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A STUDY OF THE COLORADO  
RIVER SILT

By J. F. BREAZEALE

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## FOREWORD

From an economic standpoint, the Colorado River is probably the most valuable single asset that is possessed by the Great Southwest. The quality of its water is excellent, and the flow, if properly directed, is sufficient to irrigate and to bring under cultivation, at least 3,000,000 acres of desert land. However, the river carries an enormous amount of silt and clay.

Up to the present time, very few of the potential possibilities of the river have been utilized. There is already abundant evidence to the effect that the handling of this silty water presents difficulties that will, in the future, tax the ingenuity of irrigation engineers. The silt collects in the canals and must be removed by expensive methods; it builds up the soils under irrigation, especially at the upper ends of the borders, at a rapid rate, so that the land constantly requires releveling; eventually it will raise the level of the land so high that it cannot be reached by gravity water. Last, but not least, the silt covers the soil as a slightly permeable layer or blanket, in varying thicknesses. This, at first, upon sandy soils, may be beneficial, but as the silt blanket accumulates, it soon becomes so thick as to make cultivation very difficult and the penetration of water exceedingly slow.

From the indications upon lands in the lower Colorado basin around Yuma, which have been under irrigation only about twenty years, it is evident that some practical method of handling the silt must be found before a permanent irrigation agriculture can be established in this valley. It will never be possible to desilt the water completely, but some method of treating the silt in order to flocculate and render it more permeable, is quite possible. These facts show the need of research work upon the transportation and deposition of silt, for in great undertakings of this kind an intelligent working hypothesis is the first essential.

For many years irrigation engineers have been studying the silt-carrying capacities of streams from the standpoint of the velocity of the currents, and similar physical factors, but the relationship of the quality or chemical composition of water to the quantity of silt that a stream may carry, apparently has been largely overlooked.

Soils are either flocculated or deflocculated depending upon whether or not sodium, in replaceable form, is present in the soil zeolites. Soils whose zeolites are completely satisfied with calcium, and contain no replaceable sodium (normal soils), are flocculated. They take water readily and, if shaken with a large volume of water, settle quickly. On the other hand, soils containing basic sodium compounds or sodium zeolites

are deflocculated. They are impervious to water and, if shaken with an excess of it, do not settle out, but remain in suspension almost indefinitely. Thus, irrigation waters that contain an excess of soluble calcium flocculate the soils to which they may be applied, while "soft" waters (those containing basic sodium compounds in solution) deflocculate and disperse soils to which they may be added.

The data presented in this bulletin show that soil dispersion and silt (or clay) transportation by streams are closely allied phenomena, and that oftentimes the solutes present in the water of a stream exert as great an influence upon its silt-carrying capacity as do the velocity of the current and other physical factors.

This bulletin is the result of a rather extensive series of silt and soil studies with Colorado River water, which have been carried on in the Agricultural Chemistry laboratories of the University of Arizona during the past 2½ years. This work shows the necessity of such studies where heavy silt loads are encountered in streams to be used for irrigation purposes.

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# A STUDY OF THE COLORADO RIVER SILT

By J. F. BRAZEALE

## INTRODUCTION

The term silt, as applied to the sediment that is carried in suspension by the water of the Colorado River, must not be misunderstood. The sediment is not true silt, but consists mainly of clay particles so finely divided at times as to be partly colloidal. The term silt, however, will be used in this discussion.

The Colorado River is nearly always muddy. The silt in the water as it comes into the lateral irrigation ditches at the Yuma Experiment Station Farm, varies from about 2 percent during certain flood times, to about .01 percent or less, at extreme low water. It will be seen that an enormous amount of silt is thus brought down annually and spread out upon the land under irrigation. The total amount of silt that is brought down annually by the river has been estimated by many investigators. Forbes, for example, in 1900, determined the amount to be in the neighborhood of 61,000,000 tons, or enough to make 53 square miles of alluvial soil 1 foot deep.\*

When sandy soils are first placed under irrigation, the addition of this silt is beneficial, but the time may come when the percentage of sediment may reach a point where it is injurious to the soil. The silt also clogs the irrigation ditches, and hence entails considerable expense to farmers. In many other ways the silt offers serious problems to the irrigation engineer.

The alluvial lands in the lower Yuma Valley of Arizona, and a great area in the Imperial Valley of California, were formed during past ages by the silt that was brought down by the Colorado and Gila rivers. The Gila, however, flows in appreciable amounts at flood times only, and the total amount of silt that is brought down by this river is small in comparison with that brought down by the Colorado. We can safely assume that most of the soil of these two valleys was brought down by the Colorado River.

The Colorado, in its upper basin, receives the drainage of the Grand and the Green rivers and of many smaller streams. During the winter months this mountainous territory is covered with snow and there is little runoff, but in the spring the snow melts and a great volume of flood water comes down the river bringing with it the sediment that it has eroded from the mountain canyons. About the time that the flood

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\*Ariz. Agri. Exper. Sta. Bull. No. 44: River Irrigating Waters of Arizona, their Character and Effects, R. H. Forbes. 1902.

waters from the northern drainage basin begin to subside, the summer rains in northern Arizona and New Mexico commence, and periodic floods are again poured into the Colorado from the San Juan and the Little Colorado rivers. These bring with them the sediments that have been eroded from the bad-lands and from the Painted Desert in their basins. At Yuma, Arizona, the Colorado is joined by the Gila, which is sometimes referred to as the "muddiest stream in the world," but except at very high water, it seldom reaches the Colorado with its silt load.

It will thus be seen that the Colorado River silt is derived either from the canyon country far to the north, or from the bad-lands and painted deserts of the south. In either case, especially the latter, the soil from which the silt is derived might be expected to be colloidal and dispersed.

The soils of the lower basin of the Colorado are often deflocculated or dispersed. The fresh silt that is now being brought down and spread out over the land or deposited along the irrigation ditches, is badly dispersed. However, if a large amount of gypsum is added to the dispersed soils of the valley, they become flocculated, and if gypsum is added to the muddy waters of the Colorado, the silt is also flocculated and it will settle readily. It is reasonable to assume, therefore, that if the river itself had a sufficient amount of gypsum in solution, the silt would be flocculated and would not be carried in suspension. In such a case the river would either never pick up its load or else the silt would be deposited at its head waters or at places along the course where the speed of the current is appreciably checked.

In many ways the Colorado River silt, as it is delivered in the lower basin, shows signs of being dispersed, that is, the colloidal particles seem to be carrying negative charges. When the dry silt is shaken with water, it will remain suspended and usually will not settle for a long time. If pure water is used, the solution will show a pink color upon the addition of phenolphthalein, indicating the presence of an excess of hydroxyl ions. When the silt is purified by repeated washings with distilled water, and then shaken with pure water it will continue to give an alkaline reaction with phenolphthalein. When the silt is obtained dry, and treated with a strong solution of gypsum, it is flocculated and settles rapidly, but when the excess of gypsum is removed by repeated washings, the silt will again become dispersed, and will give an alkaline reaction with phenolphthalein in much the same way as did the untreated silt. It must be remembered that the silt was transported a long distance in, and was laid down from the Colorado River water, which, during a greater part of the year, contains an excess of gypsum. The dry silt upon washing, gives a filtrate that contains some gypsum, yet the silt, when shaken with pure water, gives a solution that contains an appreciable amount of hydroxyl ions. The silt, it is true, contains

some calcium and, in the absence of carbon dioxide, this would give some hydroxyl ions to the solution. There is every indication, however, that the solutions of the silt in distilled water contain hydroxyl ions that are associated with sodium ions. Dr. Paul S. Burgess, in his work with the soils that have been deposited upon the Yuma Mesa, has found this to be the case.

The silt as it appears in the irrigation ditches in the lower Colorado basin is certainly dispersed, and this dispersion has been brought about largely by the following factors: First, the soil from which the silt is derived, as it exists *in situ* upon the northern plateaus is colloidal and dispersed, no change having been brought about in its condition by the water in the course of its transportation; and second, the silt is originally flocculated, but at times the quality of the water is such as to bring about deflocculation.

#### THE SILT-CARRYING CAPACITY OF A RIVER AS INFLUENCED BY COLLOIDAL DISPERSION

The current of the Colorado River is rapid, and this is a great factor in the movement of silt, but there are other factors in this silt movement that seem to be associated with colloidal dispersion. The silt-carrying capacity of a stream is determined largely by the velocity of the current at the slowest point in its course. If the velocity of the current is doubled, its silt-carrying capacity is multiplied by 32, while the maximum size of the particles that may be removed by the current is multiplied by 64. Doubling the velocity of the stream would be equivalent to dividing the silt particles into 64 parts. When clays are flocculated, the individual particles are fairly large, but when the same clays are dispersed each particle splits into a great number of other particles, sometimes so small as to be colloidal. A colloidal particle may be as small as one-millionth of a millimeter in diameter, so it is evident that the division brought about by dispersion may be infinitely great. In many instances, therefore, the size of the particle may amount to a great deal more than the speed of the current, in the consideration of the silt-carrying capacity of the stream.

#### CLASSIFICATION OF THE SILT LOAD

According to Mr. Porter J. Preston, Superintendent of the Yuma Irrigation Project, the material that is carried by the Colorado River may be divided into two classes: First, the bed-load, or that part of the silt that tends to settle readily, or to move with the lower strata of water; and, second, the suspended load, or that part of the silt that does not settle rapidly when the velocity of the current is checked.

The speed of settling of silt is a good index of its state of dispersion, the greater the dispersion the more slowly the silt will settle. The



heavier part of the bed-load may be only slightly dispersed or it may even be flocculated, while the suspended load may be highly dispersed. The suspended load is the silt that usually gets into the irrigation laterals, and is of the most concern to the farmers.

If a river is flowing at a certain velocity, with a maximum load of suspended silt, a slight change in the velocity of the water may occur that may precipitate a part of the suspended material which will then settle and the river may thereafter carry only a fraction of a load. The reverse of this also is true, the river may be carrying only one-half of a suspended load, and one-half of a bed-load, and a change in the quality of the water may bring about a partial dispersion of the bed-load which may convert it into a suspended load. Even if the velocity of the river is maintained at a fixed rate, there is no doubt a constant adjustment between the bed and the suspended loads.

Dispersion is concerned with the reduction of the size of particles, and the size of particles is of the utmost consideration in the transportation and redeposition of silt.

#### THE DISPERSION OF SOIL COLLOIDS

The silt as it floats in the Colorado River is soil in motion, and no doubt it possesses many of the properties that it originally had before it was disturbed by erosion upon the high plateaus of Colorado, Utah, and Wyoming, or upon the desert bad-lands of northern Arizona and New Mexico. In a soil, the clay fraction is composed largely of hydrated silicates, or aluminosilicates, in combination with either the bases calcium and magnesium on the one hand, or sodium and potassium on the other. For want of a better name, these silicates are termed zeolites.

In a normal and neutral soil, the zeolites exist as calcium and magnesium compounds, and such soils are usually flocculated and will take water readily. If such soils are lifted by moving water they will settle rapidly, and will not be transported a long distance, except when the water is moving swiftly. If, however, the zeolites exist in combination with sodium or potassium, the soils or clays are deflocculated, and are usually impermeable or slightly permeable to water. When lifted by water such soils disperse themselves in the solution, settle very slowly, and may be transported long distances.

One of the distinctive features of these soil-zeolites is that the bases calcium, magnesium, sodium, and potassium, are easily replaced one by the other. If a flocculated and permeable soil, containing calcium zeolite, is leached with a solution containing any soluble sodium salt, sodium chloride for example, the calcium is replaced and becomes calcium chloride, and is leached out, while the sodium enters into combination with the silicate and remains in the soil. Under such conditions the soil may

become impermeable and dispersed. If the soil is now treated with a solution of calcium sulphate, the sodium in turn is replaced by the calcium, and the soil will become flocculated and permeable. Such an exchange of bases may be continued indefinitely.

Most western soils, at one time or another, have come in contact with either sodium chloride or sodium sulphate. These salts have replaced the calcium and magnesium and the zeolites now exist as sodium salts. As long as an excess of a soluble sodium salt is present, the soil will remain flocculated, but upon leaching with pure water, rain, or melted snow, the soils become dispersed.

Let us assume that such soils that have been leached with pure water until they are practically free from soluble salts, and have become dispersed, are lifted by rapidly moving water, and are brought into the river channel as silt.

Like all other chemical reactions the exchange of bases in zeolites is influenced by the concentration of the leaching solution. The stronger the solution, the more rapid and the more effective will be the replacement. When the dispersed silt, containing sodium zeolite, reaches the main channel of the Colorado River, it comes in contact with calcium, in amounts that vary with the floods. If the concentration of calcium is relatively high, the reaction upon the sodium zeolite may be pronounced, and the sodium may be largely replaced by the calcium. If, however, the concentration of calcium in the river is low, very little replacement of the sodium in the zeolite may be expected. So it seems that the replacement of the sodium ions in the zeolites of the dispersed silts, and their consequent precipitation is largely a function of the concentration of calcium in the solutions.

But the sodium zeolites are only slightly soluble in water, and in all probability the replacement of the sodium ion by calcium will go so far and no farther, and that, even though the concentration of calcium in the river water is at its highest, a small amount of sodium zeolite will still remain in the silt. If base replacement is an ordinary chemical reaction, as it seems to be, the reaction between calcium and sodium can go no farther than that represented by the ionization of the sodium zeolite. If the ionization of the zeolite is checked, or forced back, by any other salt in the solution, the ionized sodium zeolite is, for the time being, insoluble and inert, and the dispersed silt may be flocculated, and become either a bed-load or be dropped from suspension altogether. If, however, the salt that is forcing back the ionization is removed from solution or if its concentration is decreased by dilution, as in the Colorado River at flood time, the sodium zeolite will again hydrolize and ionize, manifest itself as a dispersed colloid, and become a suspended load of silt.

The phenomenon above described is shown in the treatment of the silt in the laboratory. When flocculated with a strong solution of calcium sulphate and washed with distilled water until free from sulphates, the silt will again become deflocculated, and will give an alkaline reaction if an excessive amount of water is added to it.

Any salt that tends to prevent the hydrolysis of the alkaline sodium salts, sodium carbonate and the sodium zeolites, and their subsequent ionization, will also tend to prevent soil dispersion. The Colorado River water sometimes contains considerable amounts of sodium sulphate and sodium chloride. These salts tend to flocculate silt, and their action will be discussed later, but it may be said here, that, in the case of these two sodium salts, the flocculating effect probably is partly brought about by the introduction of a common ion, Na, in the solution, in a concentration sufficient to force back the ionization of a less soluble sodium salt, sodium zeolite. The relative insolubility of the sodium zeolite, and the small amount of the ionized product necessary in the solution for the dispersion of the colloids, seems to indicate that this forcing back process may be a relatively easy task. There are other reasons for the flocculation of colloids that are not at all well understood.

#### REPLACEABLE BASES IN COLORADO RIVER SILT

The silt, as it is deposited in the lower basin of the Colorado, is a mixture of material coming from many sources, and no definite composition can be attributed to it. From a practical standpoint, however, the mixture has a fairly definite behavior, and the following measurements of its replaceable bases may be considered as representative.

One hundred grams of dry silt were shaken with 1000 c.c. of carbon-dioxide-free water, and the mixture allowed to come to equilibrium. The solution upon analysis was found to contain a total amount of .023 gram of calcium, and no magnesium. This amount of calcium represents the soluble salts in the solution and not the replaceable salts in the silt.

A large sample of silt was washed with distilled water until practically free from all soluble salts, sodium chloride, sodium sulphate, calcium sulphate, etc. The silt was dried and finely ground. One hundred grams of the silt were shaken with 1000 c.c. of saturated solution of gypsum and the mixture was allowed to stand until the silt settled. The silt was flocculated by the gypsum.

Upon analysis it was found that a total of .0430 gram of magnesium, and a total of .0315 gram of sodium and potassium (figured as sodium) had been replaced by the calcium, and had appeared in the solution.

One hundred grams of the washed silt were shaken with 1000 c.c. ,

of one-tenth normal solution of barium chloride, and the solution analyzed for the bases replaced. A total of .200 gram of calcium, .050 gram of magnesium, and .0251 gram of sodium and potassium (figured as sodium) was found in solution.

A high percentage of replaceable calcium was expected, as the river water contains gypsum, and this no doubt replaces a larger part of the sodium in the zeolites before the silt is deposited. No magnesium appeared in the water extract of the untreated silt, but, when the washed silt was extracted with a saturated solution of gypsum, 100 grams of silt yielded .0430 gram of magnesium. An equivalent amount of calcium was removed from the solution and was fixed by the soil.

The most interesting feature of these determinations, however, is the fact that the washed silt contains an appreciable amount of replaceable sodium. This replaceable sodium is the sodium that exists in combination as a zeolite, and it is the sodium zeolite that is dispersing the silt. The Colorado River silt, although it floats in suspension in a gypsum solution, contains an appreciable amount of sodium that has not been replaced by the calcium that is carried in the water.

#### PHYSICAL CHARACTER OF THE SOIL

According to Forbes, the silt that is brought down from the mountainous country by the spring floods is reddish-gray in color, while that brought down by the San Juan and Little Colorado rivers contains yellow and red material. We are told that the Painted Desert shows all the colors of the spectrum except green. The character of the silt used in this replacement work indicated its origin to be in the northern part of Arizona or New Mexico.

A set of soil samples was obtained recently from different depths in Chaco Canyon, New Mexico, and determinations of replaceable calcium and replaceable sodium were made upon them. The canyon drains into the San Juan, and its erosion furnishes a part of the silt that in the late summer appears in the lower basin of the Colorado.

TABLE NO. I.—TOTAL GRAMS OF REPLACEABLE CALCIUM, AND REPLACEABLE SODIUM IN 100 GRAMS CHACO CANYON SOIL

No.	Replaceable calcium	Replaceable sodium
1.	447 gram	.1380 gram
2.	314 gram	.0747 gram
3.	353 gram	.0747 gram
4.	425 gram	.0368 gram
5.	464 gram	.0770 gram
6.	.527 gram	.0563 gram

These soils were badly dispersed, were almost impermeable to water, and when shaken with distilled water, the finer particles remained in

suspension for weeks. It will be seen that the soils contain a relatively high percentage of replaceable calcium and a considerable amount of replaceable sodium. In many ways these soils had characters that were analagous to the Colorado River silt. All the soils contained a small amount of calcium carbonate. One would judge from their chemical composition and physical characters that they had probably originally been normal soils, or soils that contained only calcium zeolites, but that they had at some time come in contact with sodium chloride or sodium sulphate, which had replaced with sodium much, if not all, of the calcium in the zeolite. The soils then were probably leached with fairly pure water, or eroded and redeposited by pure or rain water, and the sodium salts, sodium chloride, and sodium sulphate removed. Upon removal of the soluble sodium salts, the sodium zeolite began to hydrolyze, and a part of the sodium ions was removed by leaching. As fast as a sodium ion was thus removed, a calcium ion from the slightly soluble calcium carbonate took its place, and this reaction proceeded until the impermeability of the soil that was brought about by this reaction practically put a stop to the penetration of water, and, of course, put an end to the replacement process. The author has shown that in the black alkali soils of the Rillito Valley, near Tucson, Arizona, the above described reaction between sodium zeolites and calcium carbonate does take place. It has also been shown that the most dispersed soils are usually those that contain a relatively small amount of replaceable sodium and a large excess of replaceable calcium.

It has been the experience of Mr. Porter J. Preston, that, when certain tributaries of the Colorado, particularly the San Juan and Little Colorado, are in flood, the silt is brought down in greater amounts than at other times, and that this silt settles less rapidly than does that brought down when the Grand and Green rivers are in flood. This is no doubt due largely to the fact that the floods of the Grand and Green are caused by melting snow, while the floods of the San Juan and Little Colorado are caused by toriential rains upon desert bad-lands. The melting of snow is a relatively slow process and the soils in the mountainous country are better protected by vegetation, are probably not so badly dispersed, and are not so easily eroded as are those of the bad-lands. Aside from the influence of the quality of the Colorado River water at different periods of the year, as will be discussed later, the settling power of these two kinds of silt is inherent in the character of the soils before they were eroded. The silt, derived from such soil as those from Chaco Canyon, will never settle readily unless it comes in contact with some flocculating agent. Such silt has been eroded and redeposited probably many times before it is finally taken up for its journey down the Colorado.

The presence of growing vegetation has a tendency to keep the soil flocculated and open. Any kind of organic matter in the soil, and an active bacterial growth have the same effect. Barren soils are often dispersed. The origin of much of the silt in the Colorado River is from an area that has little or no vegetable cover, an area that is barren, and one that for ages has been subjected to leaching with pure or rain water.

If two different kinds of silts, one from the mountainous country, and the other from the bad-lands, were eroded by the same kind of water, and both were subjected to the action of the same water in the river in transit, they would probably settle, not with the same but with almost equal rapidity, but the quality of the water in the river changes with the flood, and the concentration and quality of salts in solution depend upon whether the water comes from pure mountain streams or from alkaline desert flats.

#### QUALITY OF THE COLORADO RIVER WATER

During the year, the total salt content of the Colorado River water varies from about 200 parts per million during the high floods of May and June, to about 1500 parts per million at low water in February and March. The calcium content varies from about 30 to 175 parts per million, while the sulphate ( $\text{SO}_4$ ) varies from about 85 to 600 parts per million. It is a significant fact that when the calcium content is highest, the river carries very little silt, and that when the calcium content is lowest the river carries a heavy load. While this may be due largely to the increase in velocity at flood time, and to other physical factors, the quality of the water certainly plays an important part in the movement of the silt.

The Colorado River water is usually classified as a gypsum water, that is, it is supposed to have a permanent hardness. This is true for the greater part of the year but, contrary to the general belief, it does not always carry an excess of gypsum, but it may be neutral or it may even carry a slight excess of black alkali.\* An average of three weekly analyses, made during a high flood, June 25, July 2, and July 8, 1923, is given in Table No. II.

TABLE No. II.—ANALYSIS OF COLORADO RIVER WATER DURING SUMMER FLOOD.

Total soluble salts	306 parts per million
Calcium (Ca)	38 parts per million
Magnesium (Mg)	8 parts per million
Carbonates ( $\text{CO}_3$ )	Trace
Bicarbonates ( $\text{HCO}_3$ )	168 parts per million
Chlorine (Cl)	42 parts per million
Sulphates ( $\text{SO}_4$ )	84 parts per million
Silt	2300 parts per million

\**Ariz. Agri. Exper. Sta. Bull. No. 44. River Irrigating Waters of Arizona, their Character and Effects, R. H. Forbes, 1902.*

When water containing such a mixture of salts is evaporated, the calcium and magnesium in solution unite with the carbonate or bicarbonate, and precipitate out as calcium and magnesium carbonates. If the calcium and magnesium exist in excess of the amount required to precipitate fully the carbonate, the remaining calcium will unite with some other acid radical,  $\text{SO}_4$  for example, and then become calcium sulphate. A water with an excess of calcium and magnesium over the carbonates is said to have a permanent hardness.

But the percentage of gypsum does not represent the only active form of calcium. Nearly all the western, upland soils are calcareous. Calcium carbonate is only slightly soluble in water, but the presence of carbon dioxide increases its solubility greatly, so in the rivers of the West, we always have a certain amount of calcium appearing in solution as calcium bicarbonate. Upon evaporation this calcium gives up its carbon dioxide and goes out of solution as calcium carbonate. The same phenomenon is true with magnesium.

A water containing calcium and magnesium as bicarbonates, is said to have a temporary hardness. The calcium and magnesium that exist as bicarbonates are just as effective in replacing the sodium in the zeolites, that is, in flocculating colloids, as an equal concentration of calcium sulphate or magnesium sulphate, but the bicarbonates have no effect in neutralizing sodium carbonate or black alkali.

If, upon evaporation, a water does not contain enough of calcium and magnesium to neutralize all the carbonates, there will be some carbonate ions left in solution and these will come out, as evaporation proceeds, as sodium and potassium carbonates. Such a water is said to be soft, that is, it contains black alkali. The calcium and magnesium content of the Colorado River water during the period represented in Table No. II, was 38 parts per million of calcium, and 8 parts per million of magnesium. This was sufficient to neutralize only 156 out of 168 parts per million of bicarbonates, which left a small amount, 12 parts per million, of  $\text{HCO}_3$  in solution. These analyses represent the quality of the Colorado River water at Laguna Dam, and before it was mixed with the water of the Gila River.

The amount of black alkali that was contained in the water during this flood period was very small, it is true, but it is well known that an exceedingly small amount of black alkali may cause the dispersion of colloids. At every summer flood, the amount of calcium in solution gets very low, 40 to 60 parts per million, and during each of these periods the river water contains very little, if any, calcium in excess of the amount necessary to precipitate the carbonates, that is, the water at these periods has little temporary hardness and little or no permanent hardness. The silt-load of the river at this flood is usually not very

great, but the water probably carries a greater part of the silt that was eroded, yet this may not be nearly enough to make a maximum load.

As a matter of comparison the average analyses of the Colorado River water at extreme low water, for 3 weeks, January 10, 20, and 26, 1925, are given.

TABLE No. III.—ANALYSIS OF THE COLORADO RIVER AT LOW WATER.

Total soluble salts .....	1493 parts per million
Calcium (Ca).....	148 parts per million
Magnesium (Mg).....	39 parts per million
Carbonates (CO <sub>2</sub> ).....	24 parts per million
Bicarbonates (HCO <sub>2</sub> ) .....	232 parts per million
Chlorine (Cl).....	252 parts per million
Sulphates (SO <sub>2</sub> ).....	508 parts per million
Silt .....	Trace

At this period of flow it is evident that there is a considerable excess of calcium and magnesium over carbonate. The water has a temporary hardness and a decided permanent hardness, and the river at this period carries very little silt. When 1 gram of dry silt was shaken with this water the silt settled rapidly.

It has been the experience of Mr. Porter J. Preston that the silty material is likely to be carried for a considerable period after the actual flood has passed, and that the stream in its low stages is constantly transporting material down-stream that may have been eroded and brought part of the way down by a former flood and lodged along the channel. The water, the analysis of which is shown in Table No. III, was derived largely from the groundwaters along the course, particularly from the groundwaters on either side of the Grand Canyon, which came into the channel by seepage. Such a water would probably not hold any silt in suspension for a very long period, so it seems as though what little silt the river carried at this low-water period was not eroded by this water but that the silt was eroded and brought partly down-stream by a former flood, and that it was being carried as a bed-load.

In September, 1923, a great rain occurred upon the Painted Desert of northern Arizona and the Little Colorado went into flood stage. The analysis of this flood water as it appeared at Yuma, September 26, is shown in Table No. IV.

TABLE No. IV.—ANALYSIS OF THE COLORADO RIVER WATER DURING SEPTEMBER FLOOD.

Total soluble solids .....	880 parts per million
Calcium (Ca) .....	108 parts per million
Magnesium (Mg) .....	16 parts per million
Carbonates (CO <sub>2</sub> ) .....	0 parts per million
Bicarbonates (HCO <sub>2</sub> ) .....	192 parts per million
Chlorine (Cl) .....	98 parts per million
Sulphates (SO <sub>2</sub> ) .....	288 parts per million
Silt .....	22,920 parts per million



It will be seen that the calcium and magnesium content of the water existed as both temporary and permanent hardness. The percentage of calcium and magnesium is also considerably higher than that during the spring flood, but lower than that at extreme low water. The river at this period carried a very heavy load of silt which settled very slowly. Had this silt been eroded by the water whose analysis is shown in Table No. III, it would have settled very rapidly.

Thus, it seems that, while the quality of the water plays an important part in the transportation of silt, it is sometimes difficult to tell from chemical analyses which of two waters will carry the heavier load, unless we know something of the nature of the silt that has been eroded.

Unquestionably the percentage of calcium in solution is the most important factor in the flocculation of silt, but there are other reactions that take place in the solution that either add to or reduce its effectiveness. These reactions will now be discussed briefly.

It has been shown\* recently that, if a solution of sodium carbonate is prepared, and gypsum is added to the solution in increasing amounts, the sodium carbonate will be neutralized gradually, and that calcium carbonate will be thrown out of solution. This reaction, however, does not run to a finish, since the amount of sodium carbonate may be reduced to a concentration of about 25 parts per million, but no lower, and this amount of black alkali will persist in the solution even in the presence of a saturated solution of gypsum, if no carbon dioxide is present.

While the Colorado River, for the greater part of the year, contains a considerable excess of gypsum, at the same time the water will often give a strong, alkaline reaction with phenolphthalein, indicating the presence of hydroxyl ions in solution. This color with phenolphthalein appears at extreme low water, when there is unquestionably a large excess of gypsum in solution. It is true that the silt contains a certain amount of calcium carbonate, and in the absence of carbon dioxide this would give a solution containing hydroxyl ions. The water of the river, however, is in equilibrium with the air, and there is always enough carbon dioxide in the air to prevent the calcium carbonate in solution from showing color with phenolphthalein. The color seems to be due, in part at least, to the hydrolysis of sodium carbonate or sodium zeolite.

The suspended load of silt would not be in its present condition had it not come in contact with some dispersing agent. It might have done this before it was eroded, but it looks as if there is enough sodium carbonate (or sodium hydroxide) in the water, the presence of which is often masked by the excess of gypsum, to hold the silt in suspension,

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\*Brazzale, J. F. & Burgess, P. S. Technical Bulletin No. 6, Arizona Agricultural Experiment Station.

and that, except at extreme low water, there is never enough gypsum in solution to overcome the effect of the hydrolyzed sodium salt.

The Colorado River is formed by the union of many streams, and no doubt many of these tributaries carry an excess of calcium sulphate, while others carry an excess of black alkali. When one stream that carries gypsum, unites with another stream that carries black alkali, some of the calcium may even be precipitated as calcium carbonate, and, if the concentration of gypsum is great enough, the precipitation may be fairly complete. Usually, however, the concentration is low and the greater part of both the gypsum and black alkali will be held in solution, and in this case the presence of the black alkali may be masked by the excess of gypsum. The black alkali may then disperse the colloids, or it may hold the colloids in suspension that are already dispersed, and the stream may carry a heavy load of silt in spite of its gypsum content.

Suppose that the colloids in the silt load were dispersed while the soil lay *in situ*, or that they were dispersed by the black alkali of the streams in the headwaters. In either case the zeolites would be combined partly with sodium. If a stream carrying gypsum but no black alkali, emptied into the river, equilibrium would soon be established and a certain part of the zeolites would become calcium salts and would be flocculated and precipitated out. The heavier part of the silt-load would, therefore, be the first to go out, while the lighter fraction would be carried on down the river to the lower basin or even to the Gulf of California. Many streams bring gypsum into the Colorado, but the amount thus brought in is not sufficient to coagulate all of the dispersed colloids, or else they would not appear in the lower river basin. We should expect the sediment that is deposited in the valleys in the headwaters of the Colorado to be more granular and less dispersed than that brought down and spread out in the valleys of the lower basin.

Owing to the difference in the quality of the water of the tributaries, the quality of the water of the Colorado may change many times in its flow from its source to its mouth. This phenomenon of a sudden change in the reaction of rivers is common in the West, and in the groundwaters of river basins. This change in the quality of the water may cause a precipitation of silt at any point along the course of the river, and often it may explain why certain materials are laid down as the valley fill at certain places, and why different materials are laid down at other places.

#### ABSORPTION OF ALKALI BY COLLOIDS

It is a well-known fact that when an alkali, sodium hydroxide for example, is brought in contact with colloidal or any fine material, a part of the alkali will be absorbed and tenaciously held upon the surface

of the solid particle. If an alkali is once thus absorbed, it is sometimes exceedingly difficult to remove it by washing.

A large sample of Colorado River silt was collected from the edge of an irrigation canal near Yuma, Arizona, and the silt was repeatedly washed with distilled water and filtered by means of a porous filter until it was practically free from soluble salts, particularly gypsum. It was then dried and ground into fine powder. One gram of the silt was then placed in each of seven tubes, and 100 c.c. of sodium hydroxide solution, of the concentrations shown in Table No. V, were added to each tube. The tubes were stoppered, shaken, and allowed to stand for 24 hours, and then titrated for sodium hydroxide. In Table No. V are given the concentrations of the solutions before and after standing in contact with the silt, and the parts per million of OH that were removed from the solution by the silt.

TABLE No. V.—ABSORPTION OF OH FROM SOLUTIONS OF NaOH BY COLORADO RIVER SILT.

No	OH as NaOH added	OH as NaOH found after 24 hours	OH absorbed by 1 gram of silt
1.	400 p. p. m.	386 p. p. m.	14 p. p. m.
2.	350 p. p. m.	335 p. p. m.	15 p. p. m.
3.	300 p. p. m.	286 p. p. m.	14 p. p. m.
4.	250 p. p. m.	235 p. p. m.	15 p. p. m.
5.	200 p. p. m.	182 p. p. m.	18 p. p. m.

The amount of OH ion absorbed by the silt seems to be about the same in all concentrations used and, unless other factors interfere, this amount is sufficient to disperse colloids. It seems that the Colorado River silt, even if it had been flocculated when first eroded, if it had come in contact with black alkali anywhere along its course, would have taken on sodium ions and would have become dispersed.

#### EFFECT OF THE HYDROXIDES OF SODIUM, POTASSIUM, AND CALCIUM IN FLOCCULATING COLO- RADO RIVER SILT

It is well known that black alkali will either flocculate or deflocculate a soil, depending upon the amount of alkali present, the lower concentrations tend to deflocculate, while the higher concentrations tend to flocculate the colloidal material. A soil that is badly impregnated with black alkali may, therefore, be permeable to water until a part of this alkali is removed. It must be remembered that sodium carbonate itself, that is, the alkali that is not hydrolyzed, is probably more or less inert, certainly the salt itself is not a dispersing agent. It requires the presence of water and subsequent hydrolysis, with the formation of sodium hydroxide, before dispersion can take place. Both sodium hydroxide and

potassium hydroxide possess the property of either dispersing or coagulating colloidal material. In order to obtain a comparison between these alkalis the following experiment was conducted.

One gram of Colorado River silt was placed in each of several tubes, and 50 c.c. each of solutions of sodium hydroxide and potassium hydroxide were added to the tubes. The tubes were corked, shaken, and allowed to stand over-night. The approximate concentration of these two alkalis that was required to flocculate the silt and to cause the solutions to settle clear, is shown in Table No. VI. In order to bring out the comparison more clearly the concentration of alkali is expressed in terms of OH.

TABLE No. VI.—EFFECT OF SODIUM HYDROXIDE AND POTASSIUM HYDROXIDE UPON COLORADO RIVER SILT.

No.	OH as NaOH added	Effect upon silt	OH as KOH added	Effect upon silt
1.	0 p. p. m.	Dispersed	0 p. p. m.	Dispersed
2.	50 p. p. m.	Dispersed	50 p. p. m.	Dispersed
3.	100 p. p. m.	Dispersed	100 p. p. m.	Dispersed
4.	150 p. p. m.	Dispersed	150 p. p. m.	Flocculated
5.	200 p. p. m.	Dispersed	200 p. p. m.	Flocculated
6.	250 p. p. m.	Dispersed	250 p. p. m.	Flocculated
7.	300 p. p. m.	Flocculated	300 p. p. m.	Flocculated
8.	350 p. p. m.	Flocculated	350 p. p. m.	Flocculated
9.	400 p. p. m.	Flocculated	400 p. p. m.	Flocculated

This manner of determining the flocculating point of silt is not presented as a method that is applicable to all conditions, neither is any great degree of accuracy claimed for it. It can only be considered as accurate in a comparison with a control. It can be said, however, that under the conditions of this experiment, the Colorado River silt was flocculated at and above concentrations of about 250 to 300 parts per million of OH as NaOH and that the silt was flocculated at and above concentrations of from 100 to 150 parts per million of OH as KOH. If the basic ions, sodium and potassium, were alone concerned in the dispersion of the colloids, there would be a relation existing between these flocculating points very much like that just quoted, or in proportion to their atomic weights, 23 sodium : 39 potassium.

In the next experiment, the effect of calcium hydroxide and barium hydroxide upon Colorado River silt was determined in the manner just described. Boiled water was used and every care was taken to keep the carbon dioxide out of the solution. The results are given in Table No. VII.

As in the case of the sodium hydroxide solutions, some of the alkali was removed from solution by the silt. In the solutions containing 100 parts per million, 32 parts per million of OH from both the calcium

hydroxide and barium hydroxide were removed from solution.

When expressed in terms of OH, no difference was noticed in the concentrations of calcium hydroxide and barium hydroxide that were required to flocculate the silt. Above concentrations of 30 or 40 parts per million of OH, both of these alkalis flocculated the silt readily, while below these concentrations the alkalis seem to be practically inert. There was no indication of a greater dispersion than that which existed in the control, in the lower concentrations of alkali. When flocculated with calcium hydroxide or barium hydroxide the silt settled much more rapidly than it did when flocculated with sodium hydroxide or potassium hydroxide.

TABLE No. VII.—THE EFFECT OF CALCIUM HYDROXIDE AND BARIUM HYDROXIDE UPON COLORADO RIVER SILT.

No.	OH as Ca (OH) <sub>2</sub> added	Effect upon silt	OH as Ba (OH) <sub>2</sub> added	Effect upon silt
1	0 p p m	Dispersed	0 p p m	Dispersed
2	5 p p m	Dispersed	5 p p m	Dispersed
3	10 p p m	Dispersed	10 p p m	Dispersed
4	20 p p m	Dispersed	20 p p m	Dispersed
5	30 p p m	Dispersed	30 p p m	Dispersed
6	40 p p m	Flocculated	40 p p m	Flocculated
7	50 p p m	Flocculated	50 p p m	Flocculated
8	60 p p m	Flocculated	60 p p m	Flocculated
9	70 p p m	Flocculated	70 p p m	Flocculated
10	80 p p m	Flocculated	80 p p m	Flocculated
11	90 p p m	Flocculated	90 p p m	Flocculated
12	100 p p m	Flocculated	100 p p m	Flocculated

The concentration of calcium hydroxide that was required to flocculate the silt was shown in another way. One gram of silt was placed in a large test tube with 100 c.c. of a solution of calcium hydroxide which contained 750 parts per million of OH. The solution was shaken and the silt was flocculated and settled rapidly. One half, or 50 c.c., of the clear solution was drawn off and 50 c.c. of carbon-dioxide-free water were added to the tube. The addition of this water lowered the concentration of the calcium hydroxide to 375 parts per million of OH, and the silt remained flocculated and settled rapidly. This process was continued until the concentration of the OH in the tube was down to about 47 parts per million, when a slight dispersion of the silt set in. Below 47 parts per million of OH the silt remained dispersed.

It looks as though the sodium hydroxide and potassium hydroxide are concerned with both flocculation and deflocculation, while calcium hydroxide and barium hydroxide are concerned with flocculation only. Thirty parts per million of OH is equivalent to over 65 parts per million of calcium hydroxide, so it appears that concentrations of less than

65 parts per million of calcium hydroxide are practically inert, as far as flocculating clay colloids is concerned. This is a very important fact in the consideration of the silt-carrying capacity of rivers.

#### EFFECT OF GYPSUM UPON THE FLOCCULATION OF COLORADO RIVER SILT

As the Colorado River silt is readily flocculated by strong solutions of gypsum, an effort was made to determine how strong concentrations of calcium sulphate were required to flocculate the silt. The experiment was carried on as before, and the results are shown in Table No. VIII.

TABLE No. VIII—EFFECT OF CALCIUM SULPHATE SOLUTIONS UPON COLORADO RIVER SILT

No	Parts per million CaSO <sub>4</sub> added	Effect upon the silt
Control	0	Dispersed
1	25 p p m	Dispersed
2	50 p p m	Dispersed
3	75 p p m	Dispersed
4	100 p p m	Slightly dispersed
5	125 p p m	Flocculated
6	150 p p m	Flocculated
7	200 p p m	Flocculated
8	250 p p m	Flocculated
9	300 p p m	Flocculated
10	400 p p m	Flocculated

Under the conditions of this experiment, at concentrations of about 100 parts per million or less, solutions of gypsum are not effective in flocculating Colorado River silt. It requires a concentration of over 100 parts per million to produce decided effects. One hundred parts per million of calcium sulphate equal about 55 parts per million of calcium hydroxide, so there seems to be a molecular relation between the amount of calcium hydroxide and calcium sulphate required to flocculate the Colorado River silt.

#### EFFECT OF CALCIUM SULPHATE UPON COLORADO RIVER SILT IN THE PRESENCE OF SMALL AMOUNTS OF SODIUM CARBONATE

Another set of calcium sulphate solutions, of the same concentrations shown in Table No. VIII, was prepared, and 30 parts per million of sodium carbonate were added to each of the solutions, and the flocculating effect of these mixtures was determined. Little or no increase was found in the concentration of calcium sulphate that was required to flocculate the silt in the presence of a small amount of black alkali, over that required when no black alkali was added to the solution. This fact

seems significant. The untreated dry silt, when shaken with carbon-dioxide-free water, gives a color with phenolphthalein, indicating that the solution contains free hydroxyl ions. If these ions, or the sodium ions that are dissociated with them, are responsible for the dispersion, the addition of a little more alkali as sodium carbonate would probably have little effect. This phenomenon strongly indicates that the silt as it floats dispersed in the river, carries a small amount of absorbed black alkali and a negative charge, even though an excess of gypsum exists in the solution.

#### FLOCCULATION OF COLORADO SILT AT FLOOD AND AT LOW WATER

Two conditions in the quality of the Colorado River water were now assumed, and two sets of solutions were made up to represent these conditions. In the first case the water was assumed to have a concentration of calcium about equal to that found at flood time, 30.8 parts per million of calcium or about 105 parts per million of calcium sulphate, and in the second case the water was assumed to have a concentration of calcium about equal to that at extreme low water, 150 parts per million of calcium or about 510 parts per million calcium sulphate. Sodium carbonate was added to portions of each of these solutions in amounts shown in Tables Nos. IX and X, and the effect of these solutions in flocculating the silt was determined, in the manner previously described.

TABLE No. IX.—EFFECT OF SMALL AMOUNTS OF CALCIUM SULPHATE IN THE PRESENCE OF VARYING AMOUNTS OF SODIUM CARBONATE UPON COLORADO RIVER SILT.

No	CaSO <sub>4</sub> added	CaSO <sub>4</sub> equivalent to Ca	Na <sub>2</sub> CO <sub>3</sub> added	Na <sub>2</sub> CO <sub>3</sub> equivalent to Ca	Effect upon silt
1.	0 p. p. m.	0 p. p. m.	0 p. p. m.	0 p. p. m.	Dispersed
2.	105 p. p. m.	30.8 p. p. m.	11.0 p. p. m.	4.2 p. p. m.	Dispersed
3.	105 p. p. m.	30.8 p. p. m.	33.3 p. p. m.	12.6 p. p. m.	Dispersed
4.	105 p. p. m.	30.8 p. p. m.	55.5 p. p. m.	21.0 p. p. m.	Dispersed
5.	105 p. p. m.	30.8 p. p. m.	77.7 p. p. m.	29.4 p. p. m.	Dispersed
6.	105 p. p. m.	30.8 p. p. m.	99.9 p. p. m.	37.8 p. p. m.	Dispersed
7.	105 p. p. m.	30.8 p. p. m.	122.1 p. p. m.	46.2 p. p. m.	Dispersed
8.	105 p. p. m.	30.8 p. p. m.	144.0 p. p. m.	54.6 p. p. m.	Dispersed
9.	105 p. p. m.	30.8 p. p. m.	166.0 p. p. m.	63.0 p. p. m.	Dispersed

Each of these solutions gave a color with phenolphthalein, indicating the presence of hydroxyl ions, and in every solution the silt remained dispersed. In solutions Nos. 2, 3, 4, and 5 the amount of calcium sulphate was more than equivalent to the amounts of sodium carbonate added, but the excess of calcium sulphate apparently had no effect upon the silt. Some of these solutions are representative of the quality of

the Colorado River at flood time, when it is carrying a heavy load of silt.

In Table No. X, is shown the effect of a large amount of calcium sulphate in the presence of varying amounts of sodium carbonate.

Some of the solutions are representative of the quality of the Colorado River at low water, when it is usually carrying its lightest load of silt. Although each of the solutions gave a color with phenolphthalein, in all of the solutions except the last three and the control, the

TABLE No. X.—EFFECT OF LARGE AMOUNTS OF CALCIUM SULPHATE IN THE PRESENCE OF VARYING AMOUNTS OF SODIUM CARBONATE, UPON COLORADO RIVER SILT.

N.	CaSO <sub>4</sub> , added	CaSO <sub>4</sub> , equivalent to Ca	Na <sub>2</sub> CO <sub>3</sub> , added	Na <sub>2</sub> CO <sub>3</sub> , equivalent to Ca	Effect upon silt
1	0 p. p. m.	0 p. p. m.	0 p. p. m.	0 p. p. m.	Dispersed
2	525 p. p. m.	154 p. p. m.	13 p. p. m.	5 p. p. m.	Flocculated
3	525 p. p. m.	154 p. p. m.	27 p. p. m.	10 p. p. m.	Flocculated
4	525 p. p. m.	154 p. p. m.	54 p. p. m.	21 p. p. m.	Flocculated
5	525 p. p. m.	154 p. p. m.	109 p. p. m.	42 p. p. m.	Flocculated
6	525 p. p. m.	154 p. p. m.	222 p. p. m.	84 p. p. m.	Flocculated
7	525 p. p. m.	154 p. p. m.	333 p. p. m.	126 p. p. m.	Slightly dispersed
8	525 p. p. m.	154 p. p. m.	444 p. p. m.	168 p. p. m.	Slightly dispersed
9	525 p. p. m.	154 p. p. m.	555 p. p. m.	210 p. p. m.	Dispersed

silt was flocculated. It will be noted that the dispersion of the silt began with solution No. 7, although in that and the next solution there was still an excess of calcium sulphate over the sodium carbonate. In the last number only was sodium carbonate added in excess of the gypsum. The solutions in numbers 7 and 8 suggest the actual condition of affairs as often occurs in the Colorado River itself, that is, the river often contains a large excess of calcium sulphate, yet at the same time it contains a small amount of sodium carbonate.

#### EFFECT OF NEUTRAL SODIUM SALTS UPON COLORADO RIVER SILT

There are other salts in the Colorado River water that also have an effect upon its silt-carrying capacity; these are sodium sulphate and sodium chloride. In practice, we know that these salts in appreciable amounts have a flocculating effect upon colloids, from the fact that a soil high in sodium sulphate or sodium chloride will usually take water readily, and will remain permeable until most of these salts are leached out. The amounts of sodium chloride or sodium sulphate in solution in the Colorado River water varies with the flood. The chlorine content may vary from 42 to 250 parts per million while the SO<sub>4</sub> content may



run as low as 80 parts per million at flood times and as high as 600 parts per million at low water.

Many experiments were made to determine the amounts of sodium chloride and sodium sulphate that had a flocculating effect upon the Colorado River silt, but the results were not conclusive and they are not included. Usually a concentration of about 650 parts per million of sodium sulphate, and a slightly less amount of sodium chloride, is sufficient to flocculate the silt, but often a greater amount is required. There is usually no definite change from dispersion to flocculation, as the concentration of the sodium salt is increased.

The peculiar effect of the sodium salt upon the silt may be explained by the fact that the silt contains a certain amount of calcium carbonate and that when sodium sulphate or sodium chloride is brought in contact with this calcium carbonate, a certain amount of sodium carbonate is formed in the reaction. In the concentration of salt in the Colorado River water, the amount of sodium carbonate thus formed would be small, yet very small amounts of sodium carbonate have a decided effect in dispersing colloids, and it is quite possible that the flocculating effect of sodium sulphate and sodium chloride is in part counteracted by the presence of small amounts of black alkali in the solution. It can be stated definitely, however, that sodium sulphate and sodium chloride seldom occur in Colorado River water in amounts sufficiently high to have a decidedly flocculating effect upon the silt.

## SUMMARY

1. The silt, as it floats in the Colorado River, seems to be dispersed, that is, the colloidal particles seem to be carrying negative charges.
2. In many cases, the silt-carrying capacity of a stream may depend upon the size of the particles in suspension, rather than upon the velocity of the current.
3. The colloids in the Colorado River silt were probably dispersed when they existed as soils in the upper water shed, before they were eroded.
4. The silt, as it is deposited in the lower basin, contains appreciable amounts of replaceable sodium, indicating the presence of dispersed colloids.
5. The quality of the Colorado River water varies with the flood. At low water it has a high salt-content, and contains an excess of gypsum, but during the spring flood, its concentration of soluble salts is low, and it may even carry a slight excess of black alkali.
6. The hydroxides of sodium and potassium when added to the water in low concentrations, disperse the Colorado silt but they flocculate the silt when added in high concentrations.
7. The hydroxides of calcium and barium seem to be inert in very low concentrations, but they flocculate the silt at and above concentrations of about 40 parts per million of OH.
8. Sodium and potassium hydroxides seem to be associated with both flocculation and dispersion, while calcium hydroxide and barium hydroxide seem to be associated with flocculation only.
9. Calcium sulphate flocculates the silt at and above concentrations of about 100 parts per million, but in lower concentrations calcium sulphate seems to be relatively inert.
10. Although the Colorado River water usually contains an excess of calcium sulphate, it does not always carry this salt in amounts sufficiently high to flocculate the silt.
11. Sodium sulphate and sodium chloride have a flocculating effect upon the silt, but these salts seldom occur in amounts sufficiently high to make them effective.
12. The quality of the water, as well as the velocity of the current, should be taken into consideration in many of the engineering problems that involve the silt-carrying capacity of streams.

