UNITED STATES

DEPARTMENT OF THE INTERIOR

BUREAU OF RECLAMATION

MEMORANDUM TO CHIEF DESIGNING ENGINEER

SUBJECT: NOTES ON SILT PROBLEMS OF THE ALL-AMERICAN CANAL

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by

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NOTES ON THE SILT PROBLEM OF THE ALL-AMERICAN CANAL

By [illegible], Research Engineer,

December, 19[illegible]

The problem of handling the silt and sand brought into the All-American Canal from the Colorado River or blown in from the sand hills along its course is one of considerable difficulty. Because of the magnitude of the quantities involved, an efficient method of handling this material will result in a saving of large sums of money to the users of the irrigation water, and an [illegible] study was made of the [illegible] [illegible] with silt in order that full advantage might be taken of the [illegible] knowledge in the solution of the problem. The following [illegible] the principal facts brought out by this investigation [illegible] the [illegible] of the All-American Canal, and the [illegible] be [illegible] from [illegible], the Colorado River, from which the [illegible] will [illegible] supply, normally carried large quantities of [illegible] [illegible] coming from above the Boulder [illegible] [illegible] by the dam, but large quantities [illegible] from the tributary area below the dam, and [illegible] conditions, [illegible] this will be picked up from the [illegible] the [illegible]. The intake of the canal will be at [illegible] [illegible] another dam to be built some distance upstream. [illegible] the location of the intake on the silt problem, [illegible] considered in this report. At this intake it [illegible] [illegible] works to remove as much of the silt [illegible] from the water before it enters the canal. From [illegible] about 10 miles below the Imperial dam, the canal should be [illegible], without [illegible], all the silt which is not [illegible] by the [illegible] works at the headgate, but [illegible] high to erode the banks of the canal. [illegible] section of the canal route, it enters a region of [illegible] [illegible] moved about by the wind. An attempt [illegible] to prevent this sand from blowing into the canal by [illegible] vegetation on the dunes along the route, but the success of this [illegible] is not certain and provision to remove the sand from the canal [illegible] be made. It may be removed either by dredging or it may be carried by the current in the canal to the [illegible] where conditions are favorable to depositing it in [illegible]. In case the procedure of settling it out in basins is followed, it will be necessary to design this section of the canal [illegible] to carry the sand blown into it, in addition to the silt [illegible] from the Colorado River without seriously [illegible] the [illegible] of the canal. If dredging is adopted, the design of this section [illegible] with control, will not/materially differ from that upstream from it. Just beyond the edge of the sand hills the land surface has considerable slope and two or more drops in the canal grade will be constructed, at which the power of the falling water will be used to generate electrical power. If dredging is not used to remove the blown sand, the desilting basins will be located in this region. Some distance below the power houses, branches take off from the canal and carry the water to the irrigated areas. The main canal below the power houses and the laterals will have to be designed to carry without deposit any material which still remains in the water after passing the desilting basins or the dredges. It is possible that the settling work will be designed to remove only the blow sand, in which event, it will be necessary to design the main canal and laterals below to carry out onto the irrigated land all the suspended matter which enters the canal from the Colorado River.

PRESENT CONDITIONS IN THE LOWER COLORADO RIVER BASIN

The silt problem is a serious one for the irrigated lands of the lower Colorado River Basin. On the Imperial Valley irrigation system over half a million dollars a year is spent to remove the silt from the canal system and in addition an estimated cost of $2.00 per acre is incurred by the farmers in removing silt from their ditches and leveling silt deposits on their land. The total cost to the district as a result of silt is about [illegible] one-third million dollars a year. As a result of the difficulty of handling silt, thorough study of the silt problem has been made by the United States Department of Agriculture, and much of the information regarding present silt conditions on the lower Colorado in the following pages is taken from their report, "Silt in the Colorado River and Its Relation to Irrigation", by Samuel Fortier and Harry F. Blaney. [illegible] information is largely from "Silt Transportation by the Sacramento and Colorado Rivers and by the Imperial [illegible] [illegible], Trans. Am. Soc. C. E., August, 1929, p. [illegible]. In the following [illegible] are given a brief statement of the principal conclusions of the Fortier-Blaney study which bear on the problems under consideration in this report.

*The silt transported by the Colorado River consists of finely pulverized rock with a variable proportion of organic matter. Normally, the specific gravity of this silt is 2.[illegible], 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 80 per cent passing a standard sieve of 200 meshes to the inch.

*From Fortier and Blaney's Report.

"[illegible] which [illegible] pass a 200-mesh sieve, may be [illegible] [illegible] [illegible] natural and artificial channels if the mean velocity of the [illegible] [illegible] two-thirds of a foot per second, with [illegible] uniformity [illegible] constant throughout the vertical section, although there is a tendency for the heavier particles to approach or [illegible] 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 carried in suspension. [illegible] the suspended silt entering the main canal of Imperial Valley is transported throughout the system. The water delivered to the irrigators contains most of this silt content, which is deposited in farm laterals or on the irrigated fields.

"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."

SILT IN THE COLORADO RIVER

"It is obvious that much of the coarser inorganic material, usually termed "debris", eroded during flood periods and carried by water into the main and tributary channels of the Colorado River, differs from the silt present in the lower reaches. The coarse sand, gravel, cobbles and boulders contained in such debris 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 [illegible] of only a small proportion of the output is large enough to be classified as medium sand.

"It is quite [illegible] 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 [illegible] undergoes little change in the course of its passage to the Gulf of California.

"Silt determinations have been made for the waters of the Colorado River at Yuma by the Bureau of Reclamation since 1909.

From Fortier and Blaney's Report.

"The average percentages for each month of each year from 1910 to 1925 inclusive are given in table 1.

SILT IN COLORADO RIVER IN RELATION TO IRRIGATION

Table 1.—Monthly mean proportion of silt, by weight, in Colorado River at Yuma for 1910-1925, inclusive, stated in percentages

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
1910	...	...	...	0.[illegible]	...	[illegible]	[illegible][1]	0.24	0.60	...	0.35	0.36
1911	0.[illegible]	1.09	1.[illegible]	[illegible]	0.[illegible]	[illegible]	1.[illegible]	1.87	.81	2.37	.63	.22
1912	.15	.23	.79	1.[illegible]	[illegible]	[illegible]	.71	.78	[illegible]	.46	1.16	.24
1913	.14	.15	.50	1.15	[illegible]	.66	.41	.61	1.70	1.69	.36	.39
1914	[illegible]	1.66	1.49	1.03	[illegible]	.85	1.[illegible]	1.34	.96	1.42	.81	.60
1915	1.[illegible]	[illegible]	[illegible]	1.81	[illegible]	[illegible]	[illegible]	1.14	[illegible]	.65	.43	.39
1916	1.[illegible]	[illegible]	1.[illegible]	[illegible]	.76	[illegible]	.85	1.95	.87	2.08	.68	.31
1917	[illegible]	[illegible]	.46	[illegible]	[illegible]	[illegible]	.46	.68	.50	.29	.14	.15
1918	.15	.15	.96	[illegible]	.54	[illegible]	1.01	.68	.65	.45	.34	.28
1919	.15	[illegible]	.68	[illegible]	.30	[illegible]	1.67	2.24	1.93	.78	.54	1.32
1920	.60	1.35	1.25	1.02	[illegible]	[illegible]	[illegible]	.92	1.11	.24	.59	.20
1921	[illegible]	.18	[illegible]	.54	[illegible]	.50	.67	2.12	1.71	.43	.32	.55
1922	.60	.27	1.11	1.06	1.17	[illegible]	.43	1.37	1.01	.16	.21	.26
1923	.29	.18	.35	[illegible]	.72	[illegible]	.50	1.97	2.77	1.29	1.23	.50
1924	1.65	.43	.42	1.00	.85	[illegible]	.65	.43	.57	.75	.35	.26
1925	.18	[illegible]	.48	.60	.33	.62	.74	.86	2.61	1.63	.73	.42

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

"In table 2 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. The silt content for these [illegible] years averages [illegible],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 2.—Amount of suspended silt in Colorado River at Yuma, Arizona, for 15 years

*From Fortier and Blaney's Report.

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	....	11,326,000	[1] 110,746,000	1919	0.87	10,747,000	127,275,000
1904	....	10,118,000	120,961,000	1920	.78	21,444,000	227,687,000
1905	....	19,712,000	[1] 309,728,000	1921	.70	19,428,000	185,125,000
1911	1.01	17,831,000	248,152,000	1922	.71	17,014,000	184,438,000
1912	.67	18,406,000	167,870,000	1923	.93	17,848,000	230,808,000
1913	.69	11,768,000	110,552,000	1924	.63	11,548,000	97,319,000
1914	1.00	20,656,000	281,186,000	1925	.83	12,452,000	144,077,000
1915	.93	14,641,000	185,260,000				
1916	1.18	22,140,000	371,692,000	Total	....	....	3,307,865,000
1917	.49	20,598,000	137,391,000	Mean	....	....	183,759,000
1918	.51	18,158,000	91,348,000				

[1] Computed from monthly discharges.

"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.

"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, the 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.

From Fortier and Blaney's Report.

"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 downstream in several ways and combinations of ways, one of which is by rolling along the bed. If the paths of individual particles would 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."

From Fortier and Blaney's Report.

"SILT IN SUSPENSION IN COLORADO RIVER AT YUMA, ARIZONA.

"Sampling of River Water at Yuma. Since 1909 the U. S. Geological Survey, in cooperation with the U. S. Reclamation Service, has made observations on the Colorado River at Yuma to determine the volume of silt transported. Twice a week samples have been taken in three verticals of a cross-section (one at midstream and the others at about the quarter-points). They were taken at the water surface, at mid-depth, and near the bottom of each vertical.

"The results from 1909 to 1918 are presented in table 3. The average percentage of silt carried as a suspended load during the entire ten years (0.69%) was found by comparing the total discharge with the aggregate weight of the material carried in suspension, as determined month by month. The percentages reported by the U. S. Reclamation Service for each month were accepted (for this period only) in making the calculations, although it is understood that they represent straight monthly averages instead of weighted averages. The error thus introduced for this particular period, although it is worth considering for individual months, is not material for present purposes. In table 3, the volume of silt is computed at 100 lbs. per cubic foot. The percentage of silt is as reported by the U. S. Reclamation Service. The individual determinations (8 or 9 months) appear to have been averaged--not weighted--and the monthly averages are, therefore, occasionally subject to material correction.

From Grunsky's Paper.

"Distribution Throughout Year. The large volume of silt considered in relation to discharge in January, February, and March (table 3), is not fairly representative of ordinary winter conditions for the reason that in one year of the period (1916) the winter discharge of the river at Yuma was multiplied five or six times by high states of the Gila and other lower tributaries. The admixture of these unusual freshet waters increased the average volume of silt in suspension in January, 1916, to 3% by weight, whereas ordinarily it is between 0.8% and 1.0 per cent. The discharges in February and March, to a lesser degree, were also affected. In February, 1916, the Colorado, with more than twice its ordinary discharge, had very muddy water, the silt averaging 2.[illegible] per cent. The data for the winter months of this particular group of years, because of such extreme conditions, do not properly indicate the probable or normal relation between discharge and silt in suspension.

"In the nine years, 1919 to 1927 (table 4), all original semi-weekly observations were given weight according to river discharge in the computation of monthly mean percentages. Consequently, these are to be regarded as more nearly in accord with actual fact than those preceding 1919, particularly for the individual months.

"The total quantity of silt annually transported in suspension past Yuma, estimated from these dependable figures, is shown in table 4; also, the average volume and the probable volume of silt per calendar month for the 9-year period."

From [illegible]'s Paper.

TABLE 3.—Silt Carried in Suspension by Colorado River at Yuma, Arizona, by Months, 1909–1918.

Year.	Designation.	Jan.	Feb.	Mar.	Apr.¹	May.	June.	July.	Aug.	Sept.	Oct.	Nov.	Dec.
1909	Discharge, in thousands of acre-feet	....	....	....	....	3 324	6 240	4 897	2 500	2 880	861	....	....
	Silt, percentage	....	....	....	....	0.57	0.43	0.94	0.35	1.13	0.37	....	....
	Silt, in acre-feet	....	....	....	....	11 840	16 750	28 750	11 850	20 400	1 390	....	....
1910	Discharge, in thousands of acre-feet	....	....	....	1 910	3 473	2 798	904	591	367	....	467	427
	Silt, percentage	....	....	....	0.57	0.58	0.55	0.40	0.24	0.61	....	0.36	0.28
	Silt, in acre-feet	....	....	....	6 100	12 600	9 620	2 200	652	1 330	....	1 050	745
1911	Discharge, in thousands of acre-feet	541	743	1 068	1 211	2 765	3 819	3 084	1 132	530	1 757	722	465
	Silt, percentage	1.81	1.09	1.06	0.84	0.86	0.71	1.69	1.27	0.51	2.33	0.51	0.20
	Silt, in acre-feet	2 770	5 000	7 000	350	14 870	17 600	32 250	9 000	2 680	25 600	2 200	580
1912	Discharge, in thousands of acre-feet	331	424	818	254	2 509	6 397	2 867	1 397	582	677	690	403
	Silt, percentage	0.16	0.23	0.79	.45	0.96	0.52	0.71	0.78	0.84	0.46	1.16	0.21
	Silt, in acre-feet	331	610	4 040	530	15 000	20 750	12 750	6 800	3 060	1 945	5 080	605
1913	Discharge, in thousands of acre-feet	228	337	558	1 524	2 380	2 827	1 393	580	525	635	472	393
	Silt, percentage	0.13	0.13	0.31	1.15	0.73	0.65	0.41	0.61	1.69	1.66	0.25	0.29
	Silt, in acre-feet	230	274	1 078	10 950	10 840	11 500	3 340	2 210	5 550	6 840	1 430	956
1914	Discharge, in thousands of acre-feet	462	646	923	1 364	3 308	6 575	3 168	1 350	501	840	611	818
	Silt, percentage	0.66	1.01	1.52	1.04	0.76	0.53	1.27	1.69	1.17	1.58	0.50	0.56
	Silt, in acre-feet	1 910	4 200	8 700	8 870	15 700	21 750	25 200	11 150	1 320	8 270	3 140	2 800
1915	Discharge, in thousands of acre-feet	563	1 505	951	1 789	2 941	2 892	1 897	685	270	442	356	351
	Silt, percentage	0.128	2.18	0.94	1.24	1.37	0.82	0.64	1.52	0.57	0.70	0.47	0.11
	Silt, in acre-feet	4 500	23 400	5 580	13 880	25 250	14 800	7 580	6 510	964	1 940	1 042	906
1916	Discharge, in thousands of acre-feet	2 637	1 615	2 201	2 118	3 363	3 539	2 258	1 675	736	1 636	707	451
	Silt, percentage	2.29	1.73	1.71	1.20	0.93	0.66	0.68	1.35	0.57	1.91	0.68	0.32
	Silt, in acre-feet	49 100	17 400	23 550	15 850	19 700	20 800	9 600	20 100	4 000	19 700	3 000	906
1917	Discharge, in thousands of acre-feet	562	440	603	1 565	3 030	5 350	5 775	1 412	596	465	422	420
	Silt, percentage	0.48	0.31	0.49	1.03	0.98	0.54	0.46	0.68	0.30	0.29	0.14	0.13
	Silt, in acre-feet	1 680	863	1 845	10 050	18 550	19 150	16 550	6 110	1 005	841	370	338
1918	Discharge, in thousands of acre-feet	405	323	1 008	767	1 787	3 672	2 600	740	406	471	480	451
	Silt, percentage	0.15	0.15	0.96	0.39	0.54	0.53	1.01	0.68	0.63	0.48	0.24	0.23
	Silt, in acre-feet	380	302	6 460	1 825	6 030	12 400	16 750	3 020	1 600	1 420	1 010	650
Average, 8 to 10 years	Discharge, in thousands of acre-feet	717	754	1 016	1 478	2 888	4 411	2 881	1 207	713	865	518	465
	Silt, percentage	1.70	1.30	1.14	0.93	0.83	0.50	0.86	1.41	0.97	1.41	0.59	0.33
	Silt, in acre-feet	7 600	6 520	7 240	8 600	15 000	16 350	15 520	8 310	1 490	7 500	2 035	960

TABLE 4.—SILT CARRIED IN SUSPENSION BY COLORADO RIVER AT YUMA, ARIZONA, BY MONTHS, 1919-1927.

(Volume of silt computed at 100 lb. per cu. ft. All results of daily observations have been weighted.)

Year.	Designation.	Jan.	Feb.	Mar.	Apr.	May.	June.	July.	Aug.	Sept.	Oct.	Nov.	Dec.
1919	Discharge, in thousands of acre-feet	231	398	511	1 230	2 220	2 040	1 240	658	267	325	607	917
	Silt, percentage	0.16	0.34	0.86	0.97	0.50	0.55	2.01	2.51	1.10	7.78	0.54	1.59
	Silt, in acre-feet	231	846	2 920	7 160	6 910	7 012	12 840	10 460	2 110	1 581	2 049	9 110
1920	Discharge, in thousands of acre-feet	701	2 190	1 110	1 210	2 840	7 680	2 650	1 600	502	400	619	452
	Silt, percentage	0.54	1.74	1.68	1.08	0.88	0.62	0.69	0.87	10.70	0.24	0.40	0.21
	Silt, in acre-feet	2 395	23 800	11 090	8 166	15 620	30 460	11 130	5 926	12 384	600	1 518	563
1921	Discharge, in thousands of acre-feet	427	109	821	815	2 670	6 600	2 820	2 460	1 070	552	118	633
	Silt, percentage	0.21	0.18	0.58	0.34	0.76	0.50	0.71	2.31	2.32	0.45	0.33	0.79
	Silt, in acre-feet	640	400	2 986	1 731	12 680	20 620	13 040	31 600	15 520	1 552	921	3 121
1922	Discharge, in thousands of acre-feet	720	600	296	1 130	3 110	5 840	1 940	711	624	210	326	455
	Silt, percentage	0.23	0.63	1.51	1.08	1.10	0.59	0.57	1.19	1.19	0.17	0.22	0.27
	Silt, in acre-feet	1 646	2 361	9 101	7 625	23 640	21 410	6 940	5 735	3 898	255	118	768
1923	Discharge, in thousands of acre-feet	328	321	510	1 080	2 880	5 070	2 620	1 510	1 270	736	828	666
	Silt, percentage	0.49	0.18	0.37	0.86	0.72	0.61	0.79	2.00	3.17	1.67	1.41	0.85
	Silt, in acre-feet	890	361	1 249	5 806	12 950	19 220	12 930	18 870	25 100	7 690	7 298	3 536
1924	Discharge, in thousands of acre-feet	780	181	520	1 376	2 563	3 135	1 123	288	184	244	369	355
	Silt, percentage	1.15	0.15	0.11	1.39	0.86	0.76	0.62	0.66	0.75	0.71	0.31	0.25
	Silt, in acre-feet	7 112	1 252	1 430	11 450	13 780	15 170	4 353	1 188	862	1 082	784	511
1925	Discharge, in thousands of acre-feet	212	310	521	1 090	1 780	2 128	1 740	738	1 210	1 150	677	474
	Silt, percentage	0.22	0.32	0.33	0.64	0.53	0.67	0.76	0.85	2.90	1.84	0.65	0.46
	Silt, in acre-feet	124	728	1 095	4 300	5 896	10 160	8 267	3 922	21 830	13 230	2 750	1 362
1926	Discharge, in thousands of acre-feet	356	288	416	1 410	2 776	3 560	1 117	536	290	438	255	459
	Silt, percentage	0.30	0.26	0.50	1.00	0.83	0.63	0.83	0.58	0.50	2.09	0.30	0.55
	Silt, in acre-feet	667	468	1 293	8 817	11 390	11 460	7 350	1 775	813	5 721	478	1 578
1927	Discharge, in thousands of acre-feet	280	1 070	719	959	2 990	3 150	2 670	913	1 800	1 050	732	462
	Silt, percentage	0.25	1.27	0.27	0.85	0.81	0.62	0.91	1.08	3.01	1.08	0.62	0.31
	Silt, in acre-feet	437	8 490	3 464	5 695	15 130	13 580	15 690	6 165	31 200	2 089	2 887	982
Average, 9 years	Discharge, in thousands of acre-feet	458	678	622	1 139	2 684	4 431	2 021	990	792	570	540	545
	Silt, percentage	0.66	1.63	0.91	0.26	0.80	0.61	0.81	1.58	2.40	1.21	0.63	0.71
	Silt, in acre-feet	1 879	1 317	3 955	6 729	18 498	13 447	10 642	9 463	11 875	1 312	2 121	2 431

"COMPARATIVE AMOUNT OF SILT--SURFACE TO BOTTOM.

"Conditions Affecting Data. The long-continued observations at Yuma are particularly valuable, not only because they furnish a dependable basis for estimating the quantity of silt in suspension, but also because they throw light on the distribution of the silt throughout a body of flowing water. The width of the Colorado River at the sampling station is about 650 feet. The verticals in which samples were taken were generally 130, 325, and 520 feet from the left bank.

"Occasionally, samples from near the bottom show excessive quantities of silt when compared with the corresponding samples at mid-depth and near the surface. These no doubt reflect a momentary condition of bed-load saltation and should be connected with the river's bed load rather than with its suspended load. In the following deductions such clearly discordant determinations of silt in suspension have been disregarded.

"The Yuma Reclamation Project Canal taps the river at Laguna dam about 12 miles upstream from Yuma. The headworks of the canal at this point include a desilting arrangement. When the temporary discharge through the Laguna dam sluice-gates is large in relation to the entire flow--as at low stages--the picture of silt conditions may not be dependable. At high stages this disturbing cause is negligible.

"Classification of Findings. In 1916, after seven years of observations in more than 1,100 verticals (three samples each), studies of the results of these observations were made by the writer to confirm the conclusion that the admission of river water to the Imperial Canal over flashboards, at a proposed new headgate, would reduce the entrained bed load of silt, and, perhaps, in some measure, also, the suspended load, when compared with flow under gates of the ordinary type. The sampling at Yuma has continued to the present by the U. S. Bureau of Reclamation, for the U. S. Geological Survey and therefore, it has been possible to supplement and extend the studies of 1916.

"The observations from 1909 to 1916 were first separated into groups, according as the silt content (by weight) was: (1), less than 1%; (2) between 1% and 2%; and (3) exceeded 2 per cent. There were 759 verticals in group (1); 315 in group (2) and 81 in group (3).

"A combination of the results in all verticals (1,155 in number), with sole regard to the relative quantity of material in suspension near the water surface, at mid-depth, and near the bottom, was then made. Similar combinations were made, too, for each calendar year.

From Grunsky's Paper.

"The results of the studies undertaken in 1916 are shown in Table 5. The results of the more recent studies covering the period from 1919 to 1937, are given in Table 6. These data show that a little more material in suspension is to be expected at mid-depth than at the surface and still more near the bottom. In preparing Table 6, the observations were grouped roughly by periods during which the river's silt load remained fairly uniform.

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Table 5. Distribution of the Silt in Suspension from Water Surface to Bottom in Colorado River at Yuma, Arizona.

(From observations by U. S. Reclamation Service, 1909 to 1916).

Year	Number of verticals	SILT IN PERCENTAGE BY WEIGHT. At surface.	At mid-depth	At bottom.
1909	34	0.466	0.594	0.794
1910	66	0.452	0.526	0.571
1911	153	1.040	1.063	1.095
1912	201	0.652	0.660	0.682
1913	195	0.835	0.843	0.889
1914	272	0.974	1.011	1.126
1915	196	0.901	0.922	0.998
1916	55	1.280	1.441	1.485
Weighted average	1,165	0.86	0.89	0.96
Light load	739	0.49	0.51	0.59
Moderate load	315	1.29	1.33	1.40
Heavy load	81	2.67	2.74	2.78

"Turbidity Varies with Depth. It is to be noted that in the Colorado River, which is a very muddy stream, the increase of the suspended load downward from the surface bears no fixed relation to the loads at the surface or at mid-depth. The increase with depth is very nearly constant in the sense of being independent of the total suspended load. Thus, for example, the 739 separate determinations from 1909 to 1916, during periods with a load of about 0.5%, show an actual increase from 0.49% at the surface to 0.59% at the bottom, a percentage of 0.10. The 315 determinations in the same years, during periods with a load of 1.0 to 1.5%, showed 1.29% at the surface and 1.40% at the bottom, a percentage increase of 0.11; and the 81 determinations, when the load of silt was heavy, showed 2.67% at the surface and 2.78% at the bottom,

From Grunsky's Paper.

or an increase in percentage of 0.11 at full depth. The combination of results in all the 1,105 verticals indicates that the percentage of silt at mid-depth is greater than that at the surface by 0.03 of the weight of water; and that at the bottom the percentage of silt exceeds that at the surface by 0.10. Corresponding comparisons for the period, 1919 to 1927, show the following increases from surface to bottom: For a light silt load, 0.12% of the weight of the water; for a moderate load, 0.08%; and for a heavy load, 0.15 per cent. The combination of results in all the 1,841 verticals of this period show 0.73% silt at the surface; 0.77% at mid-depth; and 0.84 at the bottom, the increase of the percentage being 0.04 from surface to mid-depth, and 0.11 from surface to bottom. In other words, if the percentage by weight of the suspended material in the Colorado River at the surface is represented by p, the percentage of suspended material at mid-depth may be taken at p + 0.04 and that at the bottom at p + 0.10.

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"Table 6. Distribution of the Silt in Suspension from Water Surface to Bottom in Colorado River at Yuma, Arizona.

(From observations by U. S. Geological Survey, 1919 to 1927).

Year.	Number of days.	Number of verticals	Average depth, in ft.	SILT IN PERCENTAGE BY WEIGHT At surface.	At mid-depth.	At bottom.
			LIGHT LOAD OF SILT IN SUSPENSION.			
1919	24	44	7.6	0.274	0.274	0.362
1920	51	122	7.3	0.397	0.444	0.502
1921	42	103	8.0	0.316	0.328	0.409
1922	45	60	8.8	0.311	0.311	0.409
1923	38	57	9.3	0.253	0.262	0.348
1924	39	49	8.4	0.248	0.245	0.346
1925	44	85	8.4	0.327	0.415	0.536
1926	57	90	8.0	0.304	0.337	0.456
1927	9	15	6.4	0.170	0.194	0.313
Average weighted..	349	625	8.2	0.306	0.332	0.429

From Grunsky's Paper.

Year.	Number of days.	Number of verticals	Average depth in feet	SILT IN PERCENTAGE BY WEIGHT At surface.	At mid-depth.	At bottom.
MODERATE LOAD OF SILT IN SUSPENSION.						
1919	46	101	9.7	0.486	0.524	0.587
1920	14	29	21.6	0.720	0.670	0.694
1921	40	65	13.0	0.534	0.556	0.595
1922	31	69	14.6	0.634	0.663	0.730
1923	41	110	13.0	0.711	0.705	0.712
1924	46	90	11.0	0.700	0.668	0.733
1925	17	35	15.0	0.598	0.550	0.590
1926	34	82	13.0	0.740	0.778	0.974
1927	71	150	13.0	0.707	0.823	0.883
Average weighted..	340	759	13.1	0.603	0.629	0.681
HEAVY LOAD OF SILT IN SUSPENSION.						
1919	27	73	8.5	1.91	1.99	2.07
1920	20	60	11.6	1.42	1.45	1.39
1921	15	43	10.6	2.23	2.34	2.22
1922	27	62	11.3	1.24	1.36	1.55
1923	22	53	9.2	2.36	2.29	2.39
1924	13	37	9.9	1.40	1.44	1.42
1925	18	50	13.1	2.22	2.28	2.21
1926	8	24	7.6	2.31	2.43	2.50
1927	19	55	11.4	1.77	2.02	2.16
Average weighted..	169	457	10.4	1.83	1.93	1.96
1919-1927, total and means.......	888	1841	10.6	0.73	0.77	0.84

"<u>Quantity of Silt in Relation to River Stage.</u> The Colorado River at Yuma flows on a bed of very fine sand. ~~Thus~~ The three-point determinations of silt in suspension, of which use was made in the foregoing comparisons, did not include observations at points where the depth was less than 5 feet. The average depths at the included sampling stations are indicated in table 6. The mean velocity of the river at low stages is generally 2 to 4 feet. At high stages it may go to 6 or 7 feet per second. When the river is in equilibrium, there is as much sand being picked up from the bed as is dropped from the suspended load. At such times the river bed, underfoot, appears firm, smooth and comparatively hard, like a felt-covered floor. With a current of about 3 to 4 feet per second, attack on the bed quickly begins whenever there is local acceleration of velocity such as may be caused by even small obstructions, for example, the legs and feet of a man standing in the stream.

From Grunsky's Paper.

"Expressed in relation to the weight of the water, there is a wide range in the turbidity of the river, as the long-continued observations disclose. The tabulated results show that the Colorado River is not as muddy at low stages as at moderately high stages--stages with a discharge of 15,000 to 50,000 second-feet. They also show that the turbidity, expressed in percentages, decreases as the river goes to still higher stages. This does not mean, however, that the river's load of silt decreases with increasing volume. This will become apparent by reference to figure 1, which shows the relation of the volume of silt carried in suspension, expressed in acre-feet per month (estimated at 100 pounds per cubic foot), to the river discharge, this being noted both in acre-feet per month and in second-feet. In plotting Fig. 1, only the mean monthly values as determined for the two periods, 1909 to 1918 and 1919 to 1927 were used. The curve representing volume of silt was first plotted and the percentage curve was deduced therefrom.

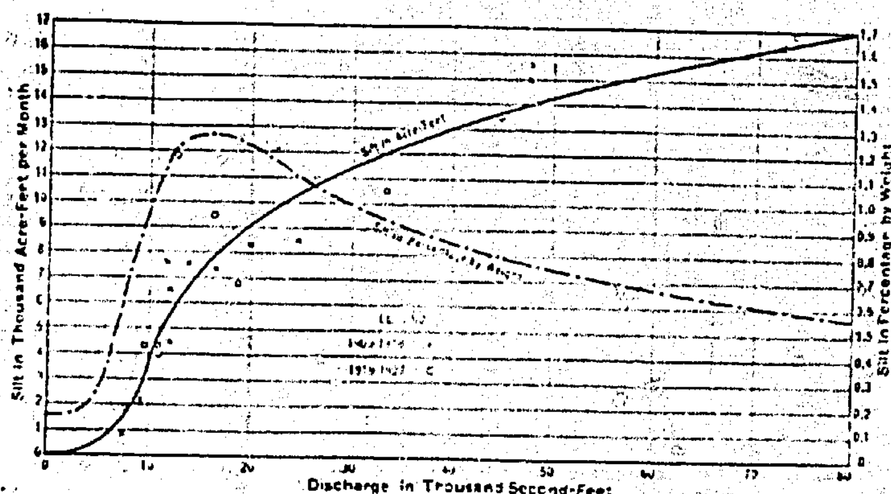


Fig. 1--Relation of Amount of Silt in Suspension to the Discharge of the Colorado River at Yuma, Arizona.

"This study should possibly have been supplemented by a more minute examination of results at the river's lowest stages when the discharge is 6,000 second-feet, or less, but in view of the complication resulting from the desilting operations at Laguna dam where upward of 1,000 second-feet of desilted water are frequently under diversion into the Yuma Canal, this additional study was not attempted.

From Grunsky's Paper.

"The curves in Fig. 2 show a moderate increase of load until the river reaches a 6,000 second-foot stage, thereupon the load in suspension, considered in its entirety, rapidly increases from about 1,000 to 10,000 acre-feet per month, this quantity being reached when the river is at a 25,000 second-foot stage. Thereafter, the increase of load continues as the river rises, but the rate of increase is less rapid. At 80,000 second-feet the silt carried in suspension amounts to about 16,500 acre-feet per month, and, for still higher stages, there is an increase of about 700 acre-feet for each additional 20,000 second-feet of discharge. The curve denoting percentage of silt shows that the Colorado River is muddiest when it is discharging 15,000 to 30,000 second feet.

"The probable volume of silt carried in suspension by the Colorado River changes not only with the discharge of the river, but also from month to month through the year. This change occurs with some regularity, as is made clear by the curves in Fig. 2. In preparing the curves of probable volume the average values ascertained for calendar months for the two periods, 1909-1918 and 1919-1927, were used. Turbidity has two periods of maxima in the year, but with frequent wide departure from mean values. The probable turbidity at any time of the year appears in Fig. 2.

"Fig. 2 indicates a total annual load of silt in suspension in the Colorado River of about 94,000 acre feet, estimated at 100 pounds per cubic foot (which is equivalent to 111,000 acre feet at 85 pounds per cubic foot of deposited silt/). This does not include the river's bed load, which, as shown elsewhere, may amount to about 20,000 to 30,000 acre-feet per annum. Considered from the standpoint of probability and by months it is to be noted that silt transportation is at a maximum in June at the river's spring high stage. It is at a minimum in the winter months when the river is low. The turbidity is highest in the early spring and in the fall. It is lowest in June at the river's highest stage and in the winter at its lowest stages. The silt carried in suspension since the beginning of the observations by the U. S. Reclamation Service, has amounted to 0.90% by weight of the river's total discharge.

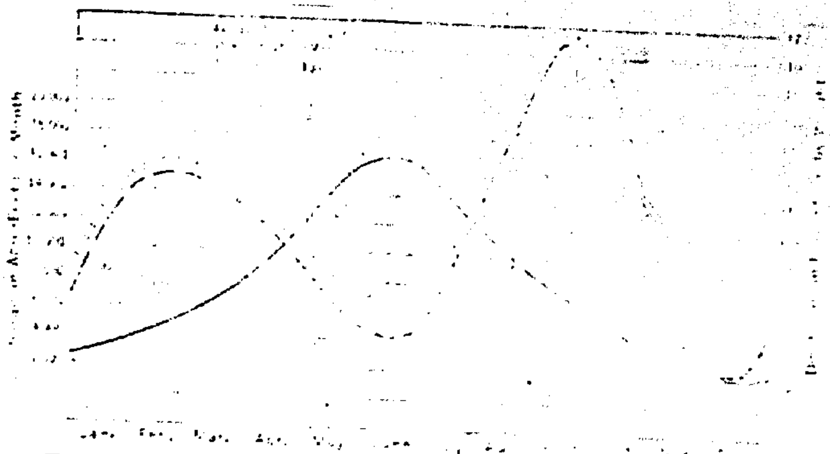


Fig. 2.—Silt in Suspension in Colorado River.

From Grunsky's Paper.

"Perhaps there are other causes affecting the degree of muddiness besides the river stage. It is suggested by Mr. J. F. Brenzeale that the silt in the lower river in many ways shows 'signs of being dispersed, that is, the colloidal particles seem to be carrying negative charges.' He believes that the source of the water and its chemical composition affects the degree of dispersion, or of flocculancy, as the case may be, and, therefore, causes a greater or smaller volume of silt in suspension. He explains that when clays are flocculated, the individual particles are fairly large, but when they are dispersed, carrying charges of negative electricity, each flocculated particle splits into many subdivisions, sometimes so small as to be colloidal."

From Grunsky's Paper.

"SILT OBSERVATIONS IN THE IMPERIAL VALLEY IRRIGATION DISTRICT.

"The irrigation project which has experienced the greatest difficulty from silt, and consequently the one on which the most information has been collected, is the Imperial Valley irrigation project. This district covers about 500,000 acres in the United States and Mexico, and involves about 1,800 miles of irrigation canals.

"The main Imperial Canal, known as the Alamo, has a maximum capacity of 7,000 second-feet and in some dry periods carries the entire flow of the Colorado River.

"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 diverted 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 the Rockwood heading, which was completed in [illegible], was to admit the surface waters of the river and prevent the [illegible] silt from entering the Imperial Valley canal system. [illegible] this is not always possible on account of the scarcity of water at the extreme low stages of the river. During these periods the [illegible] 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.

"[illegible] 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:

From Fortier and Blaney's Report.

"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 0.322 per cent. On February 18, 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.

"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.

"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. 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 62-1/2 pounds of dry material, table 7 has been prepared to show the annual load of suspended silt entering the Imperial Valley canal system from 1912 to 1925, inclusive.

- From Fortier and Blaney's Report.

"Table V.—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
	Acre-feet	Per cent	Acre-feet
1912	1,433,800	0.60	8,600
1913	1,667,300	.62	10,300
1914	1,863,500	.90	16,800
1915	1,912,900	.84	16,100
1916	2,236,200	1.06	23,700
1917	2,412,500	.44	10,600
1918	2,876,800	.46	13,200
1919	2,854,200	.78	22,300
1920	3,095,000	.70	21,700
1921	2,535,000	.63	16,000
1922	2,890,300	.64	18,500
1923	3,275,400	.86	28,200
1924	3,078,300	.57	17,500
1925	3,158,700	.77	24,300
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.

From Fortier and Blaney's Report."

"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 results are given in table 8.

Table 8.--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....	1/2	1.9	1.0	0.6	0.3	1.5
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.

Station	Proportion of silt by volume							
	Mar.	Apr.	May	June	July	Aug.	Sep.	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	1.4	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	.8	.6	.8	4.5	1.5	1.4
Dahlia heading..............................	1.4	.8	.6	.6	.4	3.5	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....	1.3	.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

From Fortier and Blaney's Report.

"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. 8 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 9.

"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.

From Fortier and Blaney's Report.

Table 9.--Proportions of Silt by Weight at Three Stations in the Main Imperial Valley Canal System in 1914.

Month	Hanlon heading: Maximum	Hanlon heading: Minimum	Hanlon heading: Mean	Allison heading: Maximum	Allison heading: Minimum	Allison heading: Mean	No. 5 heading: Maximum	No. 5 heading: Minimum	No. 5 heading: Mean
	Per cent	Per cent	Per cent	Per cent	Per cent	Per cent	Per cent	Per cent	Per cent
January	1.7488	0.2660	0.[illegible]	1.7798	0.2216	0.4982	1.7586	0.1598	0.5963
February	1.7602	.4146	.8047	1.[illegible]	.[illegible]	.8344	1.5820	.[illegible]	.7816
March	[illegible]	.3370	1.[illegible]	2.2114	.9412	1.3396	2.1[illegible]	.9060	1.3722
April	1.1980	.[illegible]	.[illegible]	1.0156	.[illegible]	.7839	1.9932	.6600	.8361
May	.[illegible]	.2068	.[illegible]	.[illegible]	.2470	.5715	.7880	.1518	.5192
June	[illegible]	.1184	[illegible]	.2616	.1160	.1738	.2544	.1126	.1899
July	[illegible]	[illegible]	1.[illegible]	1.[illegible]	.0920	.3549	1.2858	.1704	.5443
August	[illegible]	[illegible]	[illegible]	[illegible]	.7690	1.3486	1.8172	.6984	1.1486
September	[illegible]	[illegible]	[illegible]	1.[illegible]	.[illegible]08	.7485	1.8702	.3494	1.0182
October	[illegible]	.3780	1.[illegible]	2.[illegible]	.5404	1.0481	2.5740	.3540	1.1806
November	[illegible]	[illegible]	[illegible]	1.[illegible]	.2600	.6652	1.3146	.2940	.6516
December	[illegible]	[illegible]	[illegible]	[illegible]	.3422	.7374	2.8250	.2898	.6408
Average			.[illegible]			.7652			.7706

DISTRIBUTION OF SUSPENDED SILTS IN 1917 AND 1918.

Three 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 3 were selected.

*From Fortier and Blaney's Report.

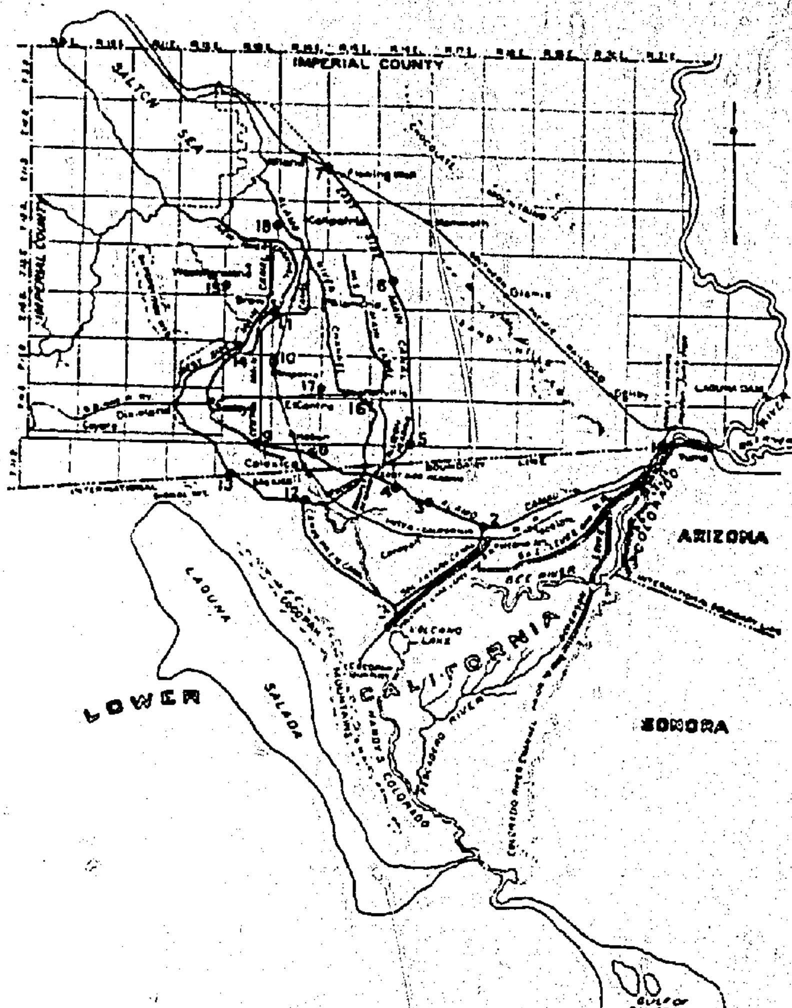


Fig. 3.--Map of Imperial Valley Showing Locations of Sampling Stations.

"The monthly average percentages are given in Table 1[illegible]. For the 12-month period from July 1, 1917, to June 30, 19[illegible], the suspended silt in the Colorado River at Yuma averaged [illegible].39 per cent, while the average in the Alamo Canal at Hanlon Heading was [illegible] 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

[illegible] Fortier and Blaney's Report.

TABLE 10—*Average monthly proportions of suspended silt by weight at sampling stations on Imperial Valley canals, July, 1917, to June, 1918, inclusive*

Station: No.	Distance from river	Canal	Location	July	August	September	October	November	December	January	February	March	April	May	June	Mean
	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	0.262	0.574	0.115	0.371	0.111	0.080	0.088	0.083	0.040	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	.334
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	46	East side main	Check No. 1	.175	.605	.352	.315	.112	.121	.139	.153	.597	.356	.319	.299	.304
6	71	....do	Myrtle check	.188	.679	.336	.360	.149	.069	.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	59	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	.310	.247	.132	.141
13	[1] 65	....do	International boundary	.181	.119	.186	.162	.052	.054	.081	.070	.204	.291	.213	.172	.148
14	[1] 91	....do	No. 8 delivery	.231	.175	.221	.244	.157	.095	.085	.146	.205	.258	.145	.136	.175
15	[1] 101	Trifolium	No. 6 heading	.282	.408	.229	.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	.866	.367	.302	.317	.312
17	60	Rositas	Heading	.302	.515	.335	.567	.229	.224	.189	.188	.682	.408	.176	.411	.377
18	83	North end	....do	.355	.359	.401	.854	.362			.266	.393	.466	.601	.486	

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

Imperial canal system in 19 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 0.53 per cent, or 90 per cent of the silt in the river at Yuma, this being the same ratio found in 1914.

"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 11 to 14, inclusive.

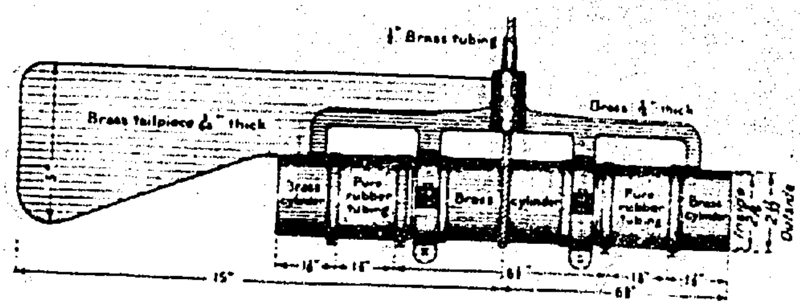


Fig. 4.--Tait-Binckley Sampler.

From Fortier and Blaney's Report.

"Table 11.--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 Passing	Retained	Total
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	2.37	.181	.022	.203
		2.0	2.61	.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	.216
		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	3.36	.175	.080	.255
		5.0	2.27	.194	.205	.399
18	5.0	.5	3.65	.174	.079	.253
		2.0	3.70	.159	(1)	(1)
		3.5	3.24	.169	.071	.240
		4.9	2.86	.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	2.36	.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	2.79	.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

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

(Continued)

From Fortier and Blaney's Report.

(Continued) Table 11.

Distance between station* and bank	Total depth	Depth to sample	Velocity	Proportion of silt by weight: Sieve No. 200: Passing	Retained	Total
Feet	Feet	Feet	Feet per second	Per cent	Per cent	Per cent
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	.178	.315
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	....	....	....	....	....

"Table 12.--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	Retained	Total
Feet	Feet	Feet	Feet per second	Per cent	Per cent	Per cent
0	1.5	....	....	....	....	....
1.5	1.6	0.2	1.34	0.069	0.011	0.080
		.96	1.39	.082	.058	[illegible]
		1.40	1.05	.089	.211	.300
4.5	1.2	.20	1.74	.081	.013	.094
		.72	1.98	.095	.133	.228
		1.00	1.54	.089	.300	[illegible]
7.5	1.2	.20	2.15	.088	.015	.103
		.72	2.08	.098	.091	[illegible]
		1,00	1.59	.125	[illegible]	[illegible]
10.5	1.2	.20	1.64	.069	.007	[illegible]
		.73	1.98	.105	.111	[illegible]
		1.00	1.69	.093	.402	[illegible]
13.5	1.0	.20	1.44	.080	.012	[illegible]
		.60	1.49	.081	.045	.126
		.80	1.34	.094	.306	[illegible]
15	1.0	....	....	....	....	....

From Fortier and Blaney's Report.

Table [illegible].—Distribution of Silt in Cross Section of Kidar Canal, March 28, 1918

(The canal is 10 feet wide, 3.5 feet deep at the center, and has a gradient of 0.785 feet per 1,000 feet).

Distance between standard and sample	Water depth	Depth to sample	Velocity	Proportion of silt by weight: Sieve No. 200: Passing	Retained	Total
Feet	Feet	Feet	Feet per second	Per cent	Per cent	Per cent
0	3.0					
[illegible]	3.1	0.2	1.70	0.657	0.002	0.659
		1.0	2.06	.648	.002	.650
		2.0	1.99	[illegible]	.003	.656
		[illegible]	1.82	.651	.003	.654
		2.9	1.16	.657	[illegible]	.662
[illegible]	3.4	.2	2.33	.646	.002	.648
		[illegible]	2.40	.645	[illegible]	.655
		[illegible]	1.70	[illegible]	.002	.654
		[illegible]	[illegible]	[illegible]	.003	.655
		[illegible]	[illegible]	.657	[illegible]	.661
[illegible]	[illegible]	.2	[illegible]	[illegible]	[illegible]	.639
		1.0	[illegible]	[illegible]	.002	.639
		[illegible]	[illegible]	[illegible]	.003	.651
		[illegible]	[illegible]	[illegible]	.004	.670
		3.0	[illegible]	[illegible]	.005	.641
		[illegible]	[illegible]	[illegible]	[illegible]	.656
[illegible]	3.[illegible]	[illegible]	[illegible]	(1)	.002	(1)
		1.0	[illegible]	.644	.004	.648
		2.0	3.0[illegible]	.651	[illegible]	.653
		2.5	2.07	[illegible]	.002	[illegible]
		3.1	[illegible]	[illegible]	.002	[illegible]
[illegible]	[illegible]	.2	2.21	[illegible]	.003	.644
		[illegible]	2.1[illegible]	[illegible]	.003	.650
		[illegible]	1.70	[illegible]	.002	[illegible]
		[illegible]	2.1[illegible]	[illegible]	.002	.658
		[illegible]	1.45	[illegible]	.003	.662
10	[illegible]					

(1) [illegible] passing 200-mesh sieve not recorded.

From [illegible] Kinney's Report.

"Table 14.--Distribution of Silt in Cross Section of [illegible] Canal, 130 [illegible] Heading, March [illegible], 1919

(The canal is [illegible] feet wide, [illegible] 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 of sample	Velocity	Proportion of silt by weight: No. 200 sieve: Passing	Retained	Total
Feet	Feet	Feet	Feet per second	Per cent	Per cent	Per cent
0	[illegible]					
0.25	2.2	0.2	[illegible]	[illegible]	0.002	0.521
		1.0	1.434	.586	.012	[illegible]
		1.5	[illegible]	.588	.011	[illegible]
		2.0	[illegible]	.591	.047	[illegible]
[illegible]75	2.5	.5	1.72	.575	.006	.579
		1.0	2.15	[illegible]	[illegible]	[illegible]
		1.5	1.81	.575	.018	[illegible]
		2.0	1.60	.584	.028	[illegible]
		2.5	1.41	.577	[illegible]	[illegible]
11.[illegible]	[illegible]	.5	1.70	.575	.005	.580
		1.0	2.50	.572	.025	[illegible]
		1.5	2.01	.579	.015	[illegible]
		2.0	1.60	[illegible]	(1)	(1)
15.75	[illegible]	.5	1.80	[illegible]	.001	.586
		1.0	2.25	.574	.003	.577
		1.5	2.16	[illegible]	.008	.588
		2.0	[illegible]	.621	.061	[illegible]
20.25	2.[illegible]	.5	[illegible]	[illegible]	.002	.575
		1.0	[illegible]	.576	.004	.580
		1.5	[illegible]	.578	.005	.582
		2.0	1.83	.585	.024	.587
22.5[illegible]	[illegible]					

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

The results shown in Tables 11 to 14 inclusive indicate that there is [illegible] difference in the amount of fine silt (passing No. 200 sieve) at [illegible] points along any horizontal in the cross section of a canal [illegible] carried by water at higher velocities at the middle of the stream is [illegible] greater than that carried by the water of slower velocities near the banks at the same elevation. In the upper [illegible] of [illegible] this is generally [illegible] of the total amount of silt carried, which includes the coarser material (that retained on No. 200 sieve). In most cases the silt was fairly equally distributed throughout the entire section considering that on the larger canals several

From Fortier and Blaney's Report.

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.

"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. 3.) A summary of the results is given in Table 15.

"Table 15.—Mean Results of Analyses of Bed Silt in Imperial Valley Canals, 1917-18

Station No.	Station Distance from river	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	Pounds		Per Cent	Per Cent	Per Cent	Per Cent	Per Cent	Per Cent	Per Cent
5	43	98.50	2.645	0.00	0.25	0.52	2.55	5.08	66.26	25.40
6	71	99.01	2.645	.04	1.50	4.12	23.42	5.25	54.78	10.88
7	36	101.45	2.658	.00	.00	.69	3.77	1.22	43.78	50.54
8	52	98.48	2.654	.00	.25	.47	6.08	6.08	69.67	17.47
9	59	99.78	2.677	.08	.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	1.45	8.73	63.19	26.19
14	[1] 91	96.61	2.467	.00	.00	.20	.55	4.80	74.80	20.27
15	[1] 104	95.91	2.635	.00	4.48	2.72	6.95	1.98	50.78	31.98
16	53	98.62	2.658	.00	.02	.06	7.11	26.04	56.25	10.25
17	60	97.71	2.654	.00	.98	.24	14.04	5.54	65.66	14.44
19	83	98.16	2.644	.00	.44	2.87	10.80	2.26	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.

From Fortier and Blaney's Report.

"The mean results shown in Table 15 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 101.45 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.

"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 16. 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 168 miles above Yuma. Samples No. 3 and No. 4 were taken from a sand bar in the river at Ehrenberg, Arizona, February 2, 1919. The specific gravity of the four samples averaged 2.645.

"Table 16.--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
	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	.02	4.40	23.40	40.75	24	7.6	....	....	....	....	....	....	....	....
2	....	.60	.86	1.24	....	....	....	2.00	17.20	15.86	20.70	7.43	2.77	4.20	14.6[illegible]
3	....	.00	.00	.05	....	....	....	.30	3.75	5.95	20.53	10.20	6.30	8.05	22.30
4	....	.00	.00	.00	....	....	....	.45	2.86	6.31	18.80	11.70	5.36	7.36	21.2[illegible]

Sample No.	Passing 260, retained on 280	Passing 280
	Per cent	Per cent
1	.....	.....
2	5.72	7.06
3	6.40	16.05
4	8.48	17.15

From Fortier and Blaney's Report.

"MECHANICAL ANALYSES OF SUSPENDED SILT

"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 times 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 17.

"Table 17.--Mechanical Analyses of Suspended Silt at Top, Middle, and Bottom Depths, at Topock, Arizona, 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	3.37	20.75	31.49	20.17	4.31
Bottom	0	8.69	41.38	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 inches 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 18, 19, and 20 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.

From Fortier and Blaney's Report.

"Table 18.—Mechanical Analyses of Suspended Silt at various depths near the Middle of the Colorado River at Yuma, July 27, 1920

(Depth, 11 feet; discharge, 25,500 second-feet; main river velocity, 4.62 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..	5.22	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..	5.83	.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 19.—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	9.36	85.92
4.0..	4.62	.563	0	.37	2.68	4.83	9.13	82.99
7.0..	4.16	.369	0	.26	1.70	7.77	9.41	80.86
9.8..	3.00	.486	0	.91	5.35	16.34	15.38	62.02

From Fortier and Blaney's Report.

*Table 20.--Mechanical Analyses of Suspended Silt at various depths in the center of the Brawley Canal, 500 feet above the 15-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

From Fortier and Blaney's Report.

The results of the foregoing analyses of bed and suspended silts are shown graphically on Figure 5. It shows that most of the bed silt is, according to the Bureau of Soils' classification, fine and very fine sand, while most of the suspended load is silt or clay. The curves indicate that the average bed silt in the Imperial canals (Curve No. 2) is coarser than in the Colorado River, but since the average for the Colorado is based on only three samples, the result is not conclusive. It would be possible for the bed silt of the canals to be higher, however, as it would only mean that in the canals the finer portion of the river bed silt was carried in suspension. The analyses of bed silt in the Imperial canals indicate comparatively little variation in the values taken over a long period at any of the stations from the average over the same period at all the stations. Much of this variation may be due to blown sand entering the canals. The differences due to different conditions of flow in the Colorado, however, are striking. The sample of bed silt taken in the canal at Hanlon heading on May 1, 1917 was practically all fine sand, while that taken July 15, just after the peak of the spring flood, was largely coarse and medium sand, with a considerable proportion of fine gravel.

There are great variations in the composition of suspended material due to special conditions, comparable to those in bed load. Figure 5 shows that the samples of suspended material taken in the Colorado River at Topock, Arizona, on November 15, 1917, was practically all fine sand, while all of the other measurements in the river and canals showed that the greater part was silt or clay. As stated above, severe cutting was under way just above the Topock station at the time the measurement was taken. The samples of suspended silt, except at Topock, are remarkably similar in composition, as far as could be determined by sieve analysis. The sample from the Colorado at Yuma is slightly coarser than those taken in the canals. In computing the mechanical analyses of suspended silt, the direct average of the per cents at the various depths was taken, the data not being sufficiently complete to weight them according to velocity and proportion of total area, but the results are believed to be substantially correct.

"WEIGHT OF SILT PER CUBIC FOOT IN RIVER AND CANAL DEPOSITS

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

"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 6-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 21.

"Table 21.--Weights of Colorado River Silt Deposits, near Yuma, Arizona, 1915-16.

Date	Location of samples	Weight per cubic foot: Natural state	Weight per cubic foot: Dry
		Pounds	Pounds
1915			
Dec. 3....	Near Yuma ice plant	......	[illegible]1.2
Do.....	....do.	......	92.0
Do.....	....do.	......	77.0
Dec. 16...	Soldiers camp	......	86.0
Dec. 18...	Yuma gauging station mast, California	......	84.5
Do.....	Yuma city dump	108.0	83.1
1916			
Jan. 26...	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	......	83.4
Feb. 3....	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, Arizona, the weights of which are shown in Table 22.

From Fortier and Blaney's Report.

"Table 22.—Weights of Canal-Bed Deposits at Yuma, 1915-16

Date	Location of samples	Weight per cubic foot: Natural state	Weight per cubic foot: Dry
		Pounds	Pounds
1915			
Dec. 21...	Main canal, headquarters bridge	112.5	87.7
Do....	Main canal, First Street bridge	109.1	78.6
1916			
Jan. 4....	Main canal, California drop	. . . .	86.7
Do....	Main canal, California siphon gate . . .	. . . .	81.1
Jan. 27...	Spillway, Porter's [illegible]	. . . .	87.7
Mean....	. . . .	. . . .	[illegible].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 23 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 23.—Weights of Silt Deposits in the Colorado River at Laguna Dam, Yuma, and Rockwood Heading.

Sample No.	Weight per cu. ft.: Natural state	Weight per cu. ft.: Dry	Location of sampling
	Pounds	Pounds	
1......	[illegible]	[illegible].7	Above Potholes heading at surface.
2......	[illegible]	84.0	Above Potholes heading, 4 inches below surface.
3......	92.0	85.3	Above Potholes heading, 5 to [illegible] inches below surface.
4......	97.8	80.[illegible]	Above Potholes heading, 9 to 1[illegible] inches below surface.
5......	100.7	80.3	Above Potholes heading, 13 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.[illegible]	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	

From Fortier and Blaney's Report.

"The following day (February 23) 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 24.

"Table 24.--Weights of Bed Silt in Canals of Imperial Valley.

Sample No.	Weight per cu.ft: Natural state	Dry	Location of sampling
	Pounds	Pounds	
1......	126.2	99.6	East Highline Canal, three-fourths miles north of Lawrence heading.
2......	127.3	105.2	East Highline Canal, 1,000 feet north of Gauge 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 25 shows the weights of the samples taken on May 1, which are typical. The samples were taken in the same cross section.

From Fortier and Blaney's Report.

"Table 25.—Weights of Bed Silt in Alamo Canal, at Hanlon, May 1, 1917.

Distance between station and bank (feet)	Specific gravity	Weight per cubic foot: Wet	Weight per cubic foot: Dry
		Pounds	Pounds
5	2,657	125.62	99.08
15.	2,675	133.73	110.35
25.	2,683	124.79	101.88
35.	2,696	125.19	101.35
45.	2,725	128.02	105.96
55.	2,735	126.40	104.40
65.	2,709	125.70	103.77
75.	2,714	127.46	104.12
85.	2,695	128.15	103.69
95.	2,679	132.82	98.40
105	2,655	125.49	102.76
115	2,683	114.62	91.21
Mean.	2,694	125.64	102.24

"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 26.

"Table 26.—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	2.650	121.17	101.43
8	Ten-foot drop	Central main	52	2.654	122.83	98.48
9	Dahlia heading. . . .	Dahlia	59	2.677	119.48	99.76
10	No. 12 heading. . . .	do	69	2.634	113.85	90.11
11	No. 4 heading	No. 4 main	76	2.655	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	95.91
16	No. 5 heading	No. 5 main	83	2.658	119.24	98.63
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.

From Fortier and Blaney's Report.

"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 27.

"Table 27.--Weights of Samples taken from the Bottom of Briar Canal, February 15, 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
	Pounds	Per cent	Pounds	Per cent	
1	119.23	+1.88	90.31	+2.41	2.646
2	116.27	-.64	86.79	-1.57	2.638
3	117.85	+.71	89.23	+1.19	2.647
4	119.29	+1.94	89.09	+1.03	2.644
5	117.35	+.28	89.23	+1.19	2.647
6	115.92	-.94	87.94	-.27	2.654
7	116.33	-.59	88.78	+.68	2.645
8	116.92	-.09	88.73	+.62	2.638
9	116.56	-.39	87.79	-.44	2.637
10.	115.99	-0.88	87.73	-0.51	2.644
11.	115.48	-1.32	88.08	-.11	2.651
12.	118.21	+1.02	88.37	+.21	2.632
13.	116.63	-.33	87.08	-1.24	2.637
14.	116.42	-.51	86.08	-2.38	2.625
15.	116.63	-.33	87.51	-.76	2.636
Mean .	117.02	. . . .	88.18	. . . .	2.641

"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 71.8 to 100 pounds, averaging 84.5 pounds. The series of samples of canal-bottom deposits taken during 1917-18 period (see Table 26) 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.

"WEIGHT OF 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.

* From Fortier and Blaney's Report.

"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 [illegible], soft, and freshly deposited. The sampler consisted of a thin aluminum cylinder 7.6 centimeters in diameter and [illegible] 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 28.

"Table 28.--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	92.45	[illegible]	85.87	57.47
2	91.12	[illegible]	84.36	54.91
Mean	91.78	[illegible].75	85.[illegible]	[illegible].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 176 cubic centimeters on top of which was [illegible] 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 15 cubic centimeters of clear water. Thus there was still 15 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 29.

[illegible] and Elmore's Report.

"Table 29.—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	38.1	21...	81.8	32.3
2...	91.3	51.3	12...	84.[illegible]	36.7	22...	81.9	32.5
3...	92.5	52.2	13...	87.1	30.6	23...	82.6	37.8
4...	89.4	47.2	14...	87.6	38.6	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	38.5	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...	85.5	39.2
9...	84.3	37.8	19...	84.6	37.5	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 30.

From Fortier and Blaney's Report.

"Table 30.--Weights of Colorado River silt deposits in settling basins at Parker, Arizona.

Weight of silt per cubic foot	
Saturated	Dry
Pounds	Pounds
95.5	56.8
101.5	66.0
89.6	44.9
107.9	77.7
86.9	42.0
[1] 96.1	[1] 57.5

[1] Mean.

"Regarding the data given in Table 30, 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.

"WEIGHT OF 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. 300 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.

From Fortier and Blaney's Report.

"WEIGHT OF 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."

From Fortier and Blaney's Report.

"RELATION OF VELOCITY AND DEPTH TO THE QUANTITY AND SIZE OF SILT TRANSPORTED IN IMPERIAL VALLEY CANALS.

"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 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 31 to 34.

From Fortier and Blaney's Report.

"Table 31.--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
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.
Top...	0.000	0.001	0.001	0.003	0.005	0.007	0.007	0.005	0.005	0.027	0.015	0.020
2.0...	.003	.005	.007	.015	.009	.019	.008	.007	.016	.038	.017	.020
2.5...	.003	.007	.012	.017	.012	.023	.010	.012	.010	.041	.022	.020
3.0...	.005	.010	.015	.027	.014	.026	.012	.008	.004	.046	.020	.025
3.5...	.009	.010	.028	.029	.016	.037	.011	.012	.013	.045	.027	.031

	Passing 300	Total
Feet	P.ct.	P.ct.
Top...	0.720	0.810
2.0...	.740	.903
2.5...	.735	.924
3.0...	.740	.952
3.5...	.724	.991

"Table 32.—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

From Fortier and Blaney's Report.

Table 33.--Proportion of silt of each of five grades at various depths in the Birch Canal one-half mile east of Calexico, California, June 30, 1920.

(The samples were taken from the center vertical, which had a depth of 1.9 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	0.005	0.017	0.334	0.354
0.5 feet	2.177	0	.000	.005	.026	.342	.371
1 foot...	2.422	0	.003	.010	.028	.347	.367
1.5 feet.	1.281	0	.008	.045	.075	.400	.528
1.7 feet.	1.293	0	.096	.134	.099	.414	.743

Table 34.--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 160 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	0.006	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	.053	.301	.383
5 feet...	4.58	.004	.046	.047	.054	.318	.469
6 feet...	4.39	.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	....	.008	.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	.025	.079	.075	.302	.485

From Fortier and Blaney's Report.

"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.

"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. Pack. The results are given in Table 35.

From Fortier and Blaney's Report.

"Table 35.--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, ret'nd on 20	Passing 20, ret'nd on 40	Passing 40, ret'nd on 60	Passing 60, ret'nd on 80	Passing 80, ret'nd on 100	Passing 100, retained on 200	Passing 200
Miles		1917	Lbs.		P.ct.	P.ct.	P.ct.	P.ct.	P.ct.	P.ct.	P.ct.
1	Hanlon heading, Alamo Canal	Mar. 14	......	2.719	0.00	0.05	1.26	33.07	23.50	34.41	7.71
		May 1	102.77	2.695	.00	.26	5.05	48.59	15.90	17.07	12.15
		July 15	......	2.654	18.09	20.88	35.13	20.58	1.54	4.26	1.72
48	Check No. 1, East Side Canal	July 16	103.36	.....	.00	.60	.90	3.50	20.00	50.50	24.70
71	Myrtle check, East Side Canal	July 18	101.70	2.641	.00	3.10	8.50	40.60	28.10	16.50	9.50
86	Junction lateral, East Side Canal	July 19	99.08	2.519	.00	.00	3.20	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
79	Lateral No. 12, Dahlia Canal	July 17	93.23	2.631	.80	.35	.00	.20	.65	78.50	20.00
76	No. 4 delivery, Brawley main	do.	......	2.670	.00	.00	1.60	4.80	12.70	50.10	30.80
94	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 9,865 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 146,000 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, 35.1 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 be kept in mind and the July 15 analysis of the Hanlon heading samples be 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."

From Fortier and Blaney's Report. 46

"In order to determine the amount of silt moved along the bed of the Alamo Canal, a special study of new and of earlier observations was made by C. E. Grunsky to ascertain whether changes in the elevation of the canal bottom during a number of years would "throw some light" on this subject. The stretch of canal selected extends downstream 18,000 feet from the Hanlon Regulating Gate which, as explained, is about 1-1/4 miles below the Rockwood Gate in the head of the canal.

"For some months after the completion of the Rockwood Gate the canal water flowed from the river through this upper gate uncontrolled, but in the summer of 1918, stop-planks were put into use and thereafter the water from the river dropped over them.

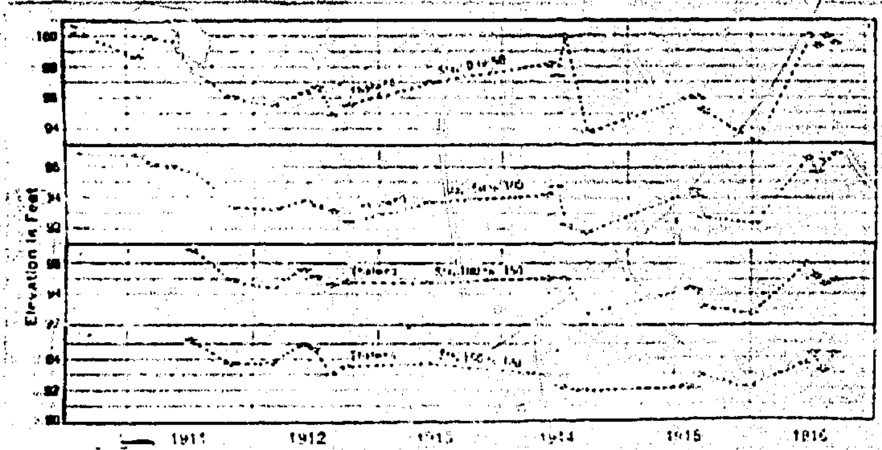


Fig. 6.--Average Elevation of Line at Greatest Depth, Imperial Canal.

"<u>Seasonal Changes.</u> It was found that in the spring while the river was rising from its low (winter) to a high (spring and summer) stage, more silt was deposited in the canal than its water could transport. The canal bed, at least in its upper stretches, rose to a highest position in June and was lowest in mid-winter. Considering only the selected 3.5 miles of canal, this rise, due to the deposit in the first four or five months of the year, ranged from a minimum of 1 foot in 1912, to a maximum of 4.4 feet in 1916. Thereupon, generally beginning in June or July, the same stretch of canal was deepened by erosion; the amount of this deepening was about 3.5 feet in 1911, about 2.1 feet in 1912, and about 2.7 feet in 1915. These changes in the average elevations of the canal bed are shown diagramatically in Figs. 6 and 7. On these diagrams each point represents the average elevation of the thalweg or of three parallel lines representing the canal bottom for the particular stretch of canal as marked. These curves bring the information relating to bottom elevation forward to the time when dredging operations in the head of the canal modified the earlier conditions.

From Grunsky's Paper.

"As was expected, these studies have thrown some light on the rate the bed-load movement of the water. It appeared obvious that an increase of deposit represented accession of silt from up stream, arriving as bed load or as material dropped from suspension, and that erosion represented depletion in excess of the material arriving from up stream and temporarily coming to rest.

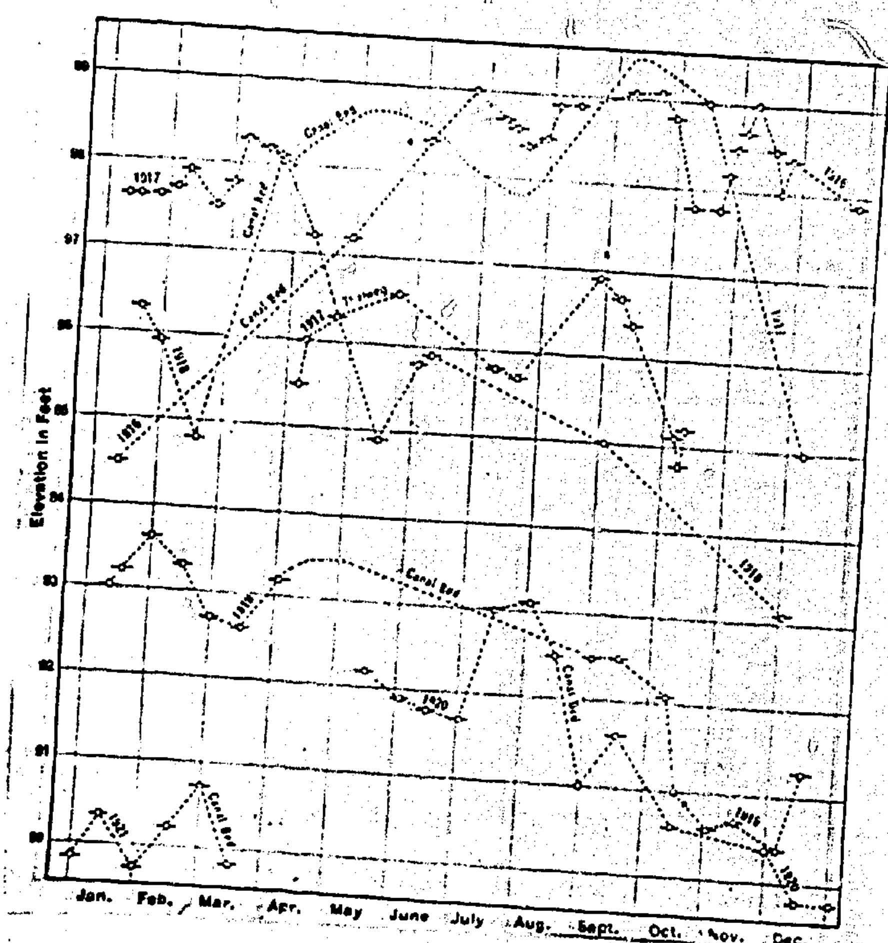


Fig. 7.—Average Elevation of Canal Bed, Imperial Canal.

"These studies show that during late winter and spring at least 280,000 cubic yards of silt per month were being deposited, temporarily, in the canal stretch under observation and that a like volume was removed later in the year. How much more silt was traveling along the bed in continuous movement in sand waves could not be ascertained, but it was suspected to be large. Inspection disclosed that the canal bed, at least near shore, was covered with small sand waves about 3/4 inches high and traveling slowly like sand dunes. The individual sand particles roll up and over the crests into the troughs.* Occasionally, the water would take

*Professional Paper No. 86, U. S. Geological Survey.
From Grunsky's Paper.

on a disturbed appearance for a time probably denoting temporary instability of "anti-dune" sand traction.

"The annual water delivery of the canal at the time of these studies was about 2,000,000 acre-feet. The water slope was about 1.5 feet per mile, and the mean velocity about 3 to 4 feet per second. The silt in suspension ranged from about 0.35% to more than 1% by weight, and averaged about 0.8 per cent.

"<u>Dredging Operations.</u> In 1918, the canal head-works were modified, suction dredges were installed, and dredging from the canal bed was commenced. This intercepting of the silt not only improved the regimen of the canal, but also reduced the cost of canal operation by obviating the more expensive removal of the same quantity of silt from downstream sections and from canal laterals and ditches.

"Table 36.—Removal of Silt by Dredging from the Head-Works Section of Imperial Canal.

Period.		Cubic yards of silt excavated and removed from the canal.		Average per month, in acre-feet.
1918	July	180,000		
	August	224,600		
	September	248,400		
	October	373,000		
	November	144,700		
	December	298,700		
Total, six months			1,469,400	150
1919	January	286,900		
	February	252,900		
	March	126,200		
	April	181,000		
	May	353,600		
	June	523,300		
Total, six months			1,724,300	170
1919	July	570,100		
	August	629,100		
	September	594,100		
	October	652,800		
	November	484,000		
	December	756,800		
Total, six months			3,686,900	380

(Cont.)

From Grunsky's Paper.

(Cont.)

Period.	Cubic yards of silt excavated and removed from the canal.		Average per month, in acre-feet.
1920 (January	798,300		....
(February	688,700		....
(March	[illegible],900		....
(April	[illegible]		....
(May	886,300		....
(June	1,134,400		....
Total, six months		5,226,300	540
1920 (July	1,122,800		....
(August	479,700		....
(September	342,600		....
(October	308,200		....
(November	354,300		....
(December	283,300		....
Total, six months		2,890,900	300
Grand total and average		14,991,800	310

"The silt thus removed is noted in Table 36. The estimates of volume dredged were made from samples of the discharge, except during the early months of dredging when the spoil was used in filling low ground at the head of the canal to canal-bank level. On the plea of economy the amount of dredging in the head reach of the canal was reduced by the Irrigation District authorities in 1920 and was stopped with the close of that year.

"Despite the large aggregate volume of dredging involved (nearly 15,000,000 cubic yards in 30 months), the effect on the regimen of the canal considered in its entirety was hardly noticeable. General conditions remained apparently unchanged; but there was some deepening of the canal bed below Hanlon's. Certainly, the dredging was beneficial and should not have stopped. It has since been resumed for a few months in the year. While it is not quite clear what effect this dredging had on the lower reaches of the canal, it is certain that if the large quantity of the removed silt had been allowed to remain in the canal it would have traveled downstream to the annoyance of the canal management and the inconvenience of the farmer who is constantly receiving excessive quantities of silt with his muddy irrigation water.

"In the upper canal reaches, even before the dredging commenced, some deepening of the canal was noted. Thus, for example, the mean elevation of the canal bottom during January and February, 1918, was about 2 feet lower than in the corresponding months of 1917. For the entire year,

From Grunsky's Paper.

1918, during the last half of which silt was removed from upstream portions of the canal by dredging, the average lowering was also about 2 feet. In 1919, the bottom of this upper canal stretch was further deepened about 2 feet. This is to be ascribed to the depletion of the supply of silt by dredging and the continuation of bed-load movement. There was some restoration of bed elevation in 1920, the canal bottom being at about the same position in August and September as in the preceding year; and then, despite cessation of the dredging operations, the bed was lowered several feet to a position early in 1921 about 7.5 feet lower than it had been in 1917. Some of this lowering (Figs. 6 and 7) is no doubt to be ascribed to the dredging in the head reach of the canal.

"It is noteworthy that the dredging did not relieve the canal entirely of its bed load. The periodical accession and depletions of silt deposits, as evidenced by the rising and lowering of the canal bottom, continued. The dredged sumps in the head of the canal did not trap all the silt which came over the flash-boards of the Rockwood Gate. It now appears that even 500,000 cubic yards per month (the average quantity removed for 2-1/2 years) does not represent the entire load of fine sand carried as a bed load by the canal. How much more was being transported is not known, and no entirely satisfactory basis for estimating it has been found.

"Dredging, as Table 5[illegible] shows, removed on an average about 310 acre feet of silt per month from the bed of the canal for 2-1/2 years, and more than 400 acre-feet per month for certain periods of 18 months. Had there been no removal by dredging it is reasonable to assume that this material would have been carried down the canal mainly as a bed load."*
From Grunsky's Paper.

This lowering of the bed of the Imperial Canal, due to the removal of its bed load at the upper end, is important in the design of the All-American Canal, since it shows what may happen in soils composed of Colorado River silt if clear water is allowed to flow over them at velocities sufficient to move appreciable quantities of bed load. This action is the same as may be expected to happen in the Colorado River below the storage dam. This seems likely to happen in the sand hill section unless the channel through it is lined, but the result might not be of importance.

"THE BED LOAD OF RIVER IN COMPARISON WITH THAT OF THE CANAL.

"It appears from the foregoing that the canal, with an annual discharge of from 2,000,000 to 2,500,000 acre-feet, transported about 4,000 acre-feet of silt (at 100 lbs. per cu. ft.) by traction, as its annual bed load. There must have been, of course, some pick-up and temporary transport in suspension. Because of this fact the estimate of canal-bed load may be accepted as a minimum.

"If this determination be accepted it affords means for estimating, approximately at least, the bed load of the Colorado River itself.

*From Grunsky's Paper.

The traction exerted by the river on its bed may be regarded as independent of the suspended load. The sand on the bottom travels by rolling or by saltation regardless of whether the water is clear or muddy. In view of general similarity of canal and river beds, the annual bed loads of the canal and of the river may be assumed to be proportional to the annual discharge. This assumption ignores the fact that the river departs most widely from the characteristics of the canal when its discharge is greatest and the attack on its bed is most vigorous. The resulting estimate, therefore, is again more likely to be too small than too large.

"On this assumption the bed load of the Colorado River, with its annual discharge of about 10,000,000 acre-feet of water, at Yuma should be about six or seven times as great as that of the canal, or 25,000 to 50,000 acre-feet per year. The assumption as to corresponding fineness of material applies to the material in the beds of river and canal, as well as to that in suspension. The larger velocities in the river at its high stages, if taken into account, would probably increase somewhat its relative and therefore, also, its total bed load."

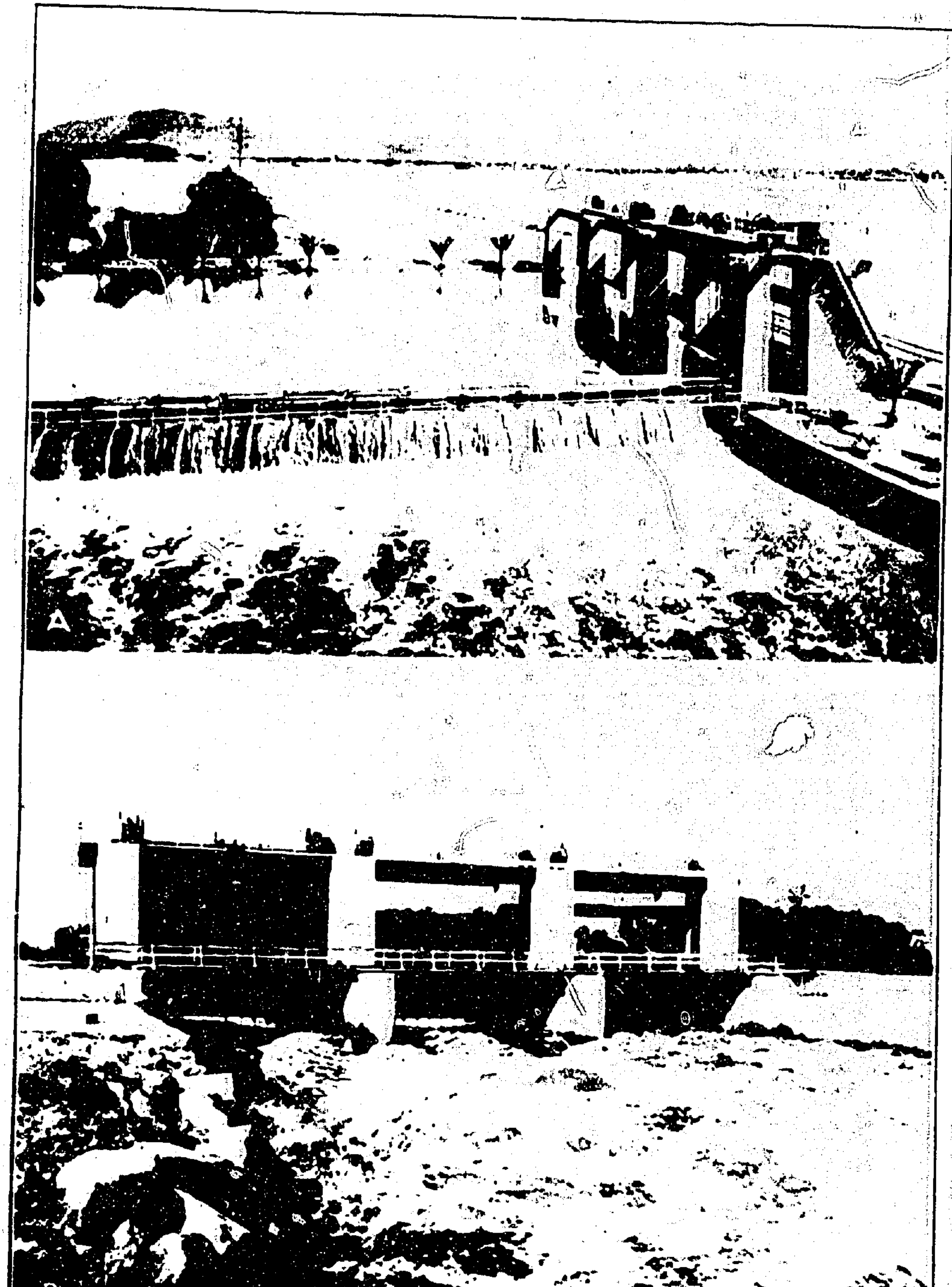
From [illegible]'s Paper.

AMOUNT OF SILT CARRIED TO IRRIGATED LANDS IN THE IMPERIAL VALLEY.

[illegible] part of the total silt in suspension in the [illegible] Valley is fine material that passes the 500-[illegible] finest screen obtainable. The silt is finer than [illegible] this material was found to be equally distributed [illegible] vertical section for all velocities under which [illegible] mean velocities of less than two-thirds foot [illegible]. In other words, any velocity that is practical [illegible] irrigation canal will carry in suspension the greater part [illegible] transported by the waters of Colorado River, and most of it, [illegible] to the irrigated land. The amount of suspended silt [illegible] is very small proportion of the total amount [illegible] the fact that large quantities of bed silt [illegible] each year.

[illegible] Station 59, mentioned in Table 10, was on one of the smaller laterals. [illegible] indicated that about 90 per cent of the silt carried in [illegible] reached the [illegible] irrigated. On the average, this would amount [illegible] 0.39 per cent [illegible] 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.

From Fortier and Blaney's Report.



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

"SILT REMOVAL ON THE YUMA PROJECT.

"Beside the Imperial Valley project, the only other large irrigation development on the lower Colorado River is the Yuma project. On this project comparatively little difficulty has been experienced from silt deposits in the canals, due to the installation of desilting works at the canal intake.

"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, Arizona, 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 intake 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 comprises an irrigable area of about 110,000 acres in Yuma County, Arizona, and Imperial County, California.

"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.

From Fortier and Blaney's Report.

"The head gate for the main canal is a simple structure with 35 openings, each 7½ feet in the clear, between concrete piers. (Fig. 8A). On these piers rests a concrete foot-bridge 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 (Fig. 8B) 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.

"A set of experiments was made 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 37, while Table 38 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.

"Table 37.--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		
		Passing	Retained	Total
	Feet	Per cent	Per cent	Per cent
Surface	0	0.438	0.001	0.439
	1.5	.534	.041	.575
Bottom	2.0	.664	.133	.797
	2.5	.647	.270	.917

From Fortier and Blaney's Report.

"Table 38.--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	.090	.064	2......	.100	3......	.088
8......	.500	.351	.540	.673	.650	4......	.198	6......	.212
						6......	.615	......	......

"While Table 37 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 feet 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 0.042 per cent at the surface and 0.465 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 0.429, 0.042 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

From Fortier and Blaney's Report.

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 OF YUMA PROJECT.

"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 39. The amount of desiltation ranged from 33 to 72 per cent and averaged about 57 per cent."

"Table 39.--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	.098	.135	58
Oct. 12...	.275	.077	.198	72
Oct. 17...	.468	.314	.154	33

From Fortier and Blaney's Report.

"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 40 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 40.--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 ct.	Per cent	Per cent	Per ct.	Per cent	Per ct.	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	.46	.21	.25	54.3
.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	52.3	.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

From Fortier and Blaney's Report.

THE EFFECT OF THE CONSTRUCTION OF THE BOULDER DAM.

The construction of the Boulder dam will, no doubt, materially change the volume and character of the silt in the lower Colorado River. Time has not been available to study deeply into this phase of the problem. Because of the lack of precedent, it is difficult to determine accurately in advance just what the changes would be. It seems certain, however, that the silt problem will be less severe than under present conditions. All, or practically all, of the silt from the greater part of the drainage area of the Colorado River will be settled out in the Boulder dam basin. The floods of the Gila River will still bring in large quantities of silt for short periods but these will enter the Colorado below the diversions. Cloudbursts on the area tributary to the Colorado below the storage dam will, no doubt, at times produce a high silt content. Although the silt from above the storage dam will probably be all removed from the water, the clear water discharged from the dam will pick up silt from the stream bed below the dam and carry it on downstream. This will eventually lower the bed of the stream, but it is not possible to determine how rapidly this will take place. Such a lowering will increase the grades in all the tributaries entering this section of the river and cause an increase in the material which they will discharge into the main river bed. A large part, possibly the greater part, of the material, which is picked up from the stream bed below the storage dam by the clear water released from storage, will be bed silt, comprised of coarser particles and the silt in the river will therefore be coarser on the average than at present. Assuming that the capacity of the clear water to transport this material is not less than that of the present silty Colorado River water, it seems probable that for some years to come, until the removal of silt from the river bed below the dam has become so great as to effect its slope, about the same quantity of bed silt for a given discharge will be present in the water at the diversion site as under present conditions. There seems to be little doubt, however, that the coarse silt problem can be satisfactorily handled by desilting works at the intake of the canal. It, therefore, seems probable that the silt problem of the All-American Canal, except for the sand hill section, will not be serious after the readjustment of the river grade below the storage dam has taken place, and it may not be serious at any time after the storage dam is built. There is a possibility, however, that if relatively high velocities are used, after the river has re-established itself on a flatter grade, some erosion of the canals may take place due to the relatively clear water picking up particles from the canal bottom and carrying them forward. This is especially likely to occur in the existing canals, due to the reduction of the silt content of the irrigation water resulting from the use of a desilting works at the intake, as well as the effect of the construction of the Boulder dam.

SCOUR AND DEPOSIT IN IRRIGATION CANALS.

In order to secure a design for the All-American Canal, which will efficiently handle the silt problem, a thorough study was made of the data available on scour and deposit in irrigation canals outside the Colorado River Basin and the laws governing these phenomena. The problem in the All-American Canal has three aspects: (1) The prevention of the deposit of fine silt in the canals; (2) The securing of velocities of flow which will not erode the banks; and (3) The securing of velocities where necessary to transport the dune sand which may blow into the canal. To a large extent these three problems are distinct and separate. Considerable confusion has arisen from Kennedy's non-silting, non-eroding velocities, and the impression has gained currency that his formula gave a velocity such that silt would be deposited if the velocity fell below that value and erosion of the banks would result if higher velocities obtained. This is not the case, and a careful reading of Kennedy's original paper* and the discussion in his Hydraulic Diagrams** shows that

*Proceedings of the Institution of Civil Engineers, Vol. CXIX (1895) page 281.
**Hydraulic Diagrams for Channels in Earth, R. G. Kennedy (Public Works Dept., India).

he had no such view. The distinction, however, was not sufficiently emphasized in these publications. Kennedy's formula gives for a certain depth a velocity such that lesser velocities will cause fine sand and silt to deposit, and greater velocities will cause the silt which has deposited to erode. Whether or not the higher velocity will cause the material composing the banks of the canal, as originally constructed, to scour, depends entirely upon the material of which they are composed. For example, to take an extreme case, in a canal through rock, low velocity would allow silt to be deposited, a somewhat higher velocity (Kennedy's critical velocity) would be just sufficient to prevent its deposit, but no erosion of the rock banks of the canal would take place until the velocity was greatly increased. It is evident, therefore, that there may be a considerable gap between the minimum permissible velocity, which is necessary to prevent excessive silt deposit, and the maximum allowable velocity, above which, bank scour will take place.

The most complete study of the first phase of the silt problem, the prevention of the deposit of fine silt in the canals, was made by R. G. Kennedy over forty years ago,* and it gives practically the only extensive quantitative data on the subject which could be discovered.

*"The Prevention of Silting in Irrigation Canals", by R. G. Kennedy, Proceedings of the Institution of Civil Engineers, Vol. 119, p. 281.

Kennedy measured the cross section of ditches in the Bari Doab canal system in India, where the channel had long reached a condition of equilibrium. The sections extended over 90 miles of the lower reaches of this canal system beginning about 50 miles below the intake, where the canals throughout the year carried a load of fine sand and silt. The discharge capacities ranged from 26 to 1700 second-feet and depths from 2.2 to 7.2 feet. The cross-sections were practically rectangular, the sides being vertical and of fine sediment, and the bed horizontal and of coarser sand. The discharge used in computing the mean velocity at these sections was the "full supply", which seems to have been the flow passing through the canals, the greater part of the time during which they were in operation. In the smaller canals the flow was entirely shut off about one-quarter of the time. From his data, Kennedy concluded that the velocity V_o, which was required to keep such channels in equilibrium, was a function only of the depth and he determined the equation of this velocity to be $V_o = 0.84\ d^{0.64}$, where d is the depth of the channel.

In his Hydraulic Diagrams,** published about twelve years later, Kennedy gives a much more thorough discussion of the conditions under which his formula applies, no doubt including the results of experience in the use of the formula for the years since its development. This discussion adds much to the usefulness of the formula and since the original publication is often not readily obtainable, the pertinent parts are quoted in full as follows:

**"Hydraulic Diagrams for Channels in Earth" - R. G. Kennedy, Public Works Dept., India.

"SILT IN CANALS, AND ITS DISPOSAL.

"Paper No. 2826, of the Proceedings of the Institution of Civil Engineers for 1894-1895, gives the data then collected, and the theory put forward on this subject. The following brief outline of what takes place when a canal takes off from a river with a steeper slope than its own, may, however, be useful, and we may take the extreme case where the river has a boulder bed, with extremely high velocities, rolling boulders in floods, and clear water in low supplies.

"The boulders to a great extent can be excluded from the canal by proper design of the head and under sluices, so devised that they will roll straight on through the latter, but if this is not wholly successful, then such boulders as do enter the canal will drop in the head reach, and must be cleared out each year.

"A little farther down the canal the shingle will be deposited, and will have to be similarly cleared out.

"Still farther down small pebbles will drop, and as they gradually raise the bed and gradient, they also must be cleared, but the quantity being small, some years may elapse before this need arises.

"Lower still the very coarsest sand deposits, but at an extremely slow rate, so slow that a great many years may elapse before it is even noticed, and eventually, action may or may not be required. The quantity carried is relatively small, and though dropped on the bed, it is not quite stationary, but very slowly travels or rolls downstream; in fact, no clear line can be drawn between the coarse and fine sand; what happens being that both are on the move, but at different rates, and the coarser kinds are left behind, gradually accumulating on the bed of the higher reaches. Thus, 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

Quoted from Kennedy.

of sand silt, without either deposit or erosion. If this is not done, then constant and costly re-modeling goes on year after year, such work being only possible by installments as canal closures permit.

"DETERMINATION OF CRITICAL NON-SILTING MEAN VELOCITIES.

"Between 1890 and 1894, observations were made by the author on the Bari Doab Canal, Punjab, to determine the mean velocities necessary for channels of various sections and discharges, so that they should each carry their full share of sand silt, i. e. be fully charged. Thirty channels were selected, all known to be more or less in permanent regime, and all having self-silted and similar sand beds. Evidently each of them was fully charged with silt, since each had the option of picking up more sand from the bed or dropping any 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 the depth had, so the two last-named were plotted as co-ordinates, and the resulting relation was found to be $V_o = 0.84 D^{0.64}$, where Vo is the "critical" or non-silting mean velocity, and D is the depth; both being for ordinary full supply. Tabulated, these are in feet and feet per second—

d	1	2	3	4	5	6	7	8	9	10	12	15	20	50	100
Vo	.84	1.30	1.70	2.04	[illegible]	2.64	2.92	3.18	3.43	3.67	4.18	4.75	5.71	10.27	16.00

"For the greatest depths, these values of Vo are, of course, only calculated as following the same law as the smaller depths; but, so far as known, the resulting figures agree fairly well with very deep rivers on sandy beds."

"Put into plain language, the interpretation of these experiments simply was, that if we take two channels of the same depth and the same mean velocity, but one being much wider and of greater discharge than the other, then both will have the same silt-carrying power, because the number of small upward eddies, which alone support the silt, are proportional to the width, and therefore also to the volume of water. If, however, the depth of either channel were increased, keeping the same velocity, then the number and force of these eddies being much the same as before, but having a larger body of water to act on, they would be unable to keep in suspension the same silt proportion, and to enable this to be done the velocity would have to be increased, thus adding to the force of the up-currents.

"LIMITATIONS IN APPLYING Vo.

"In applying the silt data here given, there are certain limitations to be observed, a disregard of which has in the past led to some misapprehension. The critical velocity Vo here referred to, may be defined as that mean velocity which, for a channel of given depth, on a sand-silted bed, or running fully silt-charged with what may be called the standard sand-silt found in river beds just after they leave the hills, will just keep that channel all the year round free from either silting or scouring its bed; though each slight temporary action may occur at different seasons, according to the amount of sand in the river supply.

Quoted from Kennedy.

"The following are the most common cases where some modification of Vo is called for; and where such is needed we may estimate its amount by the percentage or fraction of Vo, which must be substituted instead of Vo, e. g. 0.8 Vo or 1.1 Vo, etc.

"MODIFICATION OF Vo DUE TO POSITION OF OFFTAKE ON THE RIVER.

"When the offtake of the canal is far from the hills, the sand being much finer is easier carried, and therefore a less value than Vo will suffice; how much is difficult to say, perhaps down to 0.75 Vo in some cases, but the real value could be simply enough obtained by selecting a few well-defined channels in nearly permanent regime, and observing the mean velocity and depth. Then the ratio of this velocity to Vo (as given in par. 9 for that depth) will give the fraction of Vo to apply in any new designs. If, on the other hand, the canal head were in the hills, and from a boulder instead of a sand bed, it would be necessary to contemplate the annual removal of shingle, or even the coarsest sand and pebbles; and the head-reach, where this would happen, would have to be steeply graded, according to the soil. Lower down, where only the standard sand would reach, Vo would be allowed, the same as for a river with a sand bed.

"EFFECT ON Vo OF CHANGING THE METHOD OF HEAD REGULATION.

"Occasionally, means may be adopted at the head of a canal to exclude the full proportion of silt in the river water, especially in flood seasons. Thus the river may be partially ponded-up on the offtake side by means of closed undersluices and divide walls, etc; regulation being done at the far side of the river, and the pond occasionally scoured out through the sluices. This materially reduces the sand silt entering the canal, and besides this the whole canal may be shut off during really heavy floods, so that the canal supply is not fully charged, and a less value than Vo can be given. This may be exemplified by a reference to the Sirhind Canal, which, with normal river regulation, silted very heavily owing to too small a slope, but which, since the adoption of a change in regulation on the above lines, has given no trouble, and now runs with a value of 0.9 Vo.

"Vo DECREASES IN LOWER REACHES OF CANAL AND DISTRIBUTARIES.

"When a canal gives off a branch or distributary, it occasionally happens that the offtake takes off more than its proper share of the sand silt, due for the most part to the sill of the sluices being at or near the bed level, and drawing in much of the lower strata sand, which in steady flow, partly rolls along the bed. The same thing may happen, even if the sill is fairly high, due to some persistent local eddy raising up this sand, and in such a case the offtake will be overcharged with sand, and require more than Vo, and the parent channel will be left rather undercharged. On some canal branches this action is fairly well marked, and the tail reaches have comparatively little sand left, and can be graded to give less than Vo--0.90 Vo sometimes. It is on the distributaries, however, that this action is certain and most marked, because here the outlets are, and should be at the bed level, and draw off the rolling bed sand direct, with little or no

Quoted from Kennedy.

stirring-up action of the main body of the flow, which would otherwise equalize the distribution of the sand from surface to bed. The result is that the greater part of the heavy sand is drawn off by the outlets in the first few miles of the head reach of the distributary, so that the lower reaches can be graded to much less than Vo, and this accounts for the fact that the grade near the head of a distributary must always be and is much steeper than farther down. The fraction of Vo to be graded for, therefore, should usually decrease gradually from Vo at the head to 0·95, 0·90 and 0·85 Vo, and in some very long channels even 0·80 Vo may be safe; and this is fortunate, since in very flat country it would be otherwise impossible to get the requisite slope. Moreover, to grade for Vo, the whole length would in some cases of poor soil cause erosion, simply because the water, having little or no charge of its own, can pick up a local supply.

"INCREASE OF Vo AND EROSION FROM EXCESSIVE VELOCITY.

"Quite a common case is where a canal reach has been graded too steep, or when the banks are eroding from too great depth and velocity, thus overcharging the supply to such an extent that the branches or distributaries lower down are unable to carry the excess sand. The remedy here is, of course, to stop the cause, though very often this may go on for years before the evil is recognized, and many more may elapse before the remedy can be applied. In many soils an excess grading giving only 1·1Vo will cause this trouble (especially if depth is great), raising endless difficulties farther down, and this all points to the necessity of correct grading in the first place, and the danger of tampering with an existing well-established regime, especially when we remember that such mistakes cannot be remedied at once, but must wait opportunity, often for years.

"EFFECT OF PONDING-UP IN REGULATING SUPPLIES.

"Sometimes where a canal bifurcates, one branch may require a heading-up of the supply to a greater height than the other, and when each branch is run alternately in rotation, what happens is that there is alternate ponding-up accompanied by sand collection on the bed, and then lowering of the level with a consequent scour, carrying all the accumulated sediment into the lower level channel. Thus the lower channel becomes over-charged, and the higher under-charged. This action, as well as that mentioned in paragraph 13, can only be remedied by so designing all regulators that the offtakes are all similar and at one level of sill, with no ponding-up ever necessary. To facilitate this, all double regulators should be built as one work and not some distance apart, as is the case with many of the older works.

"Vo ON INUNDATION CANALS.

"When a canal runs all the year round, the clear water of the winter picks up the excess sand deposit of the flood season, so that the value of Vo, as given in paragraph 9, is an all-the-year-round or average value, applicable only to perennial canals. In inundation canals, the

Quoted from Kennedy.

clear water action is extremely limited, or even non-existent, so that a larger value than Vo might be expected to be necessary. Against this, however, we have the fact that the river offtake is usually much farther from the hills, and the sand carried much finer than in perennial canals, which usually take off near the hills. The actual value of Vo required will therefore vary a good deal, and, as explained in par. 11, it can be determined easily enough by experiment.

"EFFECT OF KUTTER'S N ON VALUE OF Vo.

"When a channel is silting badly and the cause seems inexplicable, after eliminating the possibility of any of the above-noted elements, reference will no doubt be made to the longitudinal section, and it may seem that the full Vo obtains, and that the diagrams show there should be no such trouble. This is, however, tacitly assuming that the value of Kutter's N is, really 0·0225, whereas it is a not uncommon occurrence that from long neglect the side slopes are in very bad order, and the real value may in such cases be 0·025, or in a very bad case 0·275, which, of course, would by no means give Vo. For this reason, if the real ratio of Vo is wanted in any particular case, it will not be enough merely to consult a drawing, actual observation is necessary, and not at one site but at many.

"ANALYSIS OF SAND SILT.

"Strictly speaking, a separate value of Vo should obtain at each season of the year, and for each class of sand carried in each reach of a canal, but this being impossible, the values of Vo given must be taken as an all-round figure for what may be called the standard sand, found in the river beds near the hills. The question then arises how to define this sand, and a partial reply can be furnished, by taking as the criterion of coarseness, the rate of fall of the grains in still water. Thus grade 0·10 would consist entirely of grains which dropped at the rate of 0·10 feet per second; and class $\frac{0\cdot10}{0\cdot15}$ would include atoms of all coarseness which fall between the rates of 0·10 and 0·15 feet per second. Of course, sand on a river bed will usually consist of grades extending over a considerable range, and each river may vary somewhat in the resulting analysis, but practically there is not any excessive difference in this respect, in Northern India at any rate, though it is more than probable that in other regions the sand might be quite different--full of mica for instance.

"Some information is given on this question in Punjab Irrigation, Paper No. 9, and the following analysis for the Rivers Sutlej and Chenab near the hills, giving the percentage proportion by volume of each class of sand, may be taken in the meantime as a rough gauge of the kind of sand for which Vo is directly applicable.

*Quoted from Kennedy.

"Table 41.

Class of Sand.	$\frac{.00}{.05}$	$\frac{.05}{.10}$	$\frac{.10}{.15}$	$\frac{.15}{.20}$	$\frac{.20}{.30}$	$\frac{.30}{.40}$	$\frac{.40}{.50}$
River Sutlej— percentage	11	43	25	11	7	2	1
River Chenab— percentage	11	28	27	15	14	4	1

"It will be seen that the Chenab has the coarser sand, and in corroboration of this, it has been noted that the canal channels there require, if anything, slightly more than Vo.

"Any grade of sand over grade 0.10 may be considered as course, and, speaking generally, it is only sand coarser than this which tends to slowly collect on the canal head reaches.

"The same principle of a graduated scale of Vo for various depths should be applicable to other than sand beds; e. g., to shingle or finer sediment, but so far no data exist on which to base any reliable figures."

Quoted from Kennedy.

Possibly the most important point in this discussion is that Kennedy advocated a variable coefficient in place of the 0.84 of his original formula, the value of the coefficient varying from 0.75 to 1.10 according to conditions, 0.84 being the coefficient for average conditions. Another important part of the discussion is the composition of sand which Kennedy believes would fit the 0.84 coefficient of his formula. It should be noted, however, that the sand which Kennedy thought would give a coefficient of 0.84 was from the Sutlej River, while according to F. W. Woods, "The engineers of the Sutlej Valley canals in the Punjab have been toying with $Vo = 0.67\ d^{0.64}$", or a coefficient of 0.67.

The following paragraph from Kennedy's Hydraulic Tables shows that he clearly recognized the difference between his critical velocity and that which would scour the banks of the canal: It is interesting to note that for depths over 9.0 or 9.5 feet, Kennedy suggested that his critical velocity is greater than the banks of the canals would usually stand:

"The fine clayey matter carried by the water, even in the heaviest floods does not give any trouble, being mostly carried on to the fields, and partly depositing as side berms, or on the bed of the smallest tail distributaries and water-courses, where it is useful in staunching the seepage. Clay side berms, however, will only form when the velocity is low enough, and since (as shown below) the sand question necessitates a higher mean velocity, the greater the depth is, there must be a certain depth above which berms become impossible, and bank erosion begins. This limit will depend to a great extent on the kind of soil--thus, some soils seem to almost dissolve away, however low the velocity may be; and usually, when banks are being damaged from this cause, the remedy is to widen the bed and decrease the depth and velocity, keeping the same slope; though of course there are cases where this last must also be decreased. The question of bank erosion is therefore quite distinct from the silt question, and is mostly one of experience, though its undoubted importance in the limiting of depth should be given due weight in canal design. So far as the author has collected any data on this point, a mean velocity of 3.30 feet is safe in ordinary soil; a mean velocity of 3.70 is often unsafe, which would show that anything over 3.50 may give trouble; or, in other words, when the full critical non-silting velocity obtains (see par. 9), any depth over nine or nine and a half feet should be avoided if possible."

Since Kennedy's formula was developed, as a result of experience in other localities, a number of other similar formulas have been proposed. Many of these have the same exponent for d as Kennedy derived, and are really therefore Kennedy's formula with a different coefficient. The coefficients, however, reach much lower than Kennedy suggested, being 0.56 for the formula for canals in Egypt, or 2/3 of Kennedy's 0.84, while the lowest value Kennedy suggests was 0.75. Other formulas suggested use exponents differing from Kennedy and ranging from 0.50 to 0.66. The following is a list of those found during this study:

Table 42.—Non-Silting, Non-Eroding Velocities.

		Reference
Kennedy	$V_o = 0.84\ d^{0.64}$	Proceedings A. I. C. E., V. 119, p. 282.
Madras	$= 0.67\ d^{0.55}$	F. W. Woods, The Engineer, 6-17-27, p. 648, Control of Water, Parker, p. 768.
Burma	$= 0.91\ d^{0.57}$	F. W. Woods, The Engineer, 6-17-27, p. 648.
California Project	$= 0.98\ d^{0.64}$	...ditto...
Unknown	$= 0.$[illegible] $d^{0.57}$	...ditto...
Sind	$= 0.66\ d^{0.64}$	...ditto... Control of Water, Parker, p. 768.
Suntlej	$= 0.67\ d^{0.64}$	F. W. Woods, The Engineer, 6-17-27, p. 648.
Siam	$= 0.52\ d^{0.66}$	U. S. Dept. Agr., Technical Bulletin, No. 87, p. 44.
Egypt	$= 0.56\ d^{0.64}$	...ditto... Control of Water, Parker, p. 768.
Moritz	$= 0.$[illegible] $d^{0.64}$	Working Data for Irrigation Engineers, Moritz p.40
"	$= 1.01\ d^{0.64}$	...ditto...
"	$= 1.09\ d^{0.64}$	...ditto...
"	$= 0.84\ d^{0.50}$	...ditto...
"	$= 0.92\ d^{0.50}$	...ditto...
"	$= 0.101\ d^{0.50}$	...ditto...
"	$= 0.109\ d^{0.50}$	...ditto...

Figure 9 shows the values of velocity given by each for depths ranging from 1.0 to 30.0 feet. Little is known of the conditions for which most of these formulas were derived, and no quantitative data was discovered to support any of them, except Kennedy's. In a general way, it is known that the silts of the Sind are finer than those of the Bari Doab Canal, from which Kennedy derived his formula, and that the silts of Egypt are still finer. Moritz describes in some detail the conditions to which his formulas are said to apply, but appends a note that they are based upon general hypotheses and observation of American canals, unsupported by experiments. They are as follows:

0.84 d	Silt-laden waters in fine, light sandy silt.
0.92 d	" " " in somewhat coarser light, sandy silt.
1.01 d	" " " in sandy, loamy silt.
1.09 d	" " " in rather coarse silt or debris of hard soils.
0.84 d	Fairly clear water in fine, light sandy silt.
0.92 d	" " " in somewhat coarser, light, sandy silt.
1.01 d	" " " in sandy, loamy silt.
1.09 d	" " " in rather coarse silt or debris of hard soil.

OTHER SILTING FORMULAS

Recently there has been published two new theories of silting and scour. One of these, by F. W. Woods,* is based upon the assumption that the width of the channel is also a factor in silting of irrigation ditches. He proposes for non-silting, non-scouring channels the following formulas: Log depth = 0.454 log width; velocity = 1.454 log width; fall per 1000 feet = $\frac{1}{\text{Log (discharge)}^2}$. In developing this formula he uses Kennedy's data and claims that they agree with his formula, better than with Kennedy's. Mr. W. T. Bottomley, however, brings forward data** to show that the silting depends only on the gradient of the channel. He states: "The non-silting, non-scouring velocity will be obtained when the gradient of the canal is of the same order as the gradient of the parent river." Mr. Bottomley does not agree with Mr. Woods, but states, "Woods' suggestion, for the relation between width and depth cannot, therefore, be regarded as anything more than an arbitrary formula which happens to be applicable to both groups of Kennedy's channels within certain limits."

*A New Hydraulic Formula, The Engineer, Vol. 143, 6-17-27, p. 646.
**Engineering, Vol. 125, March 16, 1928, p. 307.

Woods does not give any clear reasoning to show why the width should be a factor in non-silting velocities, and while he mentions extensive data he had collected, the proof of his formula rests only on Kennedy's data. Bottomley states that the suspension of silt depends upon the vortices which are set up by the water moving over the bottom, the number and strength of which depends upon the frictional resistance of the bed. On general principles this position seems to be well founded. The entire loss of potential energy of water in flowing through a ditch, as represented by the fall, seems to be the result of internal friction.

due to impact within the stream itself. It is not due to sliding friction, for that nothing similar to the sliding friction of solids exists is conclusively proven by the entire absence of any increase of friction in pipes with an increase of pressure. It follows then that the greater the slope (or fall) the greater must be the internal motion of the water, and therefore the greater the ability of the stream to support silt. It seems entirely reasonable that the ability to keep silt in suspension of a stream of water flowing in a smooth concrete channel (n = 0.013) with very little turbulence should be less than that of a stream of similar dimensions and discharge flowing in a rough channel excavated in rock (n = 0.030) which would be full of eddies dissipating about four times as much energy as was used up in the concrete channel. This effect of slope may have been overlooked by Kennedy because the slope of all the channels which he observed was about the same. If the ability of a stream depends upon the vertical components of the turbulence, and water passing along the side of a channel is given the same turbulence as under similar conditions at the bottom of a stream except that the vertical components are less, it would follow that the effect of the sides would be the same as the bottom in increasing the energy loss or slope of the stream but not the same as the bottom in the effect upon the silt transporting power. Under such conditions there would be grounds for Woods' contention that the width has an effect on the silt-supporting ability of water flowing in a ditch. The entire subject is little understood and there is much room for further study. Since there is very little quantitative data to support the theories of either Woods or Bottomley it would not seem wise to adopt their ideas at present. Since the roughness of the unlined sections of the All-American Canal will probably be about the same as for Kennedy's channels, assuming Bottomley's contention are true, one could still use Kennedy's formula with little error.

APPLICATION OF NON-SILTING VELOCITY FORMULAS TO THE ALL-AMERICAN CANAL.

Figure 9 shows the wide range over which non-silting velocities probably vary under different conditions. Information regarding the nature of the silt handled under these conditions is not available, except for some of those in India. For none of them is the data on which they are based, given except that given by Kennedy, and his was secured for channels not over 7.3 feet deep and 1700 second-feet discharge, as compared with depths about three times as great and discharges nine times as great under consideration for the All-American Canal. If the Boulder dam were not going to be built, the proper procedure would undoubtedly be to make field observations on the canals of the Imperial Valley system and more particularly on the Yuma project, since with its desilting works, it would give results closer to those which would exist in the new canal. The report on "Silt in the Colorado River", by Fortier and Blaney, states that the application of Kennedy's formula to Imperial Valley channels was not a success, but the context indicates that this was not due to a failure to carry the silt through the ditches without deposit, but rather because under American conditions it is cheaper to excavate the silt from the large canals by machine than to handle it after it reaches the land. In India, since hand labor would probably be used in either case, it is cheaper to handle it on the land and in the small ditches. It is reported that no great difficulty is experienced from silt deposit in the ditches of the Yuma project. These seem to have been designed for a velocity of about 2-1/4 feet per second and since the canal is enlarged, it probably has higher velocities, perhaps as much as 3.0 feet per second. If the values of the constants in Kennedy's type formula could be derived from them, it would seem that this would represent the smallest nonsilting velocity which could be expected before the Boulder dam was built, and that the velocity required would probably be considerably less soon after the dam was built, or if not, it would become less as the river between the storage dam and the intake cut down its bed.

From a study of silting in various canals in the Punjab, India, Parker* concluded that Kennedy's formula, with a variable coefficient, was generally applicable, confirming Kennedy's statements previously quoted. Parker concluded that Kennedy's coefficient, 0.84, was applicable to conditions where the bed silt was composed of grains, 40 per cent of which fall more rapidly than 0.10 feet per second in quiet water, and that the value of the coefficient under other conditions is roughly proportional to the per cent of material of this size in the bed silt. In order to compare results of analysis of silts expressed in velocity of drop through water, the method commonly used in India, with size of grain as determined by sieve analysis, which is the method commonly used in this country, Figure 10 has been drawn up showing the relation between the velocity of fall of particles of quartz (specific gravity 2.64) through the water and the size of the particles, as determined by Richard.** Richard's data gives the velocity of the particles of the various sizes which settled most rapidly and the velocities above which 90% of the material settled. Between the lines representing these relations is drawn an average line, which is assumed to represent the average velocity of fall of particles of various sizes and in converting data on silt sizes expressed in velocity of fall in water to grain sizes expressed in inches, the relation shown by this line is assumed to hold. It shows that the velocity of drop of quartz particles through water in feet per second is roughly ten times the diameter of the particles in inches, within the range covered by the diagram. Although the use of the assumed average line of Figure 10 may not give a relation which is absolutely accurate, it is believed to be sufficiently reliable for approximate comparisons. Applying Figure 10 to the relation suggested by Parker it states that the coefficient to be used in the Kennedy formula is expressed by the following formula:

$$\text{Coefficient} = \frac{0.84 \times \text{Per cent of particles of bed silt of over 0.01 in. diameter}}{40}$$

*Control of Water—Parker, p. 775.

**Ore Dressing—Richard, p. 466.

The analysis of bed silts of the Imperial Canals in Figure 5 shows that practically all of the silt is finer than 0.01 inch in diameter, and when Parker's rule is applied to this material the result is so low a velocity so to be obviously insufficient. Parker states that his rule seems to be applicable to all conditions in the Punjab but may be too small for rivers carrying a larger per cent of silt, which probably is the case for the Colorado River. In general, the silts of the Punjab rivers seem to be composed of particles about four times the size of those on the Colorado River. Figure 11 shows sieve analyses of silts from the Punjab Rivers and canals, as given by Parker (p. 760) and Kennedy (previously quoted), reduced by means of Figure 10 to grain sizes in inches, and samples under similar conditions from the Colorado River and Imperial canals. The slope of the Colorado, in the section under consideration, is about 1:3,300, while Parker states that the slopes of the Punjab rivers, at the canal intakes, are from 1:2,600 to 1:4,000. The slopes of the rivers are therefore comparable. The data on the Sutlej River, given by Buckley,* indicate that the suspended silt rarely reaches

*The Irrigation Works of India, Buckley, 2nd Ed., p. 34.

2.0% even on the days of highest content, but the measurements on the Colorado show that the proportion sometimes reaches over 2.5% for an entire month. It seems very probable that the Punjab rivers have about the same slope as the lower Colorado, and carry a smaller proportion of silt, of a coarser quality, the difference being due to the topographic and soil conditions in the respective watersheds. No information was found on the per cent or quality of silt carried by the Nile River or Egyptian canals. An attempt is being made to secure some data on this point, which will enable a comparison of the Nile River conditions to be made with those on the Colorado.

PERMISSIBLE MAXIMUM VELOCITIES IN CANALS.

The best data on the second phase of the silt and scour problem, securing velocities of flow which will not erode the banks, is contained in the paper by Fortier and Scobey, "Permissible Canal Velocities". This paper deals with the maximum velocities which will not erode the banks, and does not consider the permissible velocities from the standpoint of silt deposit in the ditch. These conclusions are given in the form of a table (Table 43) and the following statements:

"Table 20.—Permissible Canal Velocities.

Original material excavated for canal.	Velocity, in feet per second, after aging, of canals carrying: Clear water no detritus	Water transporting colloidal silts.	Water transporting non-colloidal silts, sands, gravels, or rock fragments.
(1)	(2)	(3)	(4)
Fine sand (non-colloidal)	1.50	2.50	1.50
Sandy loam (")	1.75	2.50	2.00
Silt loam (")	2.00	3.00	2.00
Alluvial silts when non-colloidal	2.00	3.50	2.00
Ordinary firm loam	2.50	3.50	2.25
Volcanic ash	2.50	3.50	2.00
Fine gravel	2.50	5.00	3.75
Stiff clay (very colloidal)	3.75	5.00	3.00
Graded, loam to cobbles, when non-colloidal	3.75	5.00	5.00
Alluvial silts when colloidal	3.75	5.00	3.00
Graded, silt to cobbles, when colloidal	4.00	5.50	5.00
Coarse gravel (non-colloidal)	4.00	6.00	6.50
Cobbles and shingles	5.00	5.50	6.50
Shales and hard-pans	6.00	6.00	5.00

"1. The laws of hydraulics governing the movement of loose silt and detritus in open channels are only distantly related to the laws governing the scouring of a canal bed and are not directly applicable.

"2. The material of seasoned canal beds is composed of particles of different sizes and when the interstices of the larger are filled by the smaller, the mass becomes more dense, stable, and less subject to the erosive action of water.

"3. The velocity required to ravel and scour a well-seasoned canal in any material is much greater than the velocity required to maintain movement of particles of that same material before becoming bedded or that have been raveled off by higher velocities than the bed would stand.

"4. Colloids in either the material of the canal bed or the water conveyed by it, or in both, tend to cement particles of clay, silt, sand and gravel in such a way as to resist erosive effects.

"5. The grading of material running from fine to coarse coupled with the adhesion between particles brought about by colloids make possible high mean velocities without any appreciable scouring effect.

From Fortier and Scobey's Paper. 71

"6. Irrigation Canals may be designed for the velocity that is permissible when seasoned by age, as the demand for water grows with the age of the canal and the maximum mean velocity grows with the supply necessary to satisfy this demand.

"7. Power canals are likely to be placed under peak load as soon as feasible after completion. For this reason a more conservative velocity should be chosen, otherwise scour may take place before seasoning.

"8. Canals, when new, may be operated with velocities less than the maximum permissible, by the use of check structures.

"9. A slight excess of velocity is preferable to insufficient velocity. Check-drop structures will correct a slope causing erosion, but there is no method within reasonable cost by which velocities may be increased.

"10. In the past, engineers have been led astray by too close an adherence to the results of experimental data on the transporting action of water on such materials as clay, silt, sand, and gravel, considered separately rather than on cohesive or mechanical combinations, and in consequence many canals have been designed and built on too flat slopes with correspondingly low velocities.

"11. The growth of aquatic plants is only partly connected with velocities. Canals designed for the highest permissible velocities, from the standpoint of erosion, will be as free from plant growth as design alone can effect."

Further explanation is given in other paragraphs as follows:

"For each grade of original material shown in Column (1) the fact is recognized in Column (2) that the final condition of a canal bed must be quite largely determined by the material through which it flows and likewise the fact that there is little or no mechanical abrasive in the water. The figures in Column (3) refer to water that contains effective colloidal silts, such as the waters from the Colorado River or Rio Grande. These silts will settle to greater or less extent under relatively high velocities. The difference between colloids and colloidal silts should be noted. The first will remain in suspension, even if all velocity be eliminated, for a long period of time, even years. The silts will precipitate under reduced velocities, and possess sufficient colloidal matter to form a plastic, highly cohesive mass. Obviously, such water will have a marked influence on the final character of the canal bed for all gradations up to the shales where the original material is more resistant than any deposit of silts. In Column (4), the figures indicate that waters conveying abrasive sand or gravel will make some materials more resistant by furnishing the constituents needed for a graded bedding. On the other hand, shales or slick tough clays are themselves resistant, and this resistance is reduced when a powerful abrasive is contained in the water.

From Fortier and Scobey's Paper.

"Deduction from Available Data. After a careful study of all the data presented and in the absence of experimental data bearing on the subject, the Committee recommends the values given in Table 43 for maximum permissible mean velocities. The figures given are for canals with long tangents predominating throughout their lengths. For the same canals in sinuous alignment a reduction of about 25% is recommended. Likewise, the figures are for depths of 3 feet or less. For greater depths a mean velocity greater by 0.5 foot per second may be allowed. The velocity in canals carrying water free from muddy silts, but bringing a powerful abrasive from the river, should be reduced 0.5 foot per second. Basalt ravelings are probably the sharpest scouring agency handled by any of the Western streams, and many of the streams from the Northwestern lava beds will contain this abrasive although the water may appear to be quite clear. Canals from streams more or less silt-laden through the year, like the Rio Grande or the Colorado River, may be designed for full-load mean velocities from 1 to 2 feet per second greater than would be permissible for the same material or new excavation, served by clear water from a reservoir. Deep canals conveying water with clean sand will develop destructive sand boils which would be absent in the same canal with clear reservoir water. In short, the character of water conveyed must be considered as well as the materials through which the canal is first excavated. In the matter of "loading," clear water is best fitted to take on a load of scoured material and a water carrying a partial load of sharp abrasive is better equipped to start erosion.

"Explanation of Table 43. The general basis of Table 43 is a tabulation of original soil materials in their order of ability to withstand erosion under usual conditions; that is, conveying relatively clear water, for the greater part of the season, either from a mountain stream or from a reservoir. In soil formations finer than gravels, it is recognized that the resistance to erosion depends on the cohesion between individual particles. For the gravels—fine, coarse, and cobbles—the resistance is by virtue of weight, shape, and density of material aided by the mechanical obstruction afforded one unit by the mixture with others. There is no element of cohesion due to viscosity, plasticity, or stickiness, such as is found in clay. In graded materials, ranging from loams to cobbles in size, such as are found mostly on the Piedmont benches and alluvial fans of Colorado, Utah, and other mountain states, the canal bottoms become finally paved after a few years. At first, there being little plastic colloidal matter, the finer grained soils are washed free and carried farther downstream, to be deposited on the inside of curves or precipitated where velocities are reduced above check structures. At the same time, the canal is degrading slowly downstream, until finally a bed is developed in which voids are filled by smaller material, such as the case of properly graded concrete aggregates. This graded bed is quite stable, entirely because of mechanical interlocking and not because of plastic cohesion, although as indicated in column (5) of Table 43, the fact is recognized that the admixture of effective colloids will make the bed all the more tough and tenacious, increasing its resistance to erosion. The shales are taken as smooth, soft rock, resistant to erosion by clear water, but not so resistant when a sharp abrasive, such as sand or gravel, is carried by this water."

*From Fortier and Scobey's Paper.

TABLE [illegible].—EXAMPLES OF CANALS CONVEYING WATER AT RELATIVELY HIGH VELOCITIES.

Authority.	Canal.	Location.	Soil.	Flow, in second-feet.	Depth, in feet.	Mean velocity, in feet per second.	Remarks.
[illegible]	[illegible]	Italy				5	Over gravel bed.
	[illegible]						
	[illegible]					5 to 6	
	[illegible]	France				5 to 6	
	[illegible] Doab	India				6.6	Jatres Branch.
	Del Norte	Colorado		3 000		5.0	Over gravel bed.
	[illegible] Jumna	India		2 400	5.5	5+	Over gravel drift and rock.
	" "	"				1.93	Perfectly adjusted to a light, sandy soil.
	" "	"				2.28	Silt being deposited.
	[illegible] Canal	India	Clay, shingle and small boulders			3.47	
	"	"	Sandy with admixture of clay			2.92	Bed silted.
	"	"	In stiff clay			4.19	Erosion trifling; no silting.
[illegible]	[illegible] Creek Canal	Montana	In very light sand			2.50	
	[illegible] River Canal	Utah				7.5	Bed washed clean of all earth and sediment.
			Clayey loam	223		8.62	Channel covered coating of sediment, but free from vegetation.
[illegible]	[illegible] Canal	Nebraska	In clay	880		4.75	
		"	"	"		3.86	
	[illegible] Valley Canal	Arizona	Graded gravel	181.8		4.66	Bed graded material, fine gravel to 6-in. radius.
	[illegible] Canal	"	In fine sand and gravel	161.7		3.12	Bed scoured clean, sides silted, slick.
	[illegible] Canal	Colorado	In clay loam	273.1		2.72	
[illegible]	D. [illegible] Project	Oregon	In fine sand	385		2.94	Now has deposit of clean sand in middle, silty mud at sides.
						1.98	
[illegible]	[illegible] Project	"	Fine to medium sand	360		2.4	60% of original soil passed a 74-mesh screen.
[illegible]	[illegible] Canal	Washington	Coarse gravel	1 280	5.4	5.35	On tangent.
	[illegible] Canal	"	Fine gravel	180	4.2	2.86	On tangent.
	[illegible] Canal	"	Fine sand	128	4.2	1.98	On tangent.
	[illegible] Canal	"	Fine sandy loam	100	4.3	1.95	On tangent.
	[illegible] Canal	"	Volcanic ash	28	2.1	1.85	On tangent.
	[illegible] Ditch	"	Alluvial silts			1.65	On tangent.
	[illegible]	"	Fine loam			1.65	On tangent.
	[illegible]	"	Fine sandy loam			1.65	On tangent.
	[illegible]	"	Volcanic ash			1.00	On tangent.
	[illegible]	"	Fine gravel			1.50	On tangent.
	[illegible]	"	Coarse gravel			3.00	On tangent.
[illegible]	[illegible]	Switzerland	Side slopes, earth; bed, fine gravel			5.50	On tangent.
						5.22	
	[illegible] Canal	"	Regular reach, detritus			4.79	

*[illegible] Supply Paper No. 43, U. S. Geological Survey.

†[illegible] 26, U. S. Dept. of Agriculture.

‡ By letter.

§ Hering and Trautwine translation.

Authority.	Canal.	Location.	Soil.	Flow, in second-feet.	Depth, in feet.	Mean velocity, in feet per second.	Remarks.
[illegible]	Smith Canal	Switzerland	Earth, no detritus		10.8	5.83	
	[illegible] Canal	"	Very coarse gravel and detritus			5.90	
	[illegible] Canal	"	Very coarse gravel and detritus			8.30	
[illegible]	Hyrum Canal	Utah		45.6	1.6	3.24	
	[illegible] Canal (No. 1 Ditch)	"		17.4	1.8	3.31	
	Paradise L. and R. Co. Canal	"		30.3	1.5	3.13	
	[illegible] Canal	"		139.5	2+	3.90	
	College and City Ditch	"		7.72	0.5	3.45	
[illegible]	Rio Grande	Colorado	In gravel	143.6		3.86	
[illegible]	" " Lateral 1	"	In graded gravel	38.0		1.66	Bed scoured clean, sides silted, slick.
U. S. [illegible]		North Platte project, Nebraska	Sandy, fair condition	1 154		2.80	Erodes, some brush rip-rap.
U. S. [illegible]		"	Sandy, good condition	1 096		3.00	
U. S. [illegible]		"	Gravelly, fair condition			3.22	
[illegible]		Boise project, Idaho	Clay and hard-pan			2.22	In good order, no weeds.
	South Side Twin Falls, Main Canal	Snake River, Idaho	Dark uniform clay loam	2 787	7.33	3.43	
	South Side Twin Falls, High Line Canal	Snake River, Idaho	Dark uniform clay loam	577	5.31	2.72	
	South Side Twin Falls, Farm Lateral	Snake River, Idaho	Medium clay loam	222	.78	2.41	
	Randall Canal	Snake River, Idaho		183.7	2.19	3.10	

Hering and Trautwine translation.

Unpublished.

Bulletin 194. Colorado Agricultural College.

‡ *Reclamation Record*, July, 1913.

‖ Ninth Biennial Rept., State Engr. of Idaho.

¶ Biennial Rept., State Engr. of Idaho, 1911-12

Other valuable data from this paper are the Table 44, giving the material in which various existing canals have been built, together with the velocities and depths of flow for which they operated. Table 45 gives the allowable values for different material given by Etcheverry.

Table 45.—Maximum Mean Velocities Safe Against Erosion. (By Etcheverry).

Material.	Mean velocity, in feet per second.
Very light pure sand of quicksand character	0.75 - 1.00
Very light loose sand	1.00 - 1.50
Coarse sand or light sandy soil	1.50 - 2.00
Average sandy soil	2.00 - 2.50
Sandy loam	2.50 - 2.75
Average loam, alluvial soil, volcanic ash soil	2.75 - 3.00
Firm loam, clay loam	3.00 - 3.75
Stiff clay soil, ordinary gravel soil	4.00 - 5.00
Coarse gravel, cobbles, shingles	5.00 - 6.00
Conglomerates, cemented gravel, soft slate, tough hard-pan, soft sedimentary rock	6.00 - 8.00
Hard rock	10.00 - 15.00
Concrete	15.00 - 20.00

It should be noted that Table 43 does not consider the effect of depth on the allowable velocity, and represents values for depths of 3.0 feet or less. The authors say that for greater depths a mean velocity of 0.5 foot per second greater may be allowed. As few, if any, irrigation canals have depths comparable with that proposed for the All-American Canal, it is probable that the same reasoning would lead to the conclusion that for very deep canals, a greater amount, possibly 1.0 feet per second additional would be permissible. It should be emphasized that all the values given in Fortier and Scobey's tables apply to channels which have been in service some time, and for new channels lower values should be used.

The writer does not have sufficient data on the character of the soil through which the proposed canals will run to draw conclusions as to permissible velocities, even under present silt conditions. The following quotation from the Fortier-Scobey paper, however, throws additional light on the question:

"In the Imperial Valley of California many of the large laterals were excavated in a light sandy soil that would have scoured when the canals were new at a velocity of 2-1/2 feet per second. The extremely fine silt particles brought in from the Colorado River prior to 1910 compacted and puddled this sand and plastered it with a coat of slick colloidal mud, so that it would withstand velocities in excess of 5 feet per second; yet the individual particles of this slick mud were so fine that they would remain in suspension at very low velocities, except when the water was "overloaded" with silt—in times of flood on the Colorado River in June and July."

Whether this condition would exist after the Boulder dam had been in service a long time is problematical.

TRANSPORTATION OF SAND BY FLOWING WATER.

The third phase of the silt problem of the All-American Canal is the transportation by the flowing water to the place where it can be deposited of such dune sand as may blow into the canal. If dredging is resorted to, to keep the canal clear, this problem will not arise. The analyses of the dune sand given in the "Report of the All-American Canal Board" (Table 46) shows that most of the material which is likely to enter the canal is fine and medium sand.

Table 46.--Analysis of Sand from the Sand Hills.

Fineness—passing screen No.—	Easterly portion, fine drifting sand.	Westerly portion, gray drifting sand	Westernmost ridge.	
			Gray drifting sand 1 foot below surface.	Surface sample of drifting sand.
	Per cent	Per cent	Per cent	Per cent
200	1.5	3.5	2.1	2.0
100	41.5	18.0	27.0	30.0
50	92.6	39.5	71.0	63.0
40	99.8	65.0	89.0	80.0
30	. . .	91.0	99.0	91.0
20	. . .	98.0	. . .	95.0
10	All	All	All	All

Figure 12 shows that the dune sand is coarser than the bed silt of the Colorado River and the Imperial canals. It more nearly resembled the silt in the Punjab rivers and canals.

In times of very heavy sand storms a great deal of the sand will be carried by the wind and fall into the water over the entire surface. It will only be necessary to keep this material in suspension to transport it to the settling basins. Much of the material during the storm, however, will move in dune formation, the sand particles being carried over the crest of the dune and falling on the windward side, thus, in effect, causing the whole dune to move. When such a dune reaches the canal, the sand will move into the canal from the side, sliding down the steep windward face of the dune into the ditch. Thus the sand will be deposited in the ditch at the side where the velocity is lowest and the water less likely to move it. It is true that this sand will be loose and less compact than sand in the canal bank but it will still require considerable velocity at the edge of the canal to scour it out.

There is considerable information on the velocities necessary to cause sand to be moved by a current of water but very little from which an estimate can be made of the quantity of sand which will be moved in a unit of time. When this is considered, together with the fact that very little is known of the quantity of sand it will be necessary to move under ~~xxxxx~~ various conditions, it will be seen that the uncertainty in this problem is great. The following table gives the bottom velocities necessary to start dragging of the material along the bottom of the stream:

Table 47.—Current Velocities at which Dragging Begins.

Authority	Reference	Velocity ft/sec	Bottom or mean	Description	Remarks
Sushiert	1	3.94	B	Size of bean	Rhine River; after being stirred up; bottom covered with sediments.
"	1	3.87	B	Smallest particles	Rhine River; river bottom free from sediments.
Login	2	0.67	B	Fresh water sand	Dragging begins.
Dubat	2	0.71	B	Large sand	
Bounicean	2	0.72	B	" "	
Telford	2	1.00	B?	Sand	
Bounicean	2	0.28	B	"	
Verein Hutte	2	1.02	B	Fine sand	
Login	2	1.10	B	Sea sand	
Dubat	2	0.38	B	Gravel (anise seed)	
Bounicean	2	0.62	B	" " "	
Dubat	2	0.62	B	" (pea size)	
Login	2	2.00	B	" " "	
Parker?	3	0.5	B	Finest sand	Minimum value with clear water.
"	3	0.7	B	Fine "	...ditto...
"	3	0.8	B	Coarse "	...ditto...
"	3	1.8	B	Gravel, coarse sand	...ditto...

1. Treatise on Sedimentation, Twenhofel, pp. 31-32.
2. The Regulation of Rivers, Van Ornum, pp. 140-141.
3. Control of Water, Parker, pp. 488, 493.

This data is conflicting due to the uncertainty of classification of the material and to the different conditions under which the observations are made. It is obvious that considerably greater velocities than that necessary to start dragging will be required at times if the dune section of the canal is to be kept clean

The following data on the condition of sand bottoms in irrigation ditches was abstracted from the U. S. D. A. Bulletin No. 194, "The Flow of Water in Irrigation Channels", by Scobey. The first three cases are for concrete-lined canals and the remainder are earth channels.

Character of bottom	Mean depth (ft.)	Mean velocity (sec. ft.)
Gravel, fine to walnut, more or less movement	0.62	1.71
Rolling sand	1.31	2.89
Rapidly shifting sand	2.07	1.70
Unshifting sand	0.[illegible]3	0.75
About to shift sand	2.45	2.09
Shifting sand in bottom 0.1' deep	1.15	1.16
Clear sand yielded 0.1 foot under foot	0.71	1.21
Deep shifting quick-sand	1.29	0.87
" " "	0.99	1.09
Fine sand, hard until disturbed	2.50	1.75
Shifting sand	1.23	1.40
Bottom of gritty sand	1.98	0.81

This data is not very consistent. It shows shifting bottoms with mean velocities as low as 0.87 and others which do not shift materially with velocities as high as 2.09. The depth of flow does not appear to exercise a material effect. The data are so inconsistent, few in number and of such limited range that a reliable conclusion cannot be based on them.

In his "Control of Water" (pages 488-496), Parker has an extended discussion of the transportation of solids by water. The principal points of the discussion are as follows: There are several phases of sand movement in water, depending on the velocity. As the velocity increases, a point is reached where movement of smaller isolated grains begins. If this velocity is maintained, the material arranges itself in sand ripples. As the velocity increases, the ripples become more perfect, and motion of the sand takes place by the particles rolling up the flat slopes of the ripples and lodging on the steep downstream side thus causing the ripples to slowly move downstream. As the velocity increases, the ripples move more rapidly and some of the particles pass in suspension from one ripple to another, and with increasing velocities more move in this way until a condition is reached where the ripples begin to disappear and the sand moves mostly in suspension. In order to move the large quantities of sand which may at times blow into the All-American Canal it seems certain that this last condition would have to exist. The velocities at which the various conditions described above occur have been observed in small troughs. Under such conditions the stage of continuous suspension of particles for sand with average diameter of 0.04 inches begins with a surface velocity of 2.9 to 3.4 feet per second. These grains are considerably larger than the dune sand which will have to be handled. The quantity of sand of 0.04-inch size, which given velocities will move, has also been observed in a small trough with water about 8 inches deep. The results are approximately represented by $q = 0.0000166 V^5$ where q is in cubic feet per second per foot of width of bottom and V is the bottom velocity in feet per second. Assuming a bottom velocity of half of the mean velocity, for a ditch 75 feet wide and having a mean velocity of 6 feet per second, the sand movement would be 3.31 cubic feet per second or 1,000 cubic yards per day, if the same law applied as for the small trough.

The quantity of material which can be transported is obviously dependent on the width of the canal; the wider the stream the more it will transport. Unfortunately, on account of the deep cuts in the sand hill section of the All-American Canal, economy favors a deep narrow canal. The volume transported also depends upon the depth, for a deep canal requires a greater mean velocity to move a given quantity of material than a shallow one. Parker gives a series of equations for the movement of material by streams as a function of their depth. These equations are as follows:

"I. For fine silt, with a mean diameter of about 0.01 inch, using feet and feet per second as units, it would appear that:

(1) Clear water scour is of importance if v exceeds 0.40 d.
(2) Heavily silted water gives no deposit if v exceeds 1.05 d.
(3) Heavily silted water begins to scour noticeably if v exceeds 1.37 d.

II. For coarse sand, say with a mean diameter of 0.04 inches, we have:

(1) Noticeable scour in clear water if v exceeds $1.6d^{0.33}$.
(2) Heavily charged water does not deposit if v exceeds $2.2d^{0.33}$.

III. For coarse gravel, say, pea-size:

(1) Scour begins if v exceeds $2.0d^{0.25}$.
(2) Heavily charged water does not deposit if v exceeds $2.5d^{0.25}$.

IV. Boulders are moved along if v exceeds $5d^{0.25}$."

Parker states that the results are only approximate, and except for the first two cases, rest on very slender experimental evidence.

Figure 13 shows the velocities according to these formulas for depths from 1 to 30 feet. The results are very inconsistent, particularly for depths of over 10 feet. For example, it indicates that for depths exceeding 5 feet, water heavily charged with silt begins to deposit pea-size gravel at a lower velocity than it begins to deposit coarse sand. It also indicates that scour of pea-sized gravel begins at velocities less than heavily silted water begins to deposit fine silt, for depths of over 13 feet. There are other inconsistencies and the results are so confusing for depths comparable with that proposed for the All-American Canal that no satisfactory conclusions can be drawn from them.

The data given by Thrupp* is much more satisfactory. His data is in the form of a diagram, a portion of which is reproduced on Figure 14. In regard to this diagram Thrupp states as follows:

*Proceedings, Institution of Civil Engineers, Vol. 171, p. 346.

"It must not be assumed that the boundaries of these zones
are quite the hard and fast lines which the exigencies of a diagram
require. There is a certain amount of shading off to be done mentally,
to account for graduations in the size and specific gravities of the
materials. All scouring action depends mainly upon the degree of tur-
bulence of the flowing water; the boundary lines may be regarded, there-
fore, as contours of equivalent degrees of turbulence at various depths
and mean velocities."

"To obtain other [illegible] as to the curvature of the boundary
lines on each side of zone III, at depths of from 1 inch to 5 feet, the
author has observed the velocities and depths in about sixty natural chan-
nels at points where the bed was changing from silt to sand, or sand to
gravel, that is to say, in channels of diminishing sectional area, and
also in places where the reverse conditions existed, and in some cases,
where the flow was controllable, observations were made at varying depths.
The weight of the evidence thus obtained is in accordance with the curves
on the diagram.

"Several instances of sand-waves in the bed of the channel are
in zone III, the waves ranging between 1 inch high in 2-1/2 inches depth
of water, and 5 feet and [illegible] high in the lower Mississippi. The peb-
ble waves on the bed of the Garonne, observed by Baumgarten, are in zone
V.

"It has been held by many engineers that scouring power depends
solely on the bottom velocity in a stream, but in the author's opinion
that view is inaccurate. Turbulence of motion is the real determining
factor, and that depends upon the depth and the mean velocity as indicated
in the diagram."

Quotations from Krupp.

The diagrams indicate that for a depth of 25 to 27 feet, a
velocity of 5 feet per second is about enough to move pea-size gravel and
that 6 feet per second will begin to move coarse sand. Since heavy silt
and fine sand would begin to move at a velocity of about 3-1/2 feet per
second, it seems probable that 6 feet per second, almost twice the 3-1/2-
foot velocity, would move large quantities of fine blown sand and the small
amount of coarse blown sand that would enter the canal.

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