and by weight in canal water at Dahlia heading, October, 1907, to September, 1908*

Month	Proportion of silt		Ratio	Month	Proportion of silt		Ratio
	By volume	By weight			By volume	By weight	
	Per cent	*Per cent*			*Per cent*	*Per cent*	
October	1.3	0.30	4.3:1	April	0.8	0.28	2.9:1
November	1.1	.27	4.1:1	May	.6	.16	3.8:1
December	1.0	.22	4.5:1	June	.6	.25	2.4:1
January	.3	.21	1.4:1	July	.4	.26	1.5:1
February	.7	.26	2.7:1	August	3.6	.82	4.4:1
March	1.4	.42	3.3:1	September	3.4	.92	3.7:1

For the purpose of determining the rate of settlement of suspended silt in still water when analyses were being made on a volume basis, samples of water were taken from several farm laterals in Imperial Valley. Each sample was well shaken and poured into a glass tube, 2.5 centimeters in diameter, to the height of 100 centimeters. At the end of the first hour the percentage of silt by volume was measured. This was continued at different intervals for 1,628 hours. The results for four different samples are shown in Table 36. Samples A, B, and C were taken from a farm lateral 6 miles east of El Centro, at Bonds Corner, and at a place 2 miles south of El Centro, respectively; while sample D was taken from the center of a field being irrigated, 2 miles west of El Centro. Table 36 and Figure 10 show the rate of settlement of the silt. These tests and many others indicated that silt analyses based on the volume method are not satisfactory.

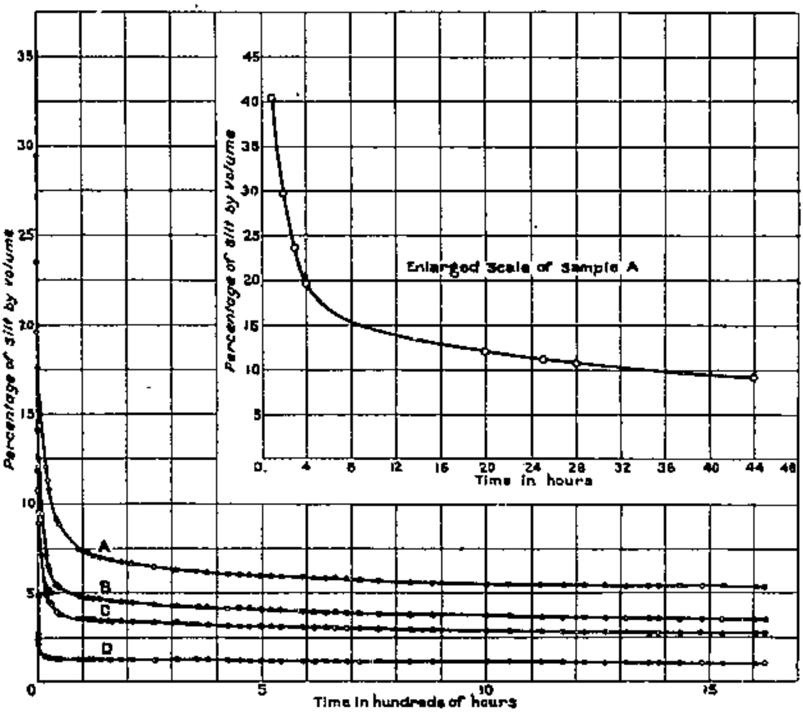


FIG. 10.—Rate of deposition of silt at different locations in Imperial Valley

TABLE 36.—*Settlement of silt*

Period of settlement	Proportion of silt by volume				Period of settlement	Proportion of silt by volume			
	A	B	C	D		A	B	C	D
Hours	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Hours*	*Per cent*	*Per cent*	*Per cent*	*Per cent*
1	40.9	17.7	17.5	4.8	524	5.95	4.0	3.1	1.1
2	20.5	14.1	10.7	2.7	548	5.9	4.0	3.1	1.1
3	23.6	12.6	9.5	2.4	596	5.85	3.9	3.05	1.1
4	19.6	11.8	8.9	2.1	620	5.8	3.9	3.0	1.1
20	12.1	7.1	4.9	1.4	644	5.8	3.9	3.0	1.1
25	11.2	6.5	4.5	1.4	668	5.8	3.9	3.0	1.1
28	10.8	6.3	4.4	1.3	692	5.75	3.9	3.0	1.1
44	9.1	5.4	3.9	1.3	720	5.7	3.8	2.95	1.1
48	8.9	5.3	3.8	1.3	764	5.7	3.8	2.95	1.1
92	7.4	4.8	3.5	1.2	836	5.6	3.75	2.9	1.1
100	7.3	4.7	3.5	1.2	886	5.6	3.75	2.9	1.1
116	7.1	4.7	3.5	1.2	1,005	5.5	3.7	2.85	1.1
124	7.0	4.6	3.5	1.2	1,052	5.5	3.7	2.85	1.1
140	6.9	4.6	3.4	1.2	1,124	5.5	3.05	2.8	1.05
164	6.8	4.5	3.4	1.2	1,172	5.5	3.65	2.8	1.05
188	6.7	4.5	3.4	1.2	1,220	5.5	3.6	2.8	1.05
212	6.6	4.4	3.3	1.2	1,268	5.45	3.6	2.8	1.05
260	6.4	4.3	3.3	1.2	1,316	5.45	3.55	2.8	1.05
311	6.3	4.25	3.3	1.2	1,364	5.45	3.55	2.75	1.05
356	6.2	4.2	3.2	1.2	1,388	5.45	3.55	2.75	1.05
380	6.15	4.2	3.2	1.2	1,430	5.4	3.55	2.75	1.05
428	6.05	4.1	3.15	1.15	1,484	5.4	3.55	2.75	1.05
452	6.00	4.1	3.1	1.15	1,532	5.4	3.5	2.7	1.0
476	6.00	4.1	3.1	1.1	1,604	5.4	3.5	2.7	1.0
500	6.00	4.05	3.1	1.1	1,628	5.35	3.45	2.7	1.0

The volume and weight of silt in the water entering the Alamo Canal during 1914 as determined by Peck are shown in Figure 11.

In comparing these it will be noted that the volumes vary widely while the corresponding weights are fairly constant, and there is no definite ratio between weight and volume.

Daily samples of the Colorado River water were taken at Parker, Ariz., by the United States Indian Service, September, 1915, to August, 1916.[1] The percentages of silt by weight and volume were determined. The average monthly percentage by volume of saturated silt after 24 hours settlement, as determined in test tubes 1½ inches in diameter and 8 inches high, and the percentage by weight of dry silt for the period are given in Table 37.

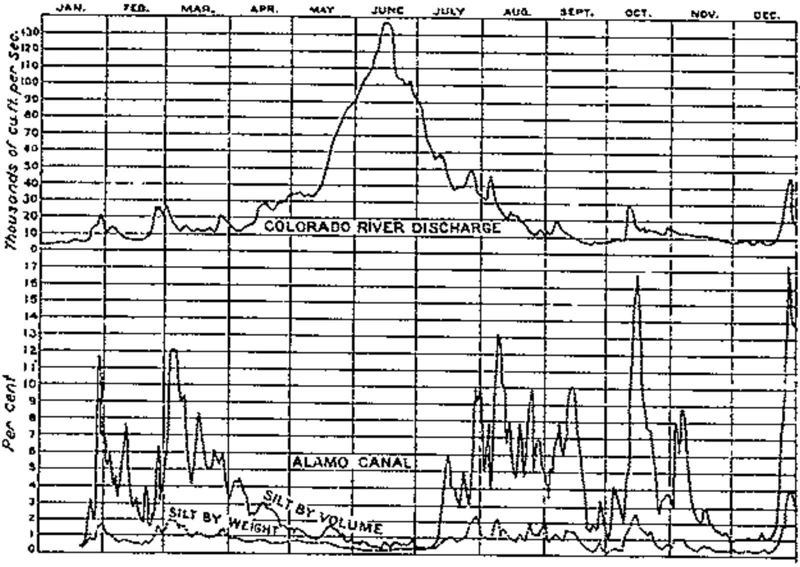


FIG. 11.—Discharge of Colorado River and amounts of silt passing into Alamo Canal during 1914

TABLE 37.—*Proportions of silt by weight and volume in Colorado River at Parker, Ariz., September, 1915, to August, 1916*

Month	Proportion of silt		Ratio of volume percentage to weight percentage	Month	Proportion of silt		Ratio of volume percentage to weight percentage
	By volume	By weight			By volume	By weight	
1915	*Per cent*	*Per cent*		1916	*Per cent*	*Per cent*	
September	4.7	1.31	3.6:1	March	6.5	1.04	6.3:1
October	5.5	1.22	4.5:1	April	3.5	.80	4.4:1
November	2.3	.44	5.2:1	May	3.3	.48	6.9:1
December	1.2	.12	10.0:1	June	1.6	.23	7.0:1
1916				July	1.3	.25	5.2:1
January	3.5	.60	5.8:1	August	8.1	.97	8.4:1
February	5.4	.68	7.9:1	Mean	3.9	.68	6.3:1

The results in Table 37 illustrate clearly that there is no constant ratio between percentage by volume and percentage by weight.

[1] Unpublished report, U. S. Indian Service, Results of Silt Investigations on Colorado Reservation, by C. A. Engle.

Mr. Engle's report says: "All volumetric percentages depend upon time of settlement, depth, diameter and shape of testing apparatus, proportion of voids, size and shape of silt particles, their specific gravity, etc. The most satisfactory method that has been proposed for expressing the silt content of water is the percentage by weight of dry silt."

Forbes (*6*) determined the silt content in the waters of Gila River near the head of the Florence Canal in 1900, in percentages of both volume and weight. The results of his tests are summarized in Table 38.

TABLE 38.—*Silt content of Gila River water expressed in weights and corresponding volumes*

Date of sample	Proportionate weight of sediment	Specific gravity of sediment	Proportionate volume of sediment after settling			
			1 day	7 days	1 month	1 year
1900	*Per cent*		*Per cent*	*Per cent*	*Per cent*	*Per cent*
Aug. 1-7	7.53	2.71	36.4	25.2	22.2	17.4
Sept. 1-7	2.98	2.63	10.0	7.6	6.6	5.6
Sept. 8-14	9.41	2.66	33.2	24.0	21.8	8 months. 17.8
Sept. 15-21	7.62	2.68	21.6	16.0	14.2	8 months. 11.8
Sept. 22-28	1.94	2.69	9.2	7.0	6.0	5.2

With the limited data available in 1907, silt determinations expressed in percentages by volume were difficult to interpret and classify, since there seemed to be no fixed relation between volume and weight. Volumetric percentages vary with size of testing tube, time of settlement, salt content, specific gravity, and shape and size of silt particles. Then, too, the proportion of silt commonly varies weekly, with the season, and yearly, depending on the part of the Colorado River drainage area from which it is derived. Samples of silt taken at the same time but at different depths of the same vertical section also differed widely. Besides requiring a large number of tubes the experiments involved a much increased cost when the results were determined by volume. It was finally decided that determinations by weight were more practical to research work than those by volume, and since 1908 all results have been calculated on a weight basis.

Notwithstanding this decision and the soundness of the reasons which prompted it, the fact remains that nearly all those who have to do with silt think of it in terms of space and volume and not in terms of weight and density. This is true of the farmer using muddy water, who notes with some concern when an alfalfa field is covered with sediment a half-inch deep, or realizes how much higher the bed of his lateral ditch is compared with its height 10 years ago. Likewise the operators of canal systems diverting silt-laden water reckon the cubic yards of material which periodically have to be removed from the channels, and those who are financially interested in hydraulic sluicing or the building of dams to impound water estimate the materials to be moved in volume. When a large sum of money is expended in creating an artificial lake, all contributors to the building fund wish to know when its effectiveness will be curtailed or destroyed by deposits of silt. In short, to meet an almost universal demand, the results of silt sampling when expressed in weight of silt must be converted into volumes in order to become usable and valuable.

The following summarized results are submitted with the object of casting more light on the relationship between volume and weight of silt in the waters of the Colorado River.

RIVER AND CANAL DEPOSITS

Between December, 1915, and April, 1916, 15 samples of freshly deposited wet silt were taken from a 2-mile stretch of the Colorado River bank in the vicinity of Yuma by the Bureau of Reclamation. In taking the samples 3-inch cubes were cut from deposits still wet but firm enough to be handled. All samples were homogeneous throughout and free from drift, gravel, and shrinkage cracks.

The results of the weight determinations are given in Table 39.

TABLE 39.—*Weights of Colorado River silt deposits, near Yuma, Ariz., 1915–16*

Date	Location of samples	Weight per cubic foot	
		Natural state	Dry
1915		*Pounds*	*Pounds*
Dec. 3	Near Yuma ice plant		71.2
Do	do		92.0
Do	do		77.0
Dec. 16	Soldiers camp		85.0
Dec. 18	Yuma gauging station mast, California		84.5
Do	Yuma city dump	108.0	83.1
1916			
Jan. 20	Soldiers camp		90.7
Do	Back of Bureau of Reclamation shop		85.5
Dec. 27	Gauge, old Southern Pacific R. R. bridge		86.8
Do	North end of Southern Pacific R. R. bridge		88.2
Do	California side, opposite Custom House		88.4
Feb. 2	West end of electric plant		100.0
Feb. 4	Foot of highway bridge, south side		78.5
Mar. 16	Back of Bureau of Reclamation shop		91.3
Apr. 5	do	121.0	94.5
Mean			86.4

During the same period the Bureau of Reclamation also took five samples of canal-bed deposits at Yuma, Ariz., the weights of which are shown in Table 40.

TABLE 40.—*Weights of canal-bed deposits at Yuma, 1915–16*

Date	Location of samples	Weight per cubic foot	
		Natural state	Dry
1915		*Pounds*	*Pounds*
Dec. 21	Main canal, headquarters bridge	118.5	87.7
Do	Main canal, First Street bridge	109.1	78.8
1916			
Jan. 6	Main canal, California drop		86.7
Do	Main canal, California siphon gate		81.1
Jan. 27	Spillway, Porter's house		87.7
Mean			84.4

On February 27, 1925, the division of agricultural engineering took seven samples of recently deposited moist silt from the banks of the Colorado River immediately above the Potholes heading, two samples from a sand bar in the river at Yuma, and one sample at Rockwood heading. Samples No. 6 and 7 in Table 41 were taken by the method outlined in the previous paragraphs, and these, with sample No. 10, contained a larger percentage of fine silt than the others. Each of the remaining eight samples was obtained by leveling the surface and forcing an accurately calibrated tin cylinder into the silt deposit. The sample was removed by excavating the surrounding material. The end was then trimmed and the volume and weight determined. The dry weights of all samples were obtained by driving off all moisture by heating in an electric oven at a temperature of 110° C.

TABLE 41.—*Weights of silt deposits in the Colorado River at Laguna Dam, Yuma, and Rockwood heading*

Sample No.	Weight per cubic foot		Location of sampling
	Natural state	Dry	
	Pounds	*Pounds*	
1	96.5	90.7	Above Potholes heading at surface.
2	93.1	84.0	Above Potholes heading, 4 inches below surface.
3	92.0	85.3	Above Potholes heading, 5 to 8 inches below surface.
4	97.8	80.9	Above Potholes heading, 9 to 12 inches below surface.
5	100.7	80.3	Above Potholes heading, 15 to 18 inches below surface.
6	110.3	73.2	50 feet above Laguna Dam at surface.
7	116.7	79.4	Do.
8	84.2	80.9	Sand bar at Yuma bridge at surface.
9	87.6	86.2	Sand bar at Yuma bridge, 12 to 15 inches below surface.
10	92.8	74.6	At Rockwood heading, at surface.
Mean	97.2	81.6	

The following day (February 28) five samples were obtained in a similar manner from the beds of canals of the Imperial Valley system. This material, which was chiefly bed silt transported in waves in the bed of the canal, was markedly different from that obtained from the river, which was a mixture of bed silt and sediment formerly carried in suspension taken from the river's edge where it had been deposited at a low stage.

Samples 1, 2, and 3 were taken from the East Highline Canal about 42 miles, 68 miles, and 75 miles, respectively, from the intake at the Colorado River. Samples 4 and 5 were taken, respectively, from a small lateral 8 miles west of the East Highline Canal and from about 86 miles from the intake. The weights of these materials are given in Table 42.

TABLE 42.—*Weights of bed silt in canals of Imperial Valley*

Sample No.	Weight per cubic foot		Location of sampling
	Natural state	Dry	
	Pounds	*Pounds*	
1	126.2	99.6	East Highline Canal, three-fourths mile north of Lawrence heading.
2	127.3	105.2	East Highline Canal, 1,000 feet north of Osage lateral.
3	126.5	97.1	East Highline Canal, between Nettle and Narcissus lateral.
4	132.2	100.1	Lateral B, 8 miles west of East Highline Canal.
5	130.4	101.5	Do.
Mean	128.5	100.7	

During 1917 many samples of bed silt were taken by Mr. Peck from the bottom of the Alamo Canal near Hanlon heading. The weight of dry silt contained in a cubic foot of wet material varied from 90 to 110 pounds, averaging about 100 pounds. Table 43 shows the weights of the samples taken on May 1, which are typical. The samples were taken in the same cross section.

TABLE 43.—*Weights of bed silt in Alamo Canal, at Hanlon, May 1, 1917*

Distance between station and bank (feet)	Specific gravity	Weight per cubic foot		Distance between station and bank (feet)	Specific gravity	Weight per cubic foot	
		Wet	Dry			Wet	Dry
		Pounds	*Pounds*			*Pounds*	*Pounds*
5	2.657	125.62	99.98	75	2.716	127.46	104.12
15	2.675	133.73	110.35	85	2.683	128.13	103.60
25	2.683	124.99	101.88	95	2.679	122.22	98.40
35	2.696	125.19	101.35	105	2.683	125.47	102.76
45	2.723	128.02	105.90	115	2.683	114.62	91.21
55	2.736	126.49	104.40	Mean	2.694	125.64	102.24
65	2.700	125.70	102.77				

During 1917–18 similar samples of bed silt were taken about once a month at 12 places (fig. 7) on Imperial Valley canals. The average weight results of the sampling at each station for the entire period, when wet and when dry, are given in Table 44.

TABLE 44.—*Average weights of bed silt in Imperial Valley canals, 1917–18*

Station No.	Station Name	Canal	Distance from river intake	Specific gravity	Weight per cubic foot: Wet	Weight per cubic foot: Dry
			Miles		*Pounds*	*Pounds*
5	Check No. 1	East Highline	48	2.645	122.14	98.50
6	Myrtle check	do	71	2.645	121.98	99.01
7	Junction lateral	do	86	2.658	121.17	101.43
8	Ten-foot drop	Central main	52	2.654	122.83	98.48
9	Dahlia heading	Dahlia	50	2.677	119.48	99.78
10	No. 12 heading	do	69	2.634	115.85	90.11
11	No. 4 heading	No. 4 main	76	2.650	120.77	94.14
14	No. 8 heading	No. 8 main	[1] 91	2.667	122.74	98.81
15	No. 6 heading	Trifolium	[1] 104	2.635	118.07	95.01
16	No. 5 heading	No. 5 main	53	2.658	119.24	98.62
17	Rositas heading	Rositas	60	2.654	121.15	97.71
18	North end heading	North end	83	2.644	123.86	92.16
	Mean			2.652	120.77	97.05

[1] 12 miles farther, via Cerro Prieto Canal.

To determine the variation from the mean of the wet and dry weights of silt samples as well as their moisture content and specific gravity, Peck, in February, 1918, took 15 samples from the bottom of Briar Canal, Imperial Valley, at as nearly as practicable, the same places and the same time. The results of the tests are given in Table 45.

TABLE 45.—*Weights of samples taken from the bottom of Briar Canal, February 16, 1918, showing similarity of results when samples are taken at the same time and place*

Sample No.	Wet weight per cubic foot	Variation from mean	Dry weight per cubic foot	Variation from mean	Specific gravity	Sample No.	Wet weight per cubic foot	Variation from mean	Dry weight per cubic foot	Variation from mean	Specific gravity
	Pounds	*Per cent*	*Pounds*	*Per cent*			*Pounds*	*Per cent*	*Pounds*	*Per cent*	
1	119.22	+1.88	90.31	+2.41	2.643	10	115.99	−0.88	87.73	−0.51	2.644
2	116.27	−.64	86.79	−1.57	2.638	11	115.48	−1.32	88.08	−.11	2.651
3	117.85	+.71	89.23	+1.19	2.647	12	118.21	+1.02	88.37	+.21	2.632
4	119.29	+1.94	89.09	+1.03	2.644	13	116.63	−.33	87.08	−1.24	2.637
5	117.35	+.28	89.23	+1.19	2.647	14	116.42	−.51	86.08	−2.38	2.625
6	115.92	−.94	87.94	−.27	2.654	15	116.63	−.33	87.51	−.76	2.635
7	116.56	−.39	88.73	+.62	2.645						
8	116.92	−.09	88.73	+.62	2.638	Mean	117.02		88.18		2.641
9	116.56	−.39	87.79	−.44	2.637						

Data on the weight of silt deposits in the Gila River are very meager. D. E. Hughes (*11*) while conducting investigations on the San Carlos irrigation project for the United States War Department, found that the average of 15 samples of Gila River deposits gave a weight of 74.2 pounds of dry silt per cubic foot of sediment. To be conservative, 70 pounds was used in estimating the deposits which would occur in a reservoir created by the Coolidge Dam now under construction near San Carlos, Ariz.

The foregoing results show that the 25 samples of Colorado deposits taken near Yuma and Laguna Dam in 1915, 1916, and 1925 varied in dry weight of silt per cubic foot of sediment from 71.2 to 100 pounds, averaging 84.5 pounds. The series of samples of canal-bottom deposits taken during 1917–18 period (see Table 44) in Imperial Valley, gave dry weights of silt per cubic foot of wet material varying from 90.1 to 101.4 pounds, the average being 97 pounds.

SILT DEPOSITS IN SETTLING BASINS

Many of the domestic waterworks systems of Imperial Valley have settling basins which afford an opportunity to determine the weight and volume of deposited silt. Water for domestic purposes is generally supplied from a secondary canal, and most of the silt is still in suspension but is very fine. For this reason the deposits should be somewhat similar in character to those on farm lands and those in the downstream portions of large reservoirs.

On January 24, 1919, the division of agricultural engineering took two silt samples apiece from the settling basins of El Centro and Imperial, two towns of Imperial Valley. The deposits at El Centro were somewhat firm and of pure silt. Those at Imperial were from the deposits in the supply ditch at the settling basin and were very fine, soft, and freshly deposited. The sampler consisted of a thin aluminum cylinder 7.6 centimeters in diameter and 4.8 centimeters high, which could be easily pushed into the silt, and both ends of the sample trimmed off without disturbing the compactness of the material. The dry weight was determined by drying the samples at 110° C. The results are given in Table 46.

TABLE 46.—*Weights of silt deposits in settling basins of El Centro and Imperial*

Sample No.	Weight per cubic foot			
	El Centro		Imperial	
	Wet	Dry	Wet	Dry
	Pounds	*Pounds*	*Pounds*	*Pounds*
1	92.43	45.96	86.87	37.47
2	91.12	45.59	84.36	34.91
Mean	91.78	45.78	85.61	36.19

Sample No. 1, taken at Imperial, after being thoroughly pulverized and screened through a 200-mesh sieve, occupied a volume of 145 cubic centimeters. Enough water was added to bring it up to its wet volume when taken. After 24 hours the volume of silt was 170 cubic centimeters on top of which was 48 cubic centimeters of clear water. The silt and water were thoroughly mixed by being shaken, and after 24 hours the volume of silt was 202 cubic centimeters topped by 16 cubic centimeters of clear water. Thus there was still 16 cubic centimeters of water to be absorbed before the sample reached its original state.

A few days later Mr. Peck took 10 similar samples at each of the settling basins of El Centro, Imperial, and Calexico. The results are shown in Table 47.

TABLE 47.—*Weights of silt deposits taken from Imperial Valley settling basins*

Sample No.	El Centro — Weight of silt per cubic foot		Sample No.	Imperial — Weight of silt per cubic foot		Sample No.	Calexico — Weight of silt per cubic foot	
	Wet	Dry		Wet	Dry		Wet	Dry
	Pounds	*Pounds*		*Pounds*	*Pounds*		*Pounds*	*Pounds*
1	92.2	52.4	11	85.8	36.1	21	81.8	32.3
2	91.3	51.3	12	84.6	36.7	22	81.9	32.7
3	92.6	52.2	13	87.1	39.6	23	82.0	37.8
4	89.4	47.2	14	87.6	38.5	24	87.0	38.8
5	90.1	47.2	15	85.2	38.1	25	86.6	39.7
6	89.6	47.0	16	86.4	41.5	26	83.7	37.5
7	84.3	36.4	17	84.6	36.9	27	86.5	39.6
8	84.6	37.9	18	84.0	36.8	28	85.6	39.2
9	84.3	37.8	19	84.6	37.3	29	87.3	40.0
10	85.3	37.7	20	85.0	37.6	30	87.1	39.9
Mean	88.4	44.7	Mean	85.5	37.8	Mean	85.0	37.7

Samples 1, 2, and 3, taken at the El Centro settling basin, were fairly well compacted. The deposits showed cracks 2 inches wide and 4 inches deep. Samples 4, 5, and 6 were taken just above the water, and the cracks were not so large. Samples 7, 8, 9, and 10 were taken below the water and were soft.

At the Imperial Water Works, samples 11 to 20 inclusive, were taken from soft deposits in the end of the supply ditch. However, they were solid enough to retain their shape.

Water had been removed from the Calexico settling basin a few hours before the time of sampling. Samples were taken from the side above water. The deposit showed no cracks but was solid enough to retain its shape.

The results obtained at the Imperial Valley settling basins indicate that the dry weight of silt in a given volume depends almost entirely on the amount of moisture contained at the time of sampling. The dry weights of silt per cubic foot of sediment ranged from 32.3 pounds for the softest material to 52.4 pounds for the most compact material with an average of about 40 pounds.

Experiments were conducted by C. A. Engle, of the United States Indian Irrigation Service, on deposition of silt from water pumped from the Colorado River at Parker and then passed through experimental settling basins. The weight of a cubic foot of material deposited in a basin by water flowing with a velocity of 0.08 foot per second is shown for a series of samples in Table 48.

TABLE 48.—*Weights of Colorado River silt deposits in settling basins at Parker, Ariz.*

Weight of silt per cubic foot	
Saturated	Dry
Pounds	*Pounds*
95.5	56.8
101.5	60.0
88.0	44.9
107.9	77.7
80.9	42.0
[1] 96.1	[1] 57.5

[1] Mean.

Regarding the data given in Table 48, it should be borne in mind that since the water is pumped from the river, the material deposited represents that carried in suspension and probably does not include any bed silt. It also consists mainly of the heavier suspended silt, because the lighter and finer material, even with such slow velocity, passes through the basin and is deposited in the laterals or on the fields. Practically all the silt remaining in the water after it had passed through the basin was a fine clay slime, which, when precipitated, contained voids of 60 to 80 per cent. One sample, when dried, weighed 28 pounds per cubic foot. The weight of dry silt contained in a cubic foot of wet deposit taken from the settling basin varied from 42 to 77.7 pounds and averaged 57.5 pounds.

SUSPENDED SILT

The results obtained from samples from the settling basins at Parker show the average dry weight of suspended silt as 57.5 pounds per cubic foot. This weight is an indication of the weight of silt carried in suspension by the river. Other data indicate that the dry weight of suspended silt as found in the river may vary greatly. The finer deposits of suspended silt as taken from the settling basins in Imperial Valley have an average dry weight of 40 pounds per cubic foot, while judging from the river deposits found at Laguna Dam and Yuma, the heavier suspended silt may have an average dry weight of about 85 pounds per cubic foot. The 12-months record at Topock shows that about 50 per cent of the silt carried in suspension was fine enough to pass through a No. 200 sieve. Assuming that these statements are correct, it is the opinion of the authors that the average weight of dry silt contained in a cubic foot of suspended silt as carried by the lower Colorado River would be approximately 62½ pounds. This weight, while only approximate, simplifies the conversion of the silt content of water from a weight to a volume basis in that the percentage of silt by weight equals the percentage by volume. In converting the silt content in the river at Yuma from a weight to a volume basis the weight of suspended silt should be used, as the samples do not include bed silt.

RESERVOIR SILT DEPOSITS

Silt deposits in a reservoir on the Colorado River will consist of material carried in as suspended silt and as bed silt. The finer grades may be mixed with the coarser, and the resulting mixed deposit may, therefore, be denser than either material separately, but since there is a preponderance of the finer and lighter silt, the combined weight per unit of volume may be expected to be considerably less than that of bed silt. The presence of clay and colloidal particles will tend to decrease the weight per unit volume. However, this may be offset eventually by the increased density of sediments due to settlement in the bed of the reservoir. Typical samples of river deposits taken in 1915, 1916, and 1925 show an average dry weight per cubic foot of 84.5 pounds. To convert the total load of silt deposited by the river in a reservoir, from a weight to a volume basis, it is necessary to know the dry weight of silt per cubic foot. The average weight of silt deposited in a large reservoir would depend on the thoroughness with which the fine silt was mixed with the coarse. If the two grades were deposited separately in the proportions commonly carried by the stream, the mean weight would approach 70 pounds per cubic foot. If mixed, the average weight would be greater, but the Yuma and Topock determinations of silt as deposited indicate that it would not exceed 84.5 pounds. In estimating the weight of dry silt contained in a cubic foot of sediment in a reservoir located near the lower end of the canyon section of the river, 85 pounds would seem to be a fair average, since there would be a little greater bed load of silt than at Topock and Yuma.

SILT ANALYSES

MECHANICAL ANALYSES OF BED-SILT DEPOSITS

From June, 1917, to February, 1918, the division of agricultural engineering cooperated with the Imperial irrigation district in taking similar samples of bed deposits about once a month at 12 stations in the Imperial Valley canal system, as shown on the map. (Fig. 7.) A summary of the results is given in Table 49.

TABLE 49.—*Mean results of analyses of bed silt in Imperial Valley canals, 1917–18*

Station		Dry weight per cubic foot	Specific gravity	Proportion of silt passing and retained on sieve with specified number of meshes per inch						
No.	Distance from river			Passing 10, retained on 20	Passing 20, retained on 40	Passing 40, retained on 60	Passing 60, retained on 80	Passing 80, retained on 100	Passing 100, retained on 200	Passing 200
	Miles	*Pounds*		*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*
5	48	98.50	2.645	0.00	0.25	0.52	2.55	5.02	66.26	25.40
6	71	99.01	2.645	.04	1.50	4.12	23.42	5.26	54.78	10.88
7	56	101.43	2.658	.00	.00	.69	3.77	1.22	43.78	50.54
8	52	98.43	2.654	.00	.23	.47	6.08	6.08	69.67	17.47
9	50	99.78	2.677	.02	.24	.44	.76	1.70	64.47	32.37
10	69	90.11	2.634	.10	.07	.02	.36	.38	62.70	36.37
11	76	94.14	2.656	.03	.09	.34	1.43	3.73	68.19	26.19
14	[1] 91	98.81	2.667	.00	.00	.20	.53	4.20	74.80	20.27
15	[1] 104	95.91	2.635	.00	4.62	3.72	6.05	1.98	50.78	31.95
16	53	98.62	2.658	.00	.01	.06	7.11	23.04	59.53	10.25
17	60	97.71	2.654	.00	.08	.24	14.04	5.54	65.66	14.44
18	83	92.16	2.644	.00	.17	2.87	10.30	2.25	46.23	38.18

[1] 12 miles farther, via Cerro Prieto Canal.

It is difficult to compare the silt deposits in the main canal near the intake with those in the lower reaches of the system, as the samples were not taken over a long enough period at the heading. At some seasons the canal beds are shifting rapidly downstream. No practical way was found to measure this shifting; moreover, some of the canals pass through sand dunes, and the wind-blown sand changes the character of the deposits in them.

The mean results shown in Table 49 are for stations within the Imperial irrigation district and at distances varying from 48 to 104 miles from the intake on the Colorado River. The proportion of silt deposit passing the No. 200 sieve varies from about 10 to 50 per cent, while that passing the No. 100 sieve ranges from about 65 per cent to 99 per cent. This would indicate that most of the bottom deposits in the lower reaches of the system are fine enough to pass through No. 100 sieve, which has 0.0055-inch interstices. The dry weight of bottom deposits ranges from 90.11 to 101.43 pounds per cubic foot. The low values found at station 10, which is on a small canal, and station 18, at the North End Dam, are perhaps not representative. The results indicate that the weight of canal bottom deposits is fairly uniform throughout the system, especially when it is remembered that Colorado silt has a wide variation in weight per cubic foot.

On April 17, 1919, samples of bottom deposits were taken from a small canal near Brawley. Charles F. Shaw, of the University of California, made mechanical analyses by the usual United States Bureau of Soils method. The results are shown in Table 50.

TABLE 50.—*Mechanical analyses of deposits in a small canal near Brawley*

	Diameter	Test A	Test B
	Millimeters	*Per cent*	*Per cent*
Fine gravel	2 to 1	0.0	0.0
Coarse sand	1 to 0.5	.0	.0
Medium sand	0.5 to 0.25	.024	.036
Fine sand	0.25 to 0.10	1.140	1.342
Very fine sand	0.10 to 0.05	79.036	78.300
Silt	0.05 to 0.005	15.316	14.456
Clay	0.005 to 0.0001	4.712	4.744

Samples of bed deposits have likewise been taken from the channel of the Colorado River at various places. The results of the mechanical analyses of four of these samples are given in Table 51. Sample No. 1 was taken August 2, 1918, from the bed of the river in midstream one-half mile above Laguna Dam. Sample No. 2 was taken December 17, 1918, at the intake of the Palo Verde Canal, about 108 miles above Yuma. Samples No. 3 and No. 4 were taken from a sand bar in the river at Ehrenberg, Ariz., February 2, 1919. The specific gravity of the four samples averaged 2.645.

TABLE 51.—*Mechanical analysis of deposits in bed of Colorado River*

Sample No.	Proportion of silt passing and retained on sieve with specified number of meshes per inch																
	Passing 20, retained on 40	Passing 40, retained on 60	Passing 60, retained on 80	Passing 80, retained on 100	Passing 100, retained on 150	Passing 150, retained on 200	Passing 200	Passing 100, retained on 120	Passing 120, retained on 140	Passing 140, retained on 160	Passing 160, retained on 180	Passing 180, retained on 200	Passing 200, retained on 220	Passing 220, retained on 240	Passing 240, retained on 260	Passing 260, retained on 280	Passing 280
	P. ct.	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*
1	0	0.02	4.40	23.40	40.75	24	7.6										
2		.00	.56	1.24				2.00	17.20	15.80	20.70	7.63	2.77	4.20	14.62	5.72	7.06
3		.00	.00	.05				.30	3.75	5.95	20.55	10.20	6.30	8.05	22.30	6.40	16.05
4		.00	.00	.00				.45	2.86	6.51	18.80	11.70	5.36	7.30	21.35	8.48	17.13

MECHANICAL ANALYSES OF TYPICAL SOILS OF IMPERIAL VALLEY

Table 52 gives the results of analyses of typical soils of Imperial Valley formed by the deposition of silt in the Colorado River, as made from time to time by the United States Bureau of Soils.

TABLE 52.—*Mechanical analyses of typical soils of Imperial Valley (14)*

Soil type	Fine gravel (2 to 1 mm.)	Coarse sand (1 to 0.5 mm.)	Medium sand (0.5 to 0.25 mm.)	Fine sand (0.25 to 0.1 mm.)	Very fine sand (0.1 to 0.05 mm.)	Silt (0.05 to 0.005 mm.)	Clay (0.005 to 0.0001 mm.)
	Per cent	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*
Imperial very fine sandy loam	0	0.0	0.0	3.7	63.6	22.8	9.9
Imperial clay loam	0	.1	.9	10.0	37.1	19.4	32.8
Imperial silty clay	0	3.4	2.2	7.6	6.6	51.6	28.7
Imperial clay	0	2.1	1.0	5.7	3.8	43.6	43.2
Holtville very fine sandy loam	0	.0	.0	1.0	33.5	56.1	9.4
Holtville loam	0	.0	.6	6.9	34.2	42.1	16.2
Holtville silty clay loam	0	.0	.0	2.0	25.6	44.0	28.6
Holtville clay	0	.4	.3	1.9	15.9	46.1	35.6

MECHANICAL ANALYSES OF SUSPENDED SILT

On November 15, 1917, samples were taken with the Topock sampler, at the top, middle, and bottom depths of the river in midstream, at Topock. The river was carrying about 9,000 second-feet and was cutting sand bars which had been deposited above the station by previous high waters. The average content of suspended silt in the river was 1.485 per cent, which was about 10 time the amount recorded at Yuma the following day. The samples were not representative of average conditions at Topock because of the large amount of coarser silt being carried in suspension as a result of the cutting action of the river above. The results of the sampling are shown in Table 53.

TABLE 53.—*Mechanical analyses of suspended silt at top, middle, and bottom depths, at Topock, Ariz., November 15, 1917*

Depth	Proportion of silt passing and retained on sieve with specified number of meshes per inch					
	Passing 20, retained on 40	Passing 40, retained on 60	Passing 60, retained on 80	Passing 80, retained on 100	Passing 100, retained on 200	Passing 200
	Per cent	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*
Top	0	2.56	4.06	32.03	55.88	5.47
Middle	0	3.27	20.76	51.49	20.17	4.31
Bottom	0	8.69	41.86	31.65	14.53	3.27

For a similar purpose many samples of water were taken during the summer of 1920, at various depths in the Colorado River at Yuma, and in the canals of Imperial Valley with a Tait-Binckley sampler. The results of the mechanical analyses of these samples indicate that most of the suspended silt was too fine to be retained on a No. 300 sieve, the particles being less than 0.0017 inch in diameter, and none was found coarser than the interstices of a No. 40 sieve, or greater than 0.015 inch in diameter. The percentage of silt passing a No. 300 sieve seemed to decrease as the depth increased, while all other grades increased with the depth.

Tables 54, 55, and 56 give results of some typical analyses of the river silt at Yuma, the Alamo Canal about 1 mile below the river intake, and the Brawley main about 65 miles farther down the canal system.

TABLE 54.—*Mechanical analyses of suspended silt at various depths near the middle of the Colorado River at Yuma, July 27, 1920*

[Depth, 11 feet; discharge, 23,500 second-feet; main river velocity, 4.82 feet per second]

Depth (feet)	Velocity of middle section	Proportion of silt by weight	Proportion of silt passing and retained on sieve with designated number of meshes per inch					
			Passing 20, retained on 40	Passing 40, retained on 60	Passing 60, retained on 100	Passing 100, retained on 200	Passing 200, retained on 300	Passing 300
	Feet per second	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*
Top	5.92	0.310	0	0.26	0.97	4.84	10.13	83.80
4.0	6.10	.456	0	1.05	5.94	15.72	17.51	59.78
7.0	5.53	.479	0	.64	4.40	14.37	20.19	60.40
10.8	5.00	.614	0	1.09	9.12	16.82	21.22	51.75

TABLE 55.—*Mechanical analyses of suspended silt at various depths in the Alamo Canal, at Hanlon, 120 feet from east bank, July 26, 1920*

[Canal width, 180 feet; depth, 10 feet; discharge, 5,749 second-feet; mean velocity, 4.1 feet per second]

Depth (feet)	Velocity	Proportion of silt by weight	Proportion of silt passing and retained on sieve with specified number of meshes per inch					
			Passing 20, retained by 40	Passing 40, retained by 60	Passing 60, retained by 100	Passing 100, retained by 200	Passing 200, retained by 300	Passing 300
	Feet per second	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*
Top	4.00	0.347	0	0.00	1.47	3.25	9.30	85.02
4.0	4.82	.363	0	.37	2.08	4.83	9.13	82.99
7.0	4.16	.369	0	.26	1.90	7.77	9.41	80.60
9.8	3.00	.486	0	.91	5.35	16.34	15.38	62.02

TABLE 56.—*Mechanical analyses of suspended silt at various depths in the center of the Brawley Canal, 500 feet above the 16-foot drop, June 26, 1920*

[Canal width, 20 feet; depth, 4.4 feet; discharge, 231.2 second-feet; mean velocity, 2.68 feet per second]

Depth (feet)	Velocity	Proportion of silt by weight	Proportion of silt passing and retained on sieve with specified number of meshes per inch					
			Passing 20, retained on 40	Passing 40, retained on 60	Passing 60, retained on 100	Passing 100, retained on 200	Passing 200, retained on 300	Passing 300
	Feet per second	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*
Top	2.30	0.274	0	0.00	0.25	0.99	5.12	93.64
2.0	3.13	.310	0	.00	.30	2.16	9.74	87.80
3.5	2.70	.450	0	.23	1.63	11.02	15.97	71.15
4.2	2.30	.542	0	.54	8.86	13.58	17.38	59.64

A 5-gallon sample of Colorado River water was taken near the surface at the Imperial irrigation district intake February 28, 1925, when the discharge of the river was about 6,390 second-feet. Another was taken June 8, 1925, when the river was flowing 52,900 second-feet, or at about the peak for the year. Edward V. Winterer, of the University of California, made the analyses shown in Table 57 by the Oden method of continuous sedimentation.

TABLE 57.—*Mechanical analyses of suspended silt in the Colorado River at Imperial irrigation district intake*

Diameter of particles (millimeters)	Proportion of silt by weight: Feb. 28, 1925	Proportion of silt by weight: June 8, 1925	Diameter of particles (millimeters)	Proportion of silt by weight: Feb. 28, 1925	Proportion of silt by weight: June 8, 1925
	Per cent	*Per cent*		*Per cent*	*Per cent*
2.000 to 1.000	1.34	0.22	0.030 to 0.020	2.07	7.28
1.000 to 0.500	.89	.32	0.020 to 0.010	6.14	13.75
0.500 to 0.250	1.94	.30	0.010 to 0.005	22.42	7.91
0.250 to 0.100	3.73	5.04	0.005 to 0.004	3.52	2.91
0.100 to 0.050	45.00	56.90	0.004 to 0.003	2.21	2.00
0.050 to 0.040	1.41	.00	0.003 to 0.000	3.15	2.60
0.040 to 0.030	3.20	.00			

CHEMICAL ANALYSES

At various times during the past third of a century analyses have been made of the chemical ingredients of the water in the Colorado River and its tributaries and in typical irrigation canals of Imperial Valley. The results show considerable variation, apparently due mainly to the stage of the stream flow when the samples were taken and the watersheds from which the water was derived. Ross [2] found in 1900 that the main river during the October and November floods occurring in the southern part of the Colorado River Basin contained nearly four times more chemicals than those borne by the May and June floods from the upper basin.

Several chemical analyses have been made of the suspended silt in the waters of Colorado River. Collingwood (*8*) took daily samples of the river water at Yuma for the seven-month period from August, 1891, to February, 1892. The average results are given in Table 58.

TABLE 58.—*Average chemical analysis of Colorado River silt at Yuma, August, 1891, to February, 1892*

Constituent	Per cent	Constituent	Per cent
Sand-silica, combination of water and organic matter	71.19	Soda soluble in water	4.18
Oxide of iron	3.32	Soda soluble in acid	1.22
Alumina (Al_2O_3)	10.01	Potash soluble in water	.16
Lime (CaO)	7.15	Potash soluble in acid	1.05
Magnesia (MgO)	2.39	Phosphoric anhydride (P_2O_5)	.17
		Nitrogen (N)	.08

A series of chemical analyses of silt in the waters of the Colorado River was made in 1907 and 1908, by the University of California for the Bureau of Public Roads. A sample of water with its quota of silt was taken daily from one of the Imperial Valley canals at Dahlia heading from October 1, 1907, to April 30, 1908, and the silt was analyzed in composite lots. The average results for the period are given in Table 59.

TABLE 59.—*Average chemical analysis of combined sediments from daily composite water samples taken at Dahlia heading, Imperial Valley, from October, 1907, to April, 1908, inclusive*

Constituent	Per cent	Constituent	Per cent
Insoluble matter	31.59	Peroxide of iron (Fe_2O_3)	5.26
Soluble silica	20.12	Alumina (Al_2O_3)	13.92
Potash (K_2O)	1.18	Phosphoric acid (P_2O_5)	.13
Soda (Na_2O)	.57	Sulphuric anhydride (SO_3)	.14
Lime (CaO)	5.35	Carbonic anhydride(CO_2) } Water and organic matter }	10.82
Magnesia (MgO)	1.89		
Brown oxide of manganese (Mn_3O_4)	.03		

SILT MEASUREMENTS IN RIVER

TOPOCK, AUGUST 1, 1917, TO JULY 15, 1918

Measurements of the quantities of suspended silt in the water of the river at Topock were made bimonthly from August 1, 1917, to July 15, 1918. Each sample of silt taken was separated into three grades as regards size of particle. Table 60 shows for each sample the proportion of silt by weight.

By averaging the total number of samples taken near the surface of the river and those taken at the middle and those taken near the bed the following percentages by weight of silt in the river are obtained: Near the surface, 0.898; at the middle, 0.967; near the bed, 1.148. Of the silt which did not pass through a sieve of 200 meshes to the inch average percentages by weight were as follows: 0.498 near the top, 0.576 at the middle, and 0.713 near the bottom of the cross

[2] W. H. Ross, of the University of Arizona.

section of the river at the gaging station. Of the percentage by weight of the fine silt which passes through a sieve of 200 meshes to the inch, the following averages appear: Near the top, 0.4 per cent; at the middle, 0.391 per cent; and near the bottom, 0.435 per cent.

TABLE 60.—*Suspended silt in three sections of the Colorado River at Topock, Ariz., at top, middle, and bottom depths, August, 1917, to July, 1918*

Date of sampling	Point of river cross section in which sample was taken		Proportion of silt by weight			
	Horizontal	Vertical	Passing No. 200 sieve	Retained on— No. 200 sieve	Retained on— No. 100 sieve	Total
1917			*Per cent*	*Per cent*	*Per cent*	*Per cent*
Aug. 1	¼ point	Top	0.925	0.415	0.153	1.340
		Middle	.911	.246	.080	1.157
		Bottom	.875	.323	.143	1.198
	Center	Top	.880	.326	.073	1.206
		Middle	.960	.390	.104	1.350
		Bottom	.892	.288	.083	1.180
	¾ point	Top	.852	.269	.055	1.121
		Middle	.905	.285	.075	1.190
		Bottom	.855	.344	.080	1.109
Aug. 16	¼ point	Top	.590	.058	.018	.648
		Middle	.593	.100	.057	.693
		Bottom	.695	.804	.430	1.499
	Center	Top	.720	.418	.156	1.138
		Middle	.675	.313	.143	.988
		Bottom	.660	1.005	.400	1.665
	¾ point	Top	.630	.054	.008	.684
		Middle	.760	.276	.031	1.036
		Bottom	.660	.055	.021	.715
Sept. 1	¼ point	Top	.186	.147	.081	.333
		Middle	.435	5.270	4.660	5.705
		Bottom	.310	2.160	1.385	2.470
	Center	Top	.247	3.325	2.725	3.572
		Middle	.171	1.085	.872	1.256
		Bottom	.372	6.000	4.500	6.372
	¾ point	Top	.168	.317	.231	.485
		Middle	.200	2.548	2.450	2.748
		Bottom	.162	.275	.132	.437
Sept. 16	¼ point	Top	.241	.064	.017	.305
		Middle	.233	.000	.000	.233
		Bottom	.221	1.575	1.052	1.796
	Center	Top	.189	.918	.562	1.107
		Middle	.283	1.375	.809	1.658
		Bottom	.289	3.420	2.735	3.709
	¾ point	Top	.199	.024	.006	.223
		Middle	.239	2.170	1.810	2.409
		Bottom	.272	1.460	.815	1.732
Oct. 1	¼ point	Top	.432	.043	.009	.475
		Middle	.451	.099	.032	.550
		Bottom	.528	.240	.065	.768
	Center	Top	.870	4.025	3.780	4.895
		Middle	.408	.089	.048	.497
		Bottom	.465	2.500	2.110	2.965
	¾ point	Top	.540	4.075	3.530	4.615
		Middle	.420	.382	.190	.802
		Bottom	.540	.506	.318	1.046
Oct. 15	¼ point	Top	.191	.032	.007	.223
		Middle	.203	.039	.000	.242
		Bottom	.204	.082	.019	.286
	Center	Top	.238	1.852	1.230	2.090
		Middle	.205	.450	.244	.655
		Bottom	.195	.432	.234	.627
	¾ point	Top	.190	1.240	.870	1.430
		Middle	.165	.066	.018	.231
		Bottom	.380	4.170	3.570	4.550
Nov. 1	¼ point	Top	.132	.181	.012	.313
		Middle	.122	.108	.019	.230
		Bottom	.159	.217	.034	.376
	Center	Top	.407	5.340	4.040	5.747
		Middle	.394	4.975	3.260	5.369
		Bottom	.166	.665	.338	.831
	¾ point	Top	.020	.000	.000	.020
		Middle	.022	.000	.000	.022
		Bottom	.061	.000	.000	.061

TABLE 60.—*Suspended silt in three sections of the Colorado River at Topock, Ariz., at top, middle, and bottom depths, August, 1917, to July, 1918*—Continued

Date of sampling	Point of river cross section in which sample was taken: Horizontal	Point of river cross section in which sample was taken: Vertical	Proportion of silt by weight: Passing No. 200 sieve	Proportion of silt by weight: Retained on— No. 200 sieve	Proportion of silt by weight: Retained on— No. 100 sieve	Proportion of silt by weight: Total
1917			*Per cent*	*Per cent*	*Per cent*	*Per cent*
Nov. 15	¼ point	Top	0.111	0.062	0.028	0.173
		Middle	.063	.109	.018	.190
		Bottom	.102	.182	.046	.284
	Center	Top	.103	1.800	.676	1.903
		Middle	.172	3.820	3.018	3.992
		Bottom	.204	6.050	5.150	6.254
	¾ point	Top	.069	.000	.000	.069
		Middle	.093	.000	.000	.093
		Bottom	.235	.159	.005	.394
Dec. 1	¼ point	Top	.091	.004	.000	.095
		Middle	.100	.000	.000	.100
		Bottom	.170	.190	.050	.360
	Center	Top	.236	1.371	.993	1.607
		Middle	.551	6.050	4.700	6.601
		Bottom	.205	1.489	1.202	1.694
	¾ point	Top	.076	.000	.000	.076
		Middle	.104	.004	.000	.108
		Bottom	.116	.007	.000	.123
Dec. 15	¼ point	Top	.138	.060	.003	.198
		Middle	.139	.024	.000	.163
		Bottom	.158	.748	.231	.906
	Center	Top	.182	.227	.007	.400
		Middle	.223	.592	.082	.815
		Bottom	.321	.378	.040	.699
	¾ point	Top	.117	.031	.000	.148
		Middle	.135	.084	.000	.219
1918		Bottom	.148	.073	.066	.221
Jan. 1	¼ point	Top	.092	.219	.000	.311
		Middle	.076	.079	.021	.155
		Bottom	.102	.046	.010	.148
	Center	Top	.091	.313	.000	.404
		Middle	.167	.538	.117	.705
		Bottom	.127	1.020	.662	1.147
	¾ point	Top	.058	.000	.000	.058
		Middle	.102	.013	.000	.115
		Bottom	.147	.048	.008	.195
Jan. 15	¼ point	Top	.061	.001	.000	.062
		Middle	.121	.113	.032	.234
		Bottom	.157	.060	.008	.217
	Center	Top	.186	.520	.328	.706
		Middle	.196	.437	.167	.633
		Bottom	.128	.927	.648	1.065
	¾ point	Top				
		Middle	.088	.026	.007	.114
		Bottom	.125	.031	.010	.156
Feb. 1	¼ point	Top				
		Middle	.077	.011	.000	.088
		Bottom				
	Center	Top	.110	.082	.012	.192
		Middle	.067	.003	.000	.070
		Bottom	.107	.107	.011	.214
	¾ point	Top	.043	.000	.000	.043
		Middle	.055	.001	.000	.056
		Bottom	.293	.026	.000	.319
Feb. 15	¼ point	Top	.077	.002	.000	.079
		Middle	.114	.065	.007	.179
		Bottom	.101	.043	.003	.147
	Center	Top	.098	.044	.006	.142
		Middle	.111	.067	.009	.178
		Bottom	.121	.131	.020	.252
	¾ point	Top	.074	.004	.000	.078
		Middle	.073	.002	.000	.075
		Bottom	.085	.002	.000	.087
Mar. 1	¼ point	Top	.155	.097		.252
		Middle	.117	.071		.188
		Bottom	.153	.082		.235
	Center	Top	.104	.326	.165	.430
		Middle	.141	.339	.075	.480
		Bottom	.205	.353	.073	.558
	¾ point	Top	.183	.616	.168	.799
		Middle	.138	.545	.103	.683
		Bottom	.224	.573	.147	.797

TABLE 60.—*Suspended silt in three sections of the Colorado River at Topock, Ariz., at top, middle, and bottom depths, August, 1917, to July, 1918*—Continued

Date of sampling	Point of river cross section in which sample was taken		Proportion of silt by weight			
	Horizontal	Vertical	Passing No. 200 sieve	Retained on—		Total
				No. 200 sieve	No. 100 sieve	
1918			*Per cent*	*Per cent*	*Per cent*	*Per cent*
Mar. 16	¼ point	Top	1.730	0.014	----------	1.744
		Middle	1.720	.038	----------	1.758
		Bottom	1.680	.022	----------	1.702
	Center	Top	1.698	.145	----------	1.843
		Middle	1.800	.384	----------	2.184
		Bottom	1.780	.319	0.142	2.099
	¾ point	Top	1.730	.168	----------	1.808
		Middle	1.760	.144	----------	1.904
		Bottom	1.690	.089	----------	1.779
Apr. 1	¼ point	Top	.388	.032	.005	.420
		Middle	.388	.032	.004	.420
		Bottom	.385	.018	.004	.403
	Center	Top	.435	1.076	.504	1.511
		Middle	.517	1.164	.529	1.681
		Bottom	.540	1.050	.755	1.590
	¾ point	Top	.366	.009	.000	.375
		Middle	.383	.007	.000	.390
		Bottom	.594	.010	.000	.604
Apr. 15	¼ point	Top	.224	.035	.007	.259
		Middle	.218	.021	.007	.239
		Bottom	.295	.040	.009	.335
	Center	Top	.280	.340	.083	.620
		Middle	.319	.935	.440	1.254
		Bottom	.338	1.565	.932	1.903
	¾ point	Top	.195	.024	.019	.219
		Middle	.184	.008	----------	.192
		Bottom	.227	.106	.028	.333
May 1	¼ point	Top	.224	.017	.003	.241
		Middle	.221	.004	.000	.225
		Bottom	.313	.069	.010	.382
	Center	Top	.218	.002	.000	.220
		Middle	.186	.023	.004	.209
		Bottom	.222	.066	.020	.288
	¾ point	Top	.070	.000	.000	.070
		Middle	.067	.001	.000	.068
		Bottom	.144	.485	.154	.629
May 16	¼ point	Top	.402	.011	.000	.413
		Middle	.440	.065	.012	.505
		Bottom	.454	.071	.014	.525
	Center	Top	.527	.505	.219	1.032
		Middle	.445	.541	.240	.986
		Bottom	.414	.377	.173	.791
	¾ point	Top	.395	.264	.103	.659
		Middle	.356	.224	.085	.580
		Bottom	.364	.362	.127	.726
June 1	¼ point	Top	.264	.048	.010	.312
		Middle	.239	.032	.007	.271
		Bottom	----------	----------	----------	----------
	Center	Top	.214	.097	.051	.311
		Middle	.302	.236	.064	.538
		Bottom	.345	.303	.086	.648
	¾ point	Top	.445	.820	.240	1.265
		Middle	.300	1.113	.750	1.413
		Bottom	.662	3.380	2.690	4.042
June 15	¼ point	Top	.239	.019	.000	.258
		Middle	.242	.027	.000	.269
		Bottom	.225	.014	.000	.239
	Center	Top	.132	1.215	.546	1.347
		Middle	.262	1.075	.618	1.337
		Bottom	.211	.402	.212	.613
	¾ point	Top	.079	.007	.000	.086
		Middle	.090	.006	.000	.096
		Bottom	.080	.000	.000	.080
July 1	¼ point	Top	.560	.071	----------	.631
		Middle	.570	.135	----------	.705
		Bottom	.580	.245	----------	.825
	Center	Top	.502	.422	----------	.924
		Middle	----------	----------	----------	----------
		Bottom	.559	.642	----------	1.201
	¾ point	Top	.410	.058	----------	.468
		Middle	.399	.037	----------	.436
		Bottom	.421	.037	----------	.458

TABLE 60.—*Suspended silt in three sections of the Colorado River at Topock, Ariz., at top, middle, and bottom depths, August, 1917, to July, 1918*—Continued

Date of sampling	Point of river cross section in which sample was taken		Proportion of silt by weight			
	Horizontal	Vertical	Passing No. 200 sieve	Retained on— No. 200 sieve	Retained on— No. 100 sieve	Total
1918			*Per cent*	*Per cent*	*Per cent*	*Per cent*
July 15	¼ point	Top	1.770	0.007		1.777
		Middle	1.944	.295		2.239
		Bottom	2.071	.122		2.193
	Center	Top	1.612	.127		1.739
		Middle				
		Bottom	1.533	.706		2.239
	¾ point	Top	1.590	.447		2.037
		Middle	2.030	.493		2.523
		Bottom	1.648	.134		1.782

The results of the investigations at Topock show that for the 12-month period 51.5 per cent of the silt carried in suspension was fine enough to pass through a No. 200 sieve. The records for the amount of silt retained on a No. 100 sieve were not complete for the year, but for the period of 11 months the records showed 57,157,000 tons of such material or 37 per cent of the total suspended-silt load for that period.

YUMA, JULY 30, 1917, TO JULY 29, 1918

To permit a comparison with the measurements made at Topock the results of somewhat similar measurements made during the same period at Yuma are given in Table 61.

TABLE 61.—*Proportion of silt by weight at three stations in the Colorado River at Yuma, at top, middle, and bottom depths, from July 30, 1917, to July 29, 1918*

Date	Station	Depth	Proportion of silt by weight — Top	Proportion of silt by weight — Middle	Proportion of silt by weight — Bottom	Discharge	Mean velocity
1917	*Feet*	*Feet*	*Per cent*	*Per cent*	*Per cent*	*Second-feet*	*Feet per second*
July 30	150	8.0	0.42	0.55		34,800	6.10
	360	11.5	.49	.64	0.57		
	540	6.0	.40	.42			
Aug. 4	150	20.0	.80	.89		38,100	6.52
	360	10.5	.80	.85	.74		
	510	5.0	.97	.78			
Aug. 6	150	15.0	.61	.74		33,000	5.84
	350	11.5	.63	.69	1.28		
	520	2.0	.78				
Aug. 10	150	18.5	.73	.76		20,100	5.24
	360	11.5	.66	.63	.84		
	540	3.5	.66				
Aug. 13	150	18.5	.51	.52		24,000	4.63
	360	10.0	.42	.51	.64		
Aug. 17	160	14.0	.59	.61	.66	18,400	4.70
	340	8.5	.63	.66	.78		
Aug. 20	160	12.5	.54	.64	.76	18,900	5.30
	340	8.0	.50	.94	.85		
	500	4.5	.47	.50	.97		
Aug. 23	160	12.0	.55	.57	.68	17,500	4.81
	340	8.0	.51	.49	1.60		
	490	5.0	.91	.63	1.09		
Aug. 27	160	12.0	.73	.84	.84	13,800	3.69
	340	8.5	.66	.84	.94		
	490	5.0	.71	.76	.82		
Aug. 30	160	11.5	.37	.37	.47	11,600	3.02
	340	7.5	.37	.40	.73		
	490	3.0	.43	.43	.47		

TABLE 61.—*Proportion of silt by weight at three stations in the Colorado River at Yuma, at top, middle, and bottom depths, from July 30, 1917, to July 29, 1918*—Continued

Date	Station	Depth	Proportion of silt by weight			Discharge	Mean velocity
			Top	Middle	Bottom		
1917	*Feet*	*Feet*	*Per cent*	*Per cent*	*Per cent*	*Second-feet*	*Feet per second*
Sept. 3	160	10.0	0.21	0.24	0.28	10,800	3.53
	340	6.0	.22	.64	.33		
	490	4.0	.22	.26	.26		
Sept. 6	160	9.0	.17	.16	.26	8,300	3.14
	340	6.5	.17	.35	.33		
	490	4.5	.21	.21	.22		
Sept. 10	160	9.5	.12	.21	.24	8,400	3.07
	340	6.5	.12	.21	.30		
	490	4.5	.14	.14	.12		
Sept. 13	160	11.0	.52	.16	.12	7,600	2.68
	340	6.0	.09	.14	.51		
	490	4.5	.09	.07	.09		
Sept. 17	160	9.0	.14	.17	.21	6,700	2.97
	340	4.0	.11	.16			
Sept. 21	170	0.0	.14	.14	.17	9,600	3.79
	350	6.5	.12	.21	.20		
	530	3.0	.12				
Sept. 24	170	8.0	.22	.24	.24	9,300	4.17
	350	5.0	.22	.21	.21		
Sept. 28	160	10.0	1.01	.90	1.11	10,100	
	340	4.0	.94	.97	.95		
Oct. 1	170	8.0	.47	.45	.42	8,100	3.28
	380	6.0	.51	.40	.42		
Oct. 5	160	9.5	.52	.61	.47	8,800	2.73
	340	7.5	.43	.54	.47		
	490	4.5	.57				
Oct. 8	160	10.0	.35	.37	.38	8,200	2.59
	340	8.0	.37	.43	.37		
	490	4.5	.33				
Oct. 12	170	10.0	.38	.28	.32	8,100	2.63
	350	8.0	.28	.30	.32		
	530	4.0	.30				
Oct. 19	160	9.0	.22	.28	.22	7,200	2.46
	350	8.0	.22	.26	.16		
	530	4.0	.21	.21	.22		
Oct. 22	170	8.5	.17	.17	.20	6,700	2.48
	320	6.5	.17		.14		
	500	5.0	.26	.22	.21		
Oct. 26	170	9.0	.17	.17	.17	6,700	2.30
	350	8.0	.14	.28	.17		
	530	4.5	.24	.21	.20		
Oct. 29	170	8.5	.12	.12	.12	5,000	2.22
	320	7.5	.09	.12	.16		
	500	4.0	.14	.09	.12		
Nov. 2	170	8.0	.12	.14	.14	7,400	2.00
	350	9.0	.12	.16	.14		
	500	4.0	.30	.21	.30		
Nov. 5	170	8.0	.14	.17	.12	5,000	2.37
	320	9.0	.16	.17	.12		
	500	3.0	.17	.20	.14		
Nov. 9	170	9.0	.14	.14	.12	7,600	2.61
	350	8.5	.12	.12	.11		
	500	3.0	.21	.03	.11		
Nov. 12	170	8.0	.12	.12	.11	6,800	2.46
	350	7.0	.14	.16	.12		
	500	3.0	.12	.17	.22		
Nov. 16	170	7.0	.12	.12	.11	7,500	2.85
	350	6.0	.14	.16	.12		
	500	3.0	.12	.17	.22		
Nov. 19	170	7.0	.14	.11	.14	6,400	2.83
	350	4.0	.11	.11	.14		
	500	2.0	.11				
Nov. 23	170	9.0	.16	.09	.11	7,300	2.61
	350	2.0	.07	.12	.12		
	500	3.0	.11	.11	.14		
Nov. 26	170	8.5	.09	.14	.12	6,800	2.00
	320	9.5	.09	.11	.09		
	500	3.0		.11			
Nov. 30	170	10.0	.11	.12	.17	7,300	2.07
	320	9.0	.11	.12	.12		
	500	3.0	.24	.09			
Dec. 3	170	11.0	.12	.11	.16	6,800	2.57
	320	5.0	.09	.14	.11		
	500	2.0	.14				

TABLE 61.—*Proportion of silt by weight at three stations in the Colorado River at Yuma, at top, middle, and bottom depths, from July 30, 1917, to July 29, 1918*—Continued

Date	Station	Depth	Proportion of silt by weight			Discharge	Mean velocity
			Top	Middle	Bottom		
1917	*Feet*	*Feet*	*Per cent*	*Per cent*	*Per cent*	*Second-feet*	*Feet per second*
Dec. 7	170	12.0	0.11	0.09	0.16	7,200	2.88
	320	4.0	.09	.11	.11		
	500	2.0	.11				
Dec. 10	170	14.0	.20	.17	.12	7,300	2.90
	320						
	520	2.0	.10				
Dec. 14	160	15.0	.07	.12	.12	7,700	2.85
	340	1.5	.09				
	520	1.0	.14				
Dec. 17	160	16.0	.11	.16	.17	7,000	2.88
	340	1.5	.14	.12	.12		
	520	1.0	.15				
Dec. 21	170	15.5	.12	.12	.12	6,200	2.61
	350	4.5	.11	.12	.11		
Dec. 24	170	14.0	.14	.14	.16	6,200	2.83
	350	6.0	.11	.14	.17		
	530	1.0	.12				
Dec. 28	160	15.5	.12	.12	.14	6,200	2.51
	340	8.0	.14	.16	.14		
	550	2.0	.17				
Dec. 31	160	12.0	.12	.17	.21	6,300	2.54
	340	8.0	.11	.14	.11		
1918							
Jan. 4	160	8.5	.12	.17	.32	7,000	2.96
	340	9.0	.26	.26	.20		
	550	1.5	.16				
Jan. 7	170	6.0	.11	.11	.16	7,700	2.85
	350	10.0	.09	.12	.14		
	550	2.0	.28				
Jan. 11	170	7.0	.24	.12	.16	7,300	2.49
	350	9.5	.07	.14	.14		
	560	2.0	.16	.14	.20		
Jan. 14	170	6.5	.12	.14	.11	7,200	2.80
	350	8.5	.09	.21	.21		
	500	7.5	.17	.14	.16		
Jan. 18	180	6.0	.12	.14	.20	6,900	2.68
	360	6.5	.07	.12	.11		
	510	7.0	.12	.20	.21		
Jan. 21	170	7.5	.12	.16	.21	7,100	2.86
	320	2.5	.12	.14	.16		
	500	9.0	.17	.16	.16		
Jan. 25	170	8.0	.09	.11	.14	5,300	
	380	4.0	.07	.12	.17		
	500	9.5	.11	.14	.22		
Jan. 28	170	5.5	.11	.11	.09	5,000	2.53
	380	2.5	.11				
	500	9.5	.07	.11	.21		
Feb. 1	170	5.5	.32	.32	.35	5,400	2.66
	370	2.0	.26				
	520	8.0	.28	.24	.40		
Feb. 4	170	6.0	.20	.16	.16	7,000	3.13
	350	2.0	.12	.16			
	530	9.0	.16	.16	.24		
Feb. 8	170	6.0	.11	.09	.11	5,700	2.86
	350	1.0	.09				
	500	9.0	.09	.11	.14		
Feb. 11	170	5.0	.11	.11	.11	5,200	2.63
	350	1.5	.07				
	500	10.0	.05	.11	.12		
Feb. 15	170	2.5	.09	.07		4,900	2.52
	360	.5	.07				
	510	9.0	.07	.07	.14		
Feb. 18	170	4.5	.11	.14		5,100	2.57
	330	1.5	.21				
	500	10.0	.10	.12	.20		
Feb. 23	170	9.0	.12	.12	.20	6,800	2.70
	350	3.0	.12	.12			
	500	10.0	.12	.12	.16		
Feb. 25	170	9.0	.12	.20	.24	6,600	
	350	3.0	.09	.16			
	530	13.0	.16	.14	.14		
Mar. 1	170	10.5	.07	.14	.12	6,700	2.01
	350	2.5	.09	.09			
	500	8.5	.09	.12	.14		

TABLE 61.—*Proportion of silt by weight at three stations in the Colorado River at Yuma, at top, middle, and bottom depths, from July 30, 1917, to July 29, 1918*—Continued

Date	Station	Depth	Proportion of silt by weight			Discharge	Mean velocity
			Top	Middle	Bottom		
1918	*Feet*	*Feet*	*Per cent*	*Per cent*	*Per cent*	*Second-feet*	*Feet per second*
Mar. 4	170	10.5	0.22	0.22	0.21	7,000	2.53
	350	2.5	.20	.20			
	500	8.5	.24	.22	.26		
Mar. 8	170	10.0	.22	.20	.22	8,400	3.05
	350	2.0	.33				
	500	9.5	.20	.28	.32		
Mar. 11	170	10.0	1.16	1.37	1.65	21,800	6.45
	350	5.5	1.39	2.01	1.80		
Mar. 15	150	15.0	1.34	1.44	1.49	40,000	8.05
	330	10.0	1.21	1.18	1.68		
	510	7.5	1.51	1.46			
Mar. 18	150	21.5	.92	1.98	1.70	27,200	4.83
	330	15.0	1.39	2.00	1.42		
	510	3.0	1.46				
Mar. 22	170	18.5	1.28	1.72	1.63	19,600	3.69
	350	13.5	1.20	1.53	1.67		
	470	6.0	1.51	1.70	1.88		
Mar. 25	170	17.0	1.39	1.15	1.32	14,300	3.60
	320	10.5	1.15	1.46	.97		
	440	7.0	.78	.78	.76		
Mar. 29	170	14.5	.71	.64	.70	11,700	3.22
	290	10.5	.61	.66	.84		
	410	8.0	1.13	.85	1.01		
Apr. 1	170	14.0	.35	.40	.45	10,300	2.65
	290	11.0	.33	.49	.51		
	410	7.0	.35	.43	.49		
Apr. 5	170	13.0	.47	.45	.52	10,300	2.91
	290	11.0	.47	.45	.62		
	410	7.0	.47	.57	.52		
Apr. 8	170	11.0	.35	.43	.51	10,500	3.33
	290	9.0	.40	.45	.52		
	410	6.5	.38	.47	.54		
Apr. 15	170	10.0	.32	.37	.52	13,100	4.58
	290	9.0	.37	.47	.51		
	410	6.0	.33	.37	.51		
Apr. 19	170	9.5	.28	.28	.37	11,300	3.84
	320	7.0	.24	.35			
	470	5.5	.26	.26	.30		
Apr. 22	170	10.0	.22	.26	.38	14,100	5.06
	320	6.5	.37	.26	.37		
	500	4.0	.22	.22	.33		
Apr. 26	170	10.0	.45	.35	.40	17,000	5.63
	320	6.5	.38	.43	.68		
	500	6.0	.45	.40	.55		
Apr. 29	170	11.0	.22	.30	.26	15,700	5.02
	350	6.0		.28	.42		
	500	3.0	.30	.28			
May 3	170	13.0	.21	.30	.35	11,100	3.07
	350	5.0	.22	.37	.30		
	530	6.0	.28	.24	.28		
May 6	170	15.0	.24	.28	.33	14,900	3.30
	350	10.0	.28	.30	.33		
	530	5.5	.57	.33			
May 10	170	13.0	.26	.40	.28	15,500	4.25
	350	7.0	.22	.49	.30		
	530	5.0	.24	.24	.30		
May 13	170	12.0	.26	.61	.49	23,000	6.25
	350	8.0	.66	.52	.91		
	530	6.0	.85	.73	.82		
May 17	140	15.5	.66	.69	.68	34,300	6.33
	350	10.0	.63	.80	.89		
	560	10.5	.66	.60	.89		
May 20	150	17.5	.68	.59	.51	34,000	5.44
	300	11.0	.51		.64		
	540	9.5	.63	.61	.63		
May 24	150	20.0	.64	.66	.69	38,000	5.18
	360	13.0		.89			
	540	10.0	.80	.69	.73		
May 27	150	25.0	.47	.57	.87	47,000	5.51
	360	21.0	.40	.59	.99		
	540	9.5		.54	.60		
May 31	140	23.0	.51	.51	.52	48,800	5.34
	350	18.0	.42	.85			
	530	9.0	.68	.55	.60		

TABLE 61.—*Proportion of silt by weight at three stations in the Colorado River at Yuma, at top, middle, and bottom depths, from July 30, 1917, to July 29, 1918*—Continued

Date	Station	Depth	Proportion of silt by weight			Discharge	Mean velocity
			Top	Middle	Bottom		
1918	*Feet*	*Feet*	*Per cent*	*Per cent*	*Per cent*	*Second-feet*	*Feet per second*
June 3	140	20.0	0.49	0.59	0.61	49,600	5.45
	350	20.0	.73	.40	.84		
	530	9.5		.52	.51		
June 7	140	27.0	.47	.52	.64	40,500	4.91
	350	19.0	.43	.47	.61		
	530	8.5	.57	.51	.51		
June 10	150	27.5	.49	.59	.52	30,300	5.00
	300	13.5		.66	.45		
	540	5.0		.45	.59		
June 14	150	24.5	.40	.49	.54	48,100	5.98
	300	14.0	.68	.52	.69		
	540	8.0	.71	.49	.57		
June 17	140	26.5	.40	.51	.40	52,600	5.93
	350	19.5	.51	.45	.60		
	530	7.5	.64	.42	.49		
June 21	140	35.0	.57	.42	.55	72,100	6.08
	350	22.0	.54	.42	.68		
	530	12.0	.51	.45	.54		
June 24	130	31.0		.42	.51	85,500	6.06
	340	26.[illegible]	.57	.38			
	550	16.[illegible]	.37	.38	.47		
June 28	130	30.5	.40	.45	.63	92,000	6.10
	340	32.5	.69				
	550	18.5		.43	.52		
July 1	140	37.0	.64	.92	.95	92,300	5.93
	350	33.5	.87	.99	1.16		
	530	17.0	1.09	.63	.69		
July 5	140	36.5	.38	.43	.45	88,000	5.76
	350	36.0	.37		.38		
	530	16.5	.54	.55	.51		
July 8	160	33.0	.59	.63	.59	50,000	5.09
	340	22.0	.51		.52		
	520	12.0	.82	.80	.52		
July 12	170	23.5	.61	.71	.52	33,200	5.01
	350	14.0	.45	.73			
	530	5.5	.47	.45	.57		
July 15	170	22.5	.43	.57	.40	33,100	5.22
	350	13.5	.82	.82	.40		
	530	6.0	.64				
July 19	170	23.5	1.04	1.36	1.04	40,500	6.01
	350	15.0	1.29	1.67	1.09		
	530	7.5	1.53	1.65	1.42		
July 22	170	22.0	1.67	1.90	1.93	32,000	5.60
	350	11.0	1.76	2.15	1.95		
	530	6.0	1.84	1.98	2.00		
July 26	170	18.0	1.42	1.69	1.65	22,400	4.83
	350	9.0	1.40	1.65	1.62		
	530	5.0	1.70	1.46	1.58		
July 29	170	10.0	.94	1.11	1.29	18,100	4.39
	350	7.5	1.02	1.22	1.29		
	530	5.5	1.08	1.04	1.11		

EARLY SILT DETERMINATIONS AT YUMA

For a period of seven months beginning August 1, 1892, C. B. Collingwood, of the University of Arizona (*3*) took samples of the Colorado River water from the railroad bridge at Yuma. A pint of water was taken daily from the river. A dry-silt content was shown, ranging from 1.031 per cent by weight in October, 1892, to 0.163 per cent in January, 1893, the average being 0.258 per cent for the seven-month period.

For over a third of a century samples of the Colorado River water at Yuma have been taken at various periods, and the silt content has been determined. The earlier measurements were made by the University of Arizona Agricultural Experiment Station and the United States Geological Survey. Later the Bureau of Reclamation began taking samples regularly and is still doing so. For this reason the division of agricultural engineering confined its silt investigations at Yuma to special studies. The results obtained by the different agencies are given briefly.

Under the direction of R. H. Forbes, director of the Arizona Agricultural Experiment Station, samples of Colorado River water were taken from the edge of the river at Yuma near the left bank from January 10, 1900, to January 24, 1901. The samples were combined in sets, six consecutive samples forming a set, and the dry-silt content of each set was determined. The results ranged from a minimum content of 0.033 per cent by weight, September 8 to 13, 1900, to a maximum of 2.072 per cent October 8 to 13, 1900, the mean for the period being 0.278 per cent (*6*).

The study was resumed at Yuma by Forbes, January 1, 1904, and continued throughout the calendar year. The percentage by weight of dry silt in the samples taken varied from 0.084 to 3.263 (*7*).

The United States Geological Survey, in cooperation with the Bureau of Reclamation, determined the content of suspended silt at this point throughout 1903. The maximum and minimum quantities of dry silt obtained expressed in percentages by weight for each month are given in Table 62, which also shows the mean monthly flow of the river in acre-feet for 1903, and an approximate estimate, by the present authors, of the mean monthly content of silt, expressed in percentages and tons.

TABLE 62.—*Monthly discharge and silt content of Colorado River at Yuma, Ariz., 1903* [1]

Month	Proportion of silt by weight			Discharge [3]	Silt content
	Maximum	Minimum	Mean [2]		
	Per cent	*Per cent*	*Per cent*	*Acre-feet*	*Tons*
January	0.0785	0.0461	0.0623	190,000	160,500
February	.1465	.0688	.1076	187,000	273,500
March	1.4468	.0876	.7672	376,000	3,927,000
April	1.9159	1.4468	1.6813	852,000	19,500,000
May	.7969	.6190	.7079	2,074,000	19,986,000
June	.5490	.7437	.6463	3,163,000	27,827,000
July	.6693	.6543	.6618	2,304,000	20,756,000
August	.6543	----------	.6543	668,000	5,950,000
September	.9197	----------	.9107	404,000	5,058,000
October	.9665	.7329	.8497	522,000	6,037,000
November	.2688	.1195	.1941	321,000	848,000
December	.1362	.0970	.1166	207,000	423,000
Total for the year	----------	----------	----------	11,328,000	110,746,000

[1] Assembled from unpublished records in Yuma project office, U. S. Bureau of Reclamation.
[2] Estimated from maximum and minimum monthly percentages.
[3] For 1903, the discharge of Colorado River at Yuma was 68 per cent of the normal flow.

During 1905 the United States Geological Survey (*25*) took daily samples of the water. In making the analyses three individual samples were combined to form composite samples. The results were given in terms of "milligrams per liter." This unit has been reduced to percentage by weight in Table 63.

TABLE 63.—*Monthly discharge and silt content of Colorado River at Yuma, Ariz., 1905*

Period	Proportion of silt by weight for period			Discharge [1]	Silt content per month
	Maximum	Minimum	Mean		
	Per cent	*Per cent*	*Per cent*	*Acre-feet*	*Tons*
Jan. 1 to Jan. 31	0.816	0.0741	0.2570	500,000	1,753,300
Feb. 2 to Feb. 28	2.350	.3080	1.3009	1,561,000	27,643,000
Mar. 1 to Mar. 30	3.080	1.8100	2.5330	3,108,000	107,105,300
Mar. 31 to May 1	2.050	1.4400	1.9560	2,251,000	59,935,200
May 2 to May 31	2.720	.6050	1.4176	2,593,000	50,037,300
June 1 to June 30	.527	.1610	.3620	4,550,000	22,421,100
July 1 to Aug. 1	.475	.2240	.3102	1,864,000	8,099,300
Aug. 4 to Aug. 30	.900	.1760	.3829	744,000	3,877,000
Aug. 31 to Oct. 2	.899	.1230	.4189	386,000	2,201,100
Oct. 3 to Nov. 2	1.300	.4660	.8706	494,000	5,804,800
Nov. 4 to Nov. 30	1.230	.1510	.4120	714,000	4,004,400
Dec. 1 to Dec. 30	2.420	.4120	1.2175	947,000	15,604,800
Total for year	----------	----------	----------	19,712,000	308,727,500

[1] For 1905, the discharge of Colorado River at Yuma was 110 per cent of the normal flow.

SILT MEASUREMENTS AT IMPERIAL IRRIGATION DISTRICT INTAKE

The suspended silt in the water entering the Imperial irrigation district through the Alamo Canal under varying discharges of the Colorado River and intake control was determined as to quantity and character by nine sets of measurements between September 29, 1917, and July 26, 1920. The results of typical sets are given in Tables 64 to 69.

On September 28, 1917, the flow of the Colorado River at Yuma was 10,100 second-feet, and the percentage by weight of suspended silt was 0.99. The next day the Alamo Canal at Hanlon heading was carrying 5,068 second-feet. The canal was 119 feet wide where the samples were taken, and its maximum depth was 13.3 feet. Rockwood intake was not then in operation, and all the gates of the Hanlon intake were wide open. The figures given in Table 64 show that almost all the silt entering the canal was fine enough to pass a sieve of 200 meshes to the inch, and that the total quantity did not differ materially from that carried in the river 8 miles above the intake.

Table 64.—*Proportion of silt by weight at each of 35 points in the cross section of the Alamo Canal immediately below Hanlon intake, September 29, 1917*

Station	Depth to sample	Velocity at point	Proportion of silt by weight		
			No. 200 sieve		Total
			Passing	Retained	
Feet	*Feet*	*Feet per second*	*Per cent*	*Per cent*	*Per cent*
8.5	0.3	2.82	0.997	0.000	0.997
	1.6	3.20	.996	.000	.996
	4.8	2.69	.990	.002	.992
	6.4	1.79	.984	.002	.986
	7.0	1.57	.978	.001	.979
25.5	.3	4.07	.968	.002	.970
	2.6	4.29	.985	.001	.986
	7.8	3.31	.990	.004	.994
	10.4	2.59	.958	.019	.977
	12.0	1.08	.977	.005	.982
42.5	.3	4.31	.955	.002	.957
	2.6	4.40	.956	.002	.958
	7.8	3.46	.957	.008	.965
	10.4	2.62	.947	.004	.951
	12.0	2.71	.945	.010	.955
59.5	.3	3.87	.914	.000	.914
	2.7	4.16	.942	.002	.944
	8.0	2.91	.942	.007	.940
	10.6	3.22	.942	.010	.952
	12.3	2.97	.950	.010	.960
76.5	.3	3.84	.920	.002	.922
	2.0	4.53	.921	.003	.924
	7.8	3.87	.936	.007	.943
	10.4	3.31	.936	.018	.954
	12.0	3.42	.941	.008	.949
93.5	.3	4.49	.924	.002	.926
	2.6	4.53	.931	.005	.936
	7.8	4.01	.942	.005	.947
	10.4	3.22	.931	.004	.935
	12.0	3.02	.931	.010	.941
110.5	.3	3.89	.930	.002	.932
	1.7	3.80			
	5.1	3.04	.990	.002	.992
	6.8	2.17	.892	.004	.896
	7.5	1.20	.883	.006	.889
119.0					

On October 14, 1918, similar investigations were made at the Rockwood intake. The Colorado River was then at a low stage, the flow at Yuma being 5,800 second-feet, of which 4,400 second-feet was being diverted through the Alamo Canal while the remainder was passing through a temporary weir below the Rockwood heading.

The gates of the Rockwood heading were open, and a stream of water about 6 feet deep was flowing through each of the 48 higher gates. Samples were taken at various depths as the water entered the second and twentieth gate of the higher series from the southwest end. The results of the sampling are given in Table 65.

TABLE 65.—*Proportion of silt, by weight, entering Rockwood heading, October 14, 1918*

Depth (feet)	Second gate from southwest end (mean velocity, 2.66 feet per second)			Depth (feet)	Twentieth gate from southwest end (mean velocity, 2.26 feet per second)		
	No. 200 sieve		Total		No. 200 sieve		Total
	Passing	Retained			Passing	Retained	
	Per cent	*Per cent*	*Per cent*		*Per cent*	*Per cent*	*Per cent*
Top	0.292	0.014	0.306	Top	0.272	0.001	0.273
2	.267	.010	.277	2	.292	.002	.294
3	.197	.009	.206	3	.206	.002	.208
4	.299	.018	.317	4	.291	.003	.294
5	.296	.018	.314	5	.292	.002	.294
5.8	.308	.018	.326	6	.298	.003	.301

The same day a few samples were taken at the center of the tenth gate of the lower series of 27 gates. The amount of fine silt passing a 200-mesh sieve varied from 0.216 to 0.32 per cent, while that of the coarser silt retained on the sieve varied from 0.02 to 0.091 per cent. The mean velocity of the water was 1.5 feet per second.

On October 15, 1918, two sets of samples were taken in the Alamo Canal, one 300 feet above Hanlon gate and another 500 feet below the gate. The results of the sampling are given in Table 66.

TABLE 66.—*Proportion of silt, by weight, in Alamo Canal at Hanlon gate, October 15, 1918*

Depth (feet)	300 feet above gate			Depth (feet)	500 feet below gate		
	No. 200 sieve		Total		No. 200 sieve		Total
	Passing	Retained			Passing	Retained	
	Per cent	*Per cent*	*Per cent*		*Per cent*	*Per cent*	*Per cent*
Top	0.490	0.002	0.492	Top	0.492	0.001	0.493
2	.450	.001	.451	3	.486	.001	.487
4	.507	.002	.509	6	(1)	.001	(1)
6	.511	.002	.513	9	.515	.007	.522
8	.475	.002	.477	12	.515	.001	.516
9	.510	.003	.513	15	.505	.001	.506
10½	.554	.008	.562	17½	.469	(1)	(1)

[1] Not available.

Several samples taken at Rockwood intake on October 15 showed an average silt percentage of 0.52, indicating that the amount had increased considerably over that during the previous days.

On October 19, 1918, 19 samples of water were taken at various depths at Rockwood heading. The sand (or that sediment held on the No. 200 sieve) varied from 0.001 to 0.013 per cent, averaging 0.004 per cent.

Samples were taken at Rockwood intake February 13, 1919, with the results shown in Table 67.

TABLE 67.—*Proportion of silt, by weight, at Rockwood heading, February 13, 1919*

Location of sample taken	Depth	Depth of water over flash-board	No. 200 sieve		Total
			Passing	Retained	
		Inches	*Per cent*	*Per cent*	*Per cent*
River, 18 feet from shore	Bottom		0.128	0.020	0.148
Do	do		.127	.011	.138
Northeast end of heading	Surface	18	.132	.011	.143
Do	1 foot	18	.123	.003	.126
Do	Bottom	18	.127	.010	.137
Center of heading	Surface	18	.131	.007	.138
Do	Bottom	18	.130	.015	.145
Southwest end of heading	Surface	18	.127	.004	.131
Do	Bottom	18	.119	.004	.123
Center of heading	Surface	8	.138	.013	.151
Do	Bottom	8	.131	.015	.146
Below heading	Surface		.127	.014	.141

On June 30, 1920, samples were taken at the current meter station of Alamo Canal 1,000 feet below Hanlon gate. There the canal was 160 feet wide, had a maximum depth of 12 feet, and was carrying 4,611 second-feet. The velocities in the vertical section varied from 1.77 feet per second near the bottom to 4.18 feet per second at 3 feet below the surface. The river discharge at Yuma was 160,000 cubic feet per second. The gates at Rockwood heading were closed, but water was flowing over the top. Water was going over the top of gates at Hanlon and all but one of the gates were closed. Table 68 shows the results of the sampling.

TABLE 68.—*Proportion, by weight, and grade of silt entering Imperial system at Hanlon, June 13, 1920*

Depth to sample (feet)	Velocity at point	Proportion of silt passing and retained on sieve with specified number of meshes per inch					
		Passing 40, retained on 60	Passing 60, retained on 100	Passing 100, retained on 200	Passing 200, retained on 280	Passing 280	Total
	Feet per second	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*
Top	3.60	0.000	0.002	0.002	0.008	0.292	0.304
2	3.98	.000	.001	.003	.019	.295	.318
4	3.60	.001	.004	.005	.017	.290	.317
6	3.47	.000	.001	.003	.013	.284	.301
8	2.91	.000	.001	.003	.019	.302	.325
9	2.57	.000	.001	.001	.019	.283	.304
10	2.06	.000	.001	.003	.018	.287	.309
10.5		.000	.002	.005	.028	.382	.417
11	1.77	.000	.001	.001	.020	.316	.338
11.5		.000	.001	.002	.031	.340	.374
11.8 [1]		.001	.001	.003	.014	.427	.446

[1] 0.2 foot above canal bed.

Samples of water entering Rockwood heading were taken July 25, 1920, at various depths in front of the structure. About 26,000 second-feet was flowing in the river, and 5,700 second-feet was entering the heading. Table 69 shows the result of the sampling.

TABLE 69.—*Proportion, by weight, and grade of silt entering Rockwood heading July 25, 1920*

Depth to sample (feet)	Velocity at point	Proportion of silt passing and retained on sieve with specified number of meshes per inch					
		Passing 40, retained on 60	Passing 60, retained on 100	Passing 100, retained on 200	Passing 200, retained on 300	Passing 300	Total
	Feet per second	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*
Top	2.17	0.000	0.000	0.001	0.003	0.204	0.208
2	5.09	.000	.000	.001	.003	.206	.210
3	5.38	.000	.000	.001	.005	.210	.216
4	5.83	.000	.000	.002	.011	.251	.264
5	5.90	.000	.001	.006	.018	.251	.276
7	4.83	.001	.008	.017	.029	.253	.308
9	4.82	.001	.007	.019	.030	.258	.315
10	4.65	.001	.004	.012	.029	.242	.288
10.5		.002	.023	.039	.044	.266	.374
10.8	3.78	.001	.007	.017	.044	.272	.341
11		.001	.004	.012	.049	.256	.322
11.2 [1]		.001	.007	.028	.031	.255	.322

[1] 0.2 foot above bed.

SILT IN THE YUMA PROJECT CANALS

The results of a number of silt determinations of the water of the Colorado River immediately above Laguna Dam and of the water in the main canal of the Federal project at Yuma, Ariz., showed that over half of the suspended silt was removed from the water during its passage through the settling basin and sluiceways. While this intake is the most effective that has been installed to date on the Colorado River, in ridding the water of its heavier silt it is creating a soil problem that may be difficult to solve. By the desilting process the clays and colloidal material are separated from the sand in the silt and deposited on the irrigated land. This annual deposition is bringing about a change in the character of the surface soil, making it more sticky, harder to cultivate, and more impervious.

The results of sampling August 1, 1918, in the main canal at meter stations 5 and 6 below the intake and at headquarters, 15 miles farther down the canal are shown in Table 70.

TABLE 70.—*Proportion of silt, by weight, and velocities in the Yuma project main canal, August 1, 1918*

(Velocity at middle depth, 2.5 feet per second)

Depth (feet)	Meter station at intake No. 5		Depth (feet)	Meter station at intake No. 6		Depth (feet)	Yuma head-quarters, silt content
	Silt content	Velocity		Silt content	Velocity		
	Per cent	*Feet per second*		*Per cent*	*Feet per second*		*Per cent*
Top	0.100		Top	0.286	2.56	Top	0.320
1		2.79	1		3.00	Middle	.328
2		3.03	2		2.80	Bottom	.334
3	.313	2.77	3		3.07		
4	.313	2.66	4				
5	.314	2.57	5	.322	2.03		
6	.315	2.20	6	.308			
7	.325	1.01	7	.330	1.27		
7.5 [1]	.338		7.8 [1]	.324			

[1] Bottom.

On August 2, 1918, the average percentage of silt in the project main canal at the intake was 0.252.

On August 3, 1918, tests were made on some of the lower canals. Their locations and the average percentage of silt found at each are shown in Figure 12. Table 71 gives a summary of the results of the sampling.

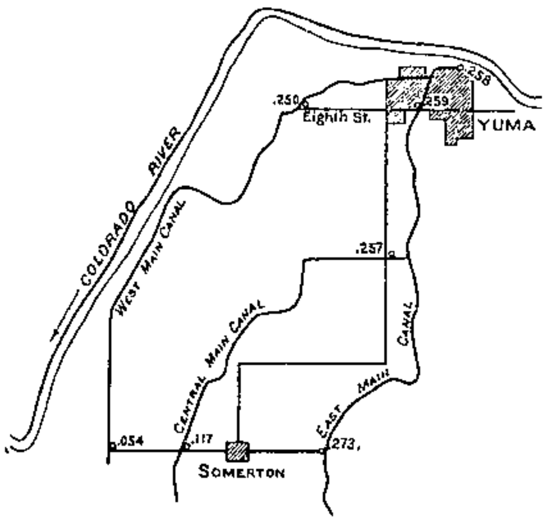


FIG. 12.—Location of silt tests on some of the lower canals of the Yuma project and the average percentage of silt in each

TABLE 71.—*Proportion of silt, by weight, at middle depths in the lower Yuma project canal system, August 3, 1918*

Canal	Location	Sample 1	Sample 2	Average
		Per cent	*Per cent*	*Per cent*
Project main	Headquarters	0.270	0.246	0.258
East main	Eighth Street	.264	.254	.259
Do	East of Somerton	.274	.272	.273
Central main	Avenue B	.260	.254	.257
Do	West of Somerton	.117	.117	.117
West main	Eighth Street	.255	.245	.250
Do	West of Somerton	.056	.052	.054

All the silt was fine enough to pass a 200-mesh sieve. The variation in the percentage of silt in the east main canal was not very great. In the central main canal over half the silt was dropped before it could reach the section west of Somerton, while in the west main canal the silt at the lower point was little more than one-fifth of that at Eighth Street, higher up.

The results of these tests and those made in 1915 and 1916, indicate that the amount of silt carried in the main canal at the intake is about the same as that found in the system near Yuma.

From November 4 to December 17, 1915, samples were taken at one-half the depth of water flowing over gates No. 1, No. 18, and No. 36 of the intake to the main canal. The results are shown in Table 72.

TABLE 72.—*Proportion of silt, by weight, entering main canal intake at Laguna Dam, November 4 to December 17, 1915*

November	4	5	6	8	10	12	15	16	17	18	22	23	24	26	30
	P. ct.	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*
Gate No. 1	0.02	0.05	0.05	0.02	0.05	0.09	0.20	0.20	0.16	-----	0.30	0.14	0.35	0.22	0.30
Gate No. 18	0	.19	.20	.14	.16	.12	.22	.20	.12	0.28	.32	-----	.35	.30	.24
Gate No. 36	0	.11	.07	.14	.09	.14	.20	.19	-----	-----	.30	.20	.30	.21	.47

December	1	2	3	6	7	8	9	13	14	15	16	17
	Per ct.	*Per ct.*	*Per ct.*	*Per ct.*	*Per ct.*	*Per ct.*	*Per ct.*	*Per ct.*	*Per ct.*	*Per ct.*	*Per ct.*	*Per ct.*
Gate No. 1	0.40	0.20	0.20	0.21	0.16	0.14	0.12	0.14	0.12	0.12	0.09	0.09
Gate No. 18	.45	.40	.37	.14	.28	.21	.21	.19	.16	.20	.16	.12
Gate No. 36	.38	.33	.22	.30	.21	.16	-------	.14	.14	.12	.14	.14

From October 4, 1915, to July 26, 1916, samples were taken to determine the amount of silt being carried in suspension at various points in the main canal from Laguna Dam to Yuma, a distance of about 14 miles. Table 73 gives the results of these determinations.

TABLE 73.—*Proportion of silt, by weight, in Yuma project main canal, from intake to Yuma, October 4, 1915, to July 26, 1916*

	Distance from river-control check	1915								1916				
		October			November				Dec. 6	Jan. 11	Mar. 21	Apr. 27	May 25	July 26
		4	13	21	9	16	23	30						
	Miles	*P. c.*	*P. c.*	*P. c.*	*P. c.*	*P. c.*	*P. c.*	*P. c.*	*P. c.*	*P. c.*	*P. c.*	*P. c.*	*P. c.*	*P. c.*
Intake, head of levee	-----	0.78	0.87	0.52	0.16	0.24	0.20	0.38	0.22	0.07	1.38	0.60	0.40	0.39
West side above dam	-----	1.13	.85	.35	.14	.32	.33	.38	.22	.11	1.00	.95	.43	.27
At Quarry bridge	-----	.64	.78	.43	.09	.19	.28	.51	.16	.03	1.01	1.15	.14	.81
River-control check:														
Main canal	-----	-----	.85	.38	.09	.21	.22	.33	.19	.03	1.04	1.44	.17	-----
Reservoir main	-----	.57	.82	.37	.09	.22	.30	.28	.21	.03	1.13	.38	.10	-----
	1	-----	.89	.47	.11	.21	.21	.32	.20	.03	1.13	-----	-----	-----
	2	-----	.85	.44	.19	.20	.28	.33	.19	.03	1.13	.64	.14	-----
	3	-----	.89	.43	.12	.19	.24	.32	.16	.03	-----	-----	-----	-----
	4	-----	.89	.34	.14	.20	.28	.33	.19	.03	.99	.35	.16	-----
	5	-----	.89	.48	.12	.20	.24	.32	.20	.03	-----	-----	-----	-----
	6	-----	.92	.38	.09	.18	.28	-----	.21	.03	1.08	1.53	.16	-----
	7	-----	.87	.50	.09	.16	.24	.32	.21	.03	-----	-----	-----	-----
Picacho	8	.61	.91	.42	.09	.19	.24	.33	.21	.03	1.04	2.12	.22	-----
	9	-----	.89	.44	.12	.19	.24	.32	.21	.03	-----	-----	-----	-----
Above drop	10	.45	1.00	.44	.09	.19	.32	-----	.21	.05	.99	4.48	.14	-----
Below drop	10	.49	.92	.38	.11	.19	.22	.32	.19	.03	1.00	.66	.12	-----
	11	-----	.92	.55	.12	.20	.28	.33	.19	.03	-----	-----	-----	-----
Powell	12	.42	.95	.44	.09	.19	.24	.32	.20	.03	1.13	1.13	.07	-----
	13	-----	.95	.46	.12	.19	.24	.30	.20	.01	-----	-----	-----	-----
California drop	14	.38	1.09	.51	.11	.19	.24	.24	.20	.02	.97	.22	.09	-----
Headquarters bridge	15	-----	.95	.40	.12	.19	.22	.32	.20	.14	.95	.24	.09	.03
Colorado River	-----	-----	.86	.54	.30	.48	1.25	.45	.30	.09	1.25	.61	.37	-----

On June 6, 1917, samples of water were taken at eight stations of the Yuma irrigation system, beginning at the sluiceway leading from the Colorado River. The location of each station and the proportion of silt found at the top and bottom of the edges and center of each canal are given in Table 74.

TABLE 74.—*Distribution of silt at various stations of the Yuma project irrigation system, June 6, 1917*

Station	Proportion of silt (by weight)						Mean
	East side		Center		West side		
	Top	Bottom	Top	Bottom	Top	Bottom	
	Per cent	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*
Sluiceway station A	0.05	0.05	0.08	0.06	0.19	0.19	0.10
Sluiceway station B	.03						.03
Project main canal, at Potholes	.05	.06	.05	.08	.11	.08	.07
Project main canal, at headquarters	.05	.03	.05	.07	.05	.05	.05
Project main canal, at boundary	.05	.17	.08	.11	.09	.11	.10
Central canal, at heading	.08	.08	.08	.08	.11	.08	.08
Central canal, at lower end	.03		.03				.03
West main canal, at Mexican boundary	.05	.05	.03	.03	.05	.06	.05

Results of similar investigations made at subsequent dates in 1917 are shown in Table 75.

TABLE 75.—*Proportion of silt, by weight, at different points of the Yuma project irrigation system, June 12 to October 10, 1917*

Station	June 12, 1917		June 19, 1917		Sept. 13, 1917		Sept. 28, 1917		Oct. 10, 1917	
	Top	Bottom	Top	Bottom	Top	Bottom	Top	Bottom	Top	Bottom
Sluiceway at intake:	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*
Station A	0.25	0.29			0.08	0.41	0.04	1.00	0.25	1.50
Station B	.07	.59			.04	.93	.08		.10	.33
Project main canal at Potholes	.11	.11			.03	.04	.80	.02	.25	.30
Project main canal at headquarters	.12	.13								
Upper central canal	.11	.12	0.06	0.08						
Lower central canal	.07	.11	.05	.05						
East main canal at Mexican boundary	.41	.16	.06	.07						
West main canal at Mexican boundary	.02	.05	.00	.02						

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