TWENTY YEARS OF SEDIMENT WORK ON THE COLORADO RIVER

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With authorization by Congress in 1928 of the construction of a dam in Black Canyon of the Colorado River and an All-American Canal, from the Colorado River to the Imperial Valley, many unusual problems arose in the planning and execution of these unprecedented works. The problems included not only the design and construction of a dam higher and of greater mass than any previously attempted and another dam on loose alluvium foundation, but also the effect of the construction of those dams and consequent flow regulation on the regimen of a river carrying large volumes of sediment.

The purpose of this paper is to cover what was done then and what has been done since to recognize and provide solutions for the problems arising from interference with the natural habits of a great river (Fig. 1). The problems fall naturally in three categories. The first deals with the effect on the reservoir, Lake Mead, formed by the new dam, Hoover Dam (formerly known as Boulder Dam), of the large quantities of silt which would enter it and be deposited after the dam was closed. The second category deals with the problems which would arise from the disturbance of the regimen of the river below Hoover Dam, as well as below other dams which were soon to be constructed downstream, following removal of the silt from the river water by deposition in the reservoirs, and the change in the characteristics of flow from alternating floods and drouths to an almost constant flow. The third category has to do with the design criteria which were to be used in the construction of the All-American Canal and its diversion dam, Imperial Dam, authorized for construction at the same time as was Hoover Dam.

The problems of the third category were considered first, because their solutions had to be translated into concrete and steel so
that construction of the canal and the diversion dam might proceed simultaneously with the construction of the storage dam. It was not until 1944 that the problems of the second category — those connected with the changed regimen of the river — became so pressing that remedial measures had to be undertaken. Not until 1948 was it possible to conduct the extensive surveys and investigations which were necessary to determine how and where the large volumes of sediments were deposited within the volume of Lake Mead.
As has been the case in many developments on western rivers, the available basic data were few and covered only a relatively brief period of time. A few silt samples had been collected at Yuma, Arizona, as early as 1892 and between 1900 and 1904. Although a gaging station was established at Yuma in 1902, only discharge measurements were made. During the summer of 1909, samples of the river water were taken by the Bureau of Reclamation and the percent of sediment in transport by weight was determined. A sampling program has been carried out continuously at Yuma at a frequency varying from one sample per month to two samples per week since April 1910. The Geological Survey secured daily sediment samples at Topock, Arizona, from October 1935 through March 1937, and sediment samples have been obtained at Grand Canyon (Bright Angel Station) since 1926, with size analyses being made since 1935.

The Problems of Imperial Dam

The first question to be answered in connection with the design of the diversion dam and headworks for the All-American Canal was the extent to which the silt load at the heading would be changed by the construction of Hoover Dam and Parker Dam, the latter being located 155 miles below Hoover, with the complete elimination of the silt load at those dams and the discharge of clear water from them (Fig. 2). The Imperial Irrigation District and its predecessors, which had diverted water from the Colorado River near Yuma since 1902, had found it necessary to expend large sums of money on silt removal so as to prevent the choking of their canals. The Yuma Irrigation District, which had diverted water from the Colorado River at Laguna Dam since 1907, had utilized a simple desilting basin to eliminate the sediment from its canals.

The investigations which it was hoped would provide the answer to these questions were started in 1933 by the Bureau of Reclamation on the initiative of E. W. Lane. The purpose was twofold: (1) To establish if possible the magnitude of the bed load in relation to the suspended load, and (2) to determine the particle-size distribution of the total load and of the material constituting the river bed. The total load was determined by securing samples at Laguna Dam, fifteen miles upstream from Yuma, from the crest, from the sluiceways, and from the Yuma Main Canal, which diverts its water at the dam. At the same time standard suspended-load sam-
Fig. 2. Map and Operational Diagrams, Colorado River Below Hoover (Boulder) Dam.
pies were collected at the Imperial Dam site, 4.5 miles above Laguna Dam. The silt samples were analyzed with sieves and hydrometers and the quantities, expressed in tons per day as a function of discharge, were plotted in seven particle-size groups, ranging from larger than 0.25 mm. to smaller than 0.005 mm. It appeared that in the coarser grades there was a fairly well-defined relation between the total load and the discharge, but that, as the material got finer, the points scattered more and more and no relation appeared to exist between the discharge and material finer than 0.01 mm. It was also determined that there was no significant difference between the total load passing Laguna Dam and the suspended load passing Imperial Dam site a few miles upstream. The conclusion was drawn that on the lower Colorado River at that time the suspended load constituted by far the greater portion of the total load and that very little if any sediment traveled as true bed load except perhaps as local shifting sand bars.

In November 1933 borings were made in the bed of the river at sections located from 18 to 25 miles apart in the reach between Parker Dam site and Imperial Dam site. Material obtained from the borings was analyzed in the same manner as was the sediment obtained from the flow. The material in the river bed was found to lie between 0.05 to 0.6 mm. This range of sizes is practically the one over which the observations at Laguna and Imperial Dams indicated a relationship between sediment load and water discharge. The conclusion was drawn that under conditions as they existed then on the lower Colorado, the river’s flow carried as much of the sediment of the grain sizes occurring in the river bed as it could and that, as a result, if the total load was removed at a given point and clear water discharged from a dam, the water would again remove material from the river bed until a concentration was reached equal to that under uncontrolled conditions. Since the finer sizes, that is, those smaller than 0.05 mm., were available in the bed to only a very limited extent, the desilting works at Imperial Dam were designed to handle, initially, the same concentration in the range 0.05 to 0.6 mm. as was determined from the suspended sediment samples.

It was recognized that as the river continues to replenish its silt supply from its bed and the bed as a result degrades downstream from the dams, the material carried by the river will gradually be taken from deeper and deeper layers of the bed. This was impor-
tant because the borings had indicated that the material got coarser with depth, so it might be expected that the silt load would gradually decrease. It could also be expected that the character of the sediment transport would change, in that, as the bed material became larger, a change from suspended to bed load would take place.

Another phenomenon was expected to effect a decrease in the sediment load, but it was more difficult to evaluate. As water flows over a bed consisting of a mixture of sediment of various grain sizes, the smaller particles would first be removed, leaving the coarser particles to form a pavement on the surface of the bed, protecting the lower strata from erosion. This is usually referred to as shingling, and a similar phenomenon is observed under the action of wind on sand grains of different sizes forming the surface of a desert. A pavement formed in this manner will effectively reduce degradation until the pavement is disturbed by greater discharges or by a shift in the river channel.

The correctness of these reasonings, new in the science of river engineering at that time, has been borne out by observations at the desilting works since they were constructed.

The sediment observations at the Imperial Dam site, intended primarily to furnish data for the design of the dam and desilting works, have been continued to the present time, in the form of suspended-sediment measurements above Imperial Dam, as have also the sediment determinations at Yuma, started in 1910. Since construction by Mexico of the Morelos Diversion Dam below Yuma, the sampling program has been expanded so as to furnish a continuing check of the behavior of the river upstream from that dam. An agreement with Mexico provides that the dam shall be operated in such a manner that above the dam water stages at ordinary flows shall not increase above the 1948 figures.

With the maximum sediment load determined for which the proposed desilting works at Imperial Dam was to be designed, there remained many technical problems connected with the design of the individual elements of the structure and the mechanical equipment which was to accumulate the material deposited on the bottom of the desilting basins and sluice it back to the river. One interesting detail was the evaluation of the required horsepower of these machines, or scrapers. To determine the frictional resistance of Colorado River sediment scraped along a surface of the same material, large quantities were shipped to the laboratories of the
Bureau of Reclamation in Denver, Colorado, for experimental determination of the various factors involved. After numerical values had been obtained, the required horsepower of the scraper mechanisms was computed. Next, a check of the computations was made by shipping another load of Colorado River sediment to the laboratories of the Dorr Company, Inc., at Westport, Connecticut, where a miniature desilting basin had been constructed similar to those that were being planned at Imperial Dam. This basin was fed with the material, the torque required to scrape it measured, and again computations were made to translate the measurements into the horsepower required in a prototype basin. The results at Westport and those in Denver, conducted in an entirely different manner, agreed to a surprising extent. Figure 3 shows an aerial photograph of the Imperial Dam and desilting works. Figure 4 shows one of the mechanical scrapers.

The Problems of River Regimen

The next problem with which the Bureau of Reclamation was confronted on the Colorado River was the effect on the regimen of the stream of the clear water discharges, first from Hoover Dam and
later from Parker Dam and Davis Dam. It was decided to follow quantitatively the rate at which material was being removed from the river bed below each dam by the retrogression process and the rate and manner of depositing the material above the downstream dams. Hoover Dam was closed Feb. 1, 1935, and the first 17 observation stations were established at that time along the reach of river between the dam and Jumbo Wash, a distance of approximately 13 miles. By July 1935 it became evident that retrogression was progressing rapidly downstream and more stations were established. By June 1941 retrogression observations were being made along the entire 120-mile reach of the river, extending from Hoover Dam into the canyon section at the headwaters of Lake Havasu. At first observations were made at approximately two-week intervals, but at the present time measurements are made only once a year. Up to the end of 1951, 63 runs of retrogression measurements had been made. Figure 5 shows various profiles of water-surface elevations adjusted to a discharge of 15,000 second-feet and the average river-bed elevations as computed from the area below a fixed base line.

It will be noted that below Hoover Dam the greatest lowering of
Fig. 5. Profiles of Colorado River from Hoover Dam to Lake Havasu.
the average river bed has taken place at section 10, 7.7 miles downstream, and amounts to about 24 feet. The retrogression in the stretch of the river between Hoover Dam and Davis Dam, 67 miles downstream, had practically stopped by the time Davis Dam was closed and Lake Mohave was formed in 1950. During the 15 years from the time Hoover Dam was closed to the time this reach of river became a lake, a total of about 98,000,000 cubic yards of material had been removed from the 67 miles.

Retrogression sections similar to those below Hoover Dam were established below Parker Dam, and measurements started with the dam closure on Oct. 16, 1938. A total of 23 sections was installed between Parker Dam and the headwaters of Imperial Dam. Construction in 1940 of Headgate Rock Dam by the Indian Service, 14.4 miles below Parker Dam, simply shifted the focal point of retrogression the same distance downstream. As of 1951 the maximum retrogression below Parker Dam has taken place at section 37, 23.6 miles downstream and 9.2 miles below Headgate Rock Dam, and amounts to approximately 11 feet. Between October 1938 and July 1951 a total volume of about 166,000,000 cubic yards of material had been removed. The node point below Parker Dam where retrogression changes to aggradation seems to be located at the present time approximately 95 miles downstream and 53 miles upstream from Imperial Dam. Profiles of water-surface elevations and average bed elevations are shown on Fig. 6.

The nearly 152,000,000 cubic yards of material eroded below Hoover Dam and transported downstream was of course deposited upstream from Parker Dam, 155 miles downstream. The deposition took place in a somewhat unexpected manner. The head of Parker Dam reservoir (Lake Havasu) is located in a canyon stretch near Topock, Arizona. The head of the reservoir, as here used, is understood to be the point at which a horizontal line drawn along the maximum water-surface elevation intersects the river bed. Upstream from the gorge at Topock is the wide alluvial Mohave Valley, extending upstream for some 33 miles.

At first, material was deposited at the head of the reservoir in the usual manner and a miniature delta began to form, which slowly extended upstream. It had all the characteristics of a regular delta, with topset, foreset, and bottomset beds. Soon, however, the development of the young delta was obscured by a phenomenon of entirely different nature.
Fig. 6. Profiles of Colorado River from Parker Dam to Imperial Dam.
In the Mohave Valley, down through the years, the Colorado River has acted as any other alluvial, meandering stream. It has moved from side to side in the valley, sometimes by gradual accretion, sometimes by avulsion. There is indisputable evidence that, at least during the past hundred years, there has been a general rise in the level of the valley because of deposition of sediment as the river moved from side to side. To this may have been added river-bed aggradation caused by the inflow of gravel from side washes. The mechanics of the river’s behavior seem to have been that it followed a certain course for a number of years, during which it would from time to time overflow its banks during floods. Since the river water was heavily laden with fine silt, suspended in an almost uniform concentration from top to bottom, that water overflowing the banks of the stream during floods would contain large volumes of fine silt. Since the banks were overgrown with tules and willows, as the silt-laden water penetrated this vegetation the silt was deposited along a fringe paralleling the river banks and natural levees were formed. As long as these natural levees kept pace with any general rise of the river bed, no avulsion would take place, but gradually the land adjacent to the river’s banks became higher than the valley farther back. Eventually, an unusually large flood would descend the valley and the overflow at some point would be heavy enough to uproot the vegetation, thus permitting the river to course down a lower portion of the valley and an avulsion had taken place. The same levee-building processes would reoccur in its new course, until a new avulsion took place. The yearly floods would keep the river channel within the natural levees relatively free of obstruction and growth.

With the closure of Hoover Dam, this pattern of annually repeating floods changed. The flow of the river was now at a nearly constant rate. A substantial silt load was still carried by the water, but gradually its character changed. Its average size increased and its concentration near the surface decreased until the river, when looked upon obliquely, appeared blue and clear. The capacity of the river to transport the coarser material now available may have been less than that to transport the finer material of the past. In any case, deposits on the bed continued and occasionally overflows across the banks took place. The overflow came from the top layers of the river, which were now almost free of silt. As it penetrated the vegetation, no deposits were made, no natural levees were
formed. A break was not again healed. Whenever a point of overflow had been created, the river continued to overflow at that point and kept on losing its water, but only a little of its silt. The result was that the remaining water was still less able to carry the sediment load and deposition on the river bed was accelerated. Soon all the water was passing through the vegetation and the river bed remained as a dry sandy ribbon where the river once flowed. Where a muddy river with a forever changing course had once meandered through an alluvial valley, but with a course which was at any one time well established, there now was a swamp with water covering an entire valley to a width of 1½ to almost 5 miles, occupying innumerable sloughs and channels or simply filtering through the vegetation. For 15 miles a river had ceased to exist.

As no open channel into Lake Havasu remained, all sediment eroded below Hoover Dam was deposited in the swamp, with the result that its general level continuously rose. It is estimated that during the period 1935 to 1951 only 32 percent of the material eroded below Hoover Dam found its way into Lake Havasu. The rest was held in the swamp. The formation of the swamp with the rising water surface inundated part of the city of Needles, California, and seriously threatened a stretch of the Santa Fe Railway Company's main line.

A somewhat parallel phenomenon has occurred upstream from Imperial Dam reservoir, below Parker Dam. The material eroded from the river bed below Parker and Headgate Rock dams has been deposited in Imperial Dam reservoir and upstream therefrom. The original storage capacity of Imperial Dam reservoir was only 85,000 acre-feet and it was rapidly filled, the resultant rise in river bed moving slowly upstream. However, for reasons which are not quite clear at this time, swamp formation as at Needles has not taken place above Imperial Dam reservoir. The rise of the water surface, however, has interfered with the drainage outlet from Palo Verde Valley at Blythe, California.

The changed regimen of the river because of the elimination of the sediment load and the equalization of the flow then becomes a matter of retrogression below the dams and aggradation above the reservoirs formed by the dams, with occasional complications, such as the swamp formation at Needles. It has been mentioned that, in the case of the city of Needles and the drainage outlet from Palo Verde Valley, aggradation had great economic consequences. The
same applies to stretches of degradation with lowered water-surface elevations, where people have been diverting water from the river without use of a diversion dam. These diversions would be destroyed because of the lower water-surface elevations. This was the case at the diversion point for Palo Verde Valley above Blythe. By 1944, the retrogression below Parker and Headgate Rock dams had progressed to a point at which it was impossible for the Valley to continue to obtain its needed water supply. As an emergency measure,

![Image of Palo Verde Weir](http://ir.uiowa.edu/uisie/34)

*Fig. 7. Temporary Palo Verde Weir.*

the Congress made available to the Bureau of Reclamation funds for the construction of a temporary rock weir in the river so as to maintain the water surface at that elevation which had existed before retrogression started. This weir was completed in 1945 and has since been maintained with some difficulty. It is still serving its purpose, the difference in water surface between the upstream and downstream sides being now about 9 feet. Investigations have been in progress for several years to decide on a permanent method of diversion at this point which would not be dependent on a temporary structure requiring constant surveillance and repairs, but an agreement has not yet been reached between the Government
and the people interested. Figure 7 shows a photograph of the weir.

To overcome the difficulties caused by the rising water surface at the drainage outlet from the Palo Verde Valley, which in turn was caused by sediment deposition upstream from Imperial Dam, a temporary river relocation was made past the mouth of the drain in 1947. The purpose of this relocation, usually referred to as the Cibola Valley Pilot Cut, was to create better conditions at the mouth of the drain, and it did result in lowering the water surface in the drain by almost two feet. The cut was excavated with a dragline, the river being diverted through a 40-foot pilot cut. It took almost two years for the cut to develop into a river with a width of about 400 feet, but it now carries almost the entire flow. Figure 8 shows an aerial view of the cut.

The situation at Needles required more drastic measures. It was obvious that to re-establish the equilibrium of the river it would be necessary to create a new channel between Needles and Topock, free of obstructing vegetation, and to constrain the river within this new channel. The only known method of accomplishing this was by dredging. To prevent the new river channel from again de-
teriorating through loss of water to the surrounding swamp, levees would have to extend the full length of the channel so that, even at high releases from upstream dams, the river would be fully confined. The channel was located along the California mesa of the valley so that only one levee was needed to prevent overflow from the channel to the swamp toward the east.

Because of the unknown difficulties which might be encountered due to the vegetation which was expected to, and did, cause clogging of the dredge pump, and because of the unknown amount of maintenance of the new channel, it was decided to be in the best interests of the Government to construct a dredge and do the work by Government forces. A contract for the construction of a 20-inch suction dredge was let on July 24, 1947, and the dredge was placed in operation on the Colorado River on Jan. 31, 1949.

Since there are no locks at the various dams on the lower Colorado River, and since in the future there will be dredging work similar to that at Needles required at other spots, the dredge was made of sectional construction so that it can be completely disassembled, moved by truck or railroad car, and reassembled at a new

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Fig. 9. Bureau of Reclamation Dredge "The Colorado."
site. The dredge has a 1350-horsepower, direct-connected, 4-cycle, Diesel engine for the operation of the main pump, and a 300 kw, Diesel-operated, motor-generator set furnishing energy for the cutter. It has also two auxiliary motor-generator sets for the operation of fire pumps, etc. A suction dredge progresses by swinging back and forth around one or the other of two spuds at the stern. The sideward swing is accomplished by pulling alternately on two anchors placed on shore adjacent to the channel and moved forward as the dredge progresses. In the dense growth which was encountered along much of the alignment between Needles and Topock, it would have been difficult to move the heavy anchors by any land-operated equipment. A device rarely used previously was re-sorted to, whereby the anchors could be moved from the dredge itself by means of long booms attached to its forward corners. Figure 9 shows the dredge and Fig. 10 an aerial view of the dredge in operation while moving material into a channel closure.

Due to the coincidence of several unlikely circumstances, the dredge sank while unattended during a week-end in November 1949. It was raised by Government forces and returned to operation. The average unit cost of dredging and depositing material along a levee
at one side of the dredge cut has been substantially less than could have been possible by any other method of operation.

Dredging was done in the downstream direction, beginning at Needles. To avoid the carrying of silt from the river into the dredged channel behind the dredge, a plug was thrown across the upstream end where it started at an existing river channel, and sloughs encountered on the way were closed off by deposition of dredge spoil. In this manner all dredging was done in still water, making possible low unit costs. As the dredge approached Topock,

FIG. 12. BEGINNING OF FLOW INTO DREDGED CHANNEL THROUGH UPPER PLUG, JUNE 25, 1951.

water in the cut was concentrated at the lower end and the upper end of the channel became dry. To bring the dredge back to the yard before the channel was opened to the river, it was necessary to first bring it half way back to Needles, then to dredge a levee across the channel, allowing its upper half to fill with water, thereby permitting the dredge to be towed back to the yard. To put the channel into operation, the middle dam was demolished with dynamite and, as soon as the flow had a good start, the upper plug was removed in the same manner. The flow through the channel was
violent for a few weeks, but within one month after the plug was blown it was possible to take the dredge out into the channel again for extension of the work upstream. Figure 11 shows an aerial photograph of the channel from Needles to Topock, taken shortly after the dredging was resumed. Figure 12 shows the initial flow through the hole shot in the upper plug.

During the early months of 1952 it became desirable to have the dredge drydocked so that its underwater surfaces might be sandblasted and repainted. The methods used for construction of an inexpensive drydock may be of interest. First, the dredge dug a large hole off the access channel to the repair yard. The material dredged was placed next to the excavation. Second, the communication between the hole and the channel was closed by pushing in the material deposited along the rim. Third, wellpoints were established around the rim and the hole unwatered. Fourth, piles were driven and ways constructed on the bottom, whereupon the water was allowed to rise, the closing dam removed, the dredge backed in, the dam closed again, and the dock unwatered. When the repainting was completed, the water was allowed to rise in the dock.
and the dredge dug itself out. Figures 13 and 14 show two stages of the work.

Because of almost unprecedented precipitation over the Colorado River watershed in the spring of 1952, releases from Hoover and Davis Dams have been substantially increased since early January. The increased flow has caused some damage to the new channel, particularly where vegetation did not exist along the banks or had not had time to become well started. Along stretches where the vegetation along the banks was heavy, the cutting of the channel banks has been moderate. Attempts were made to protect raw banks with wire mesh without much success. A bridge is now under construction which will permit rock and gravel to be hauled to the east side of the channel and no difficulties are anticipated in re-establishing the channel banks in places where they have been eroded. Some maintenance work will be required, however, at least as long as the discharges remain high.

It is planned that the dredged channel will be extended upstream. First, it is desired to extend the levee which separates the river from the low-lying lands of the Mohave Valley to the east so that

![Fig. 14. Sandblasting Hull of "The Colorado" in Drydock.](http://ir.uiowa.edu/uisie/34)
the valley may be safely developed for agricultural purposes, as well as to avoid loss of water from the channel. Second, the extension of the channel will accelerate the retrogression below Davis Dam and, in this manner, create additional head on the power plant turbines and increase generation from the same flow of water. Third, maintenance of the channel downstream will be reduced by accelerating the process of stabilization of the entire river stretch between Topock and Davis Dam.

By June 1852, the water-surface elevation in the river opposite Needles had been lowered approximately six feet, as compared with the elevation for the same discharge before the dredging work was begun. This lower river stage means increased flood protection to the city of Needles and the Santa Fe Railroad. It also means improved drainage of the lands of the Mohave Valley, where large areas are already being opened for the growing of crops. Finally, it means less water loss by evaporation and transpiration in the swamp area. Tentative figures seem to indicate that the water loss in the Mohave Valley may have increased some 300,000 acre-feet a year because of the formation of the swamp. While this increased loss can probably not be entirely recovered, it is expected to be substantially reduced.

**Sedimentation of Lake Mead**

On Feb. 1, 1935, the gates to the outlet tunnels of Hoover Dam were closed and the reservoir, later named Lake Mead, began to fill. The question of what would happen to the enormous silt mass, over 200,000,000 tons a year, which would enter the reservoir from the upper river, had been given some thought in the design of the dam. A silt storage space at the bottom of the reservoir, below the elevation of the sills of the lowest outlet gates, had been provided. Its volume at the time the gates were closed was 3,200,000 acre-feet. Since this space occupied the lowest portion of the reservoir next to the dam, it was recognized that probably only a part of the total load entering the reservoir would find its way through the lake to the space provided. The mechanics of formation of deltas where sediment-laden streams enter natural lakes of course was known. It was also known that similar deltas would form in artificial lakes, and such had been observed at the head of Elephant Butte reservoir. What was not known was how much of the silt mass would be deposited as a delta, how much would travel farther into the

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reservoir, and what would be the manner of transportation of that material. Another unknown was the volume which would be occupied by the incoming sediment, in that the weight only was determined at the Grand Canyon Station, located some 150 miles upstream from the head of the reservoir and considered representative of the total inflow.

The appearance for a brief period of muddy water coming through the tunnel outlets of Hoover Dam in September and October of 1935, after the lake had reached considerable size, and density current observations made at the laboratories of the California Institute of Technology, led to the desire for exploration of the conditions in Lake Mead so as to determine whether density currents possibly did occur in a lake of that magnitude.

In 1937 the National Research Council established a Committee on Density Currents, which in turn created a Subcommittee on Lake Mead, charged with the duties of obtaining density current data on the lake. With the cooperation of the Bureau of Reclamation, the major portion of these data was obtained during the years 1937 to 1940 and the work was continued at a reduced scale to the present time. The results were embodied in a report by the Subcommittee, published by the Bureau of Reclamation, and entitled, "Lake Mead Density Currents Investigations, 1937-1946" — 3 volumes. Subsequent data can be found in "Report of River Control Work and Investigations — Lower Colorado River — Calendar Years 1948 and 1949." It was established that at times substantial portions of the inflow into Lake Mead traveled along the bottom of the reservoir, following the old river bed, finally becoming dissipated at the face of the dam. It was also disclosed that silt depositions, reaching a depth in excess of one hundred feet, had accumulated immediately upstream from the dam. These deposits could have been made only by density currents.

So as to explore further the deposition of the sediment in the reservoir, to determine its volume, and to make a substantiated prediction of the life of the reservoir, a comprehensive sedimentation survey was initiated in 1947 as a cooperative undertaking by the Bureau of Reclamation, the Geological Survey, and the Navy. The results of the survey indicated that the approximately two billion tons of silt, which had entered the reservoir from the time the outlet gates were closed, occupied a space of approximately 1,425,000 acre-feet, corresponding roughly to an average unit weight of 64.8
pounds per cubic foot. The greatest depth of silt deposit was found at the upper reaches of the reservoir, far above the silt pocket provided when the dam was designed and thus within the useful operating volume of the lake. The maximum depth was 270 feet. Below the typical delta formation at the upper end of the reservoir, deposits 45 to 160 feet thick were found the entire distance from the head of the reservoir to the dam. Only 42 percent of the total volume had been deposited within the designated silt pocket below the lowest outlet gates. On the basis of the unit weight of the deposited silt, and taking into account the further consolidation of the silt mass, as additional layers are placed on top, it is estimated that almost 500 years will elapse before all storage capacity of the lake has been lost. The useful capacity of the lake, however, will have been reduced to an embarrassing extent much before that time; but it may be assumed with confidence that other storage works will be constructed upstream from Hoover Dam long before the operating volume of Lake Mead is reduced to any important extent.

CONCLUSION

The concerted program, here described, of measurements, investigations, remedial constructions, and reasoning, all dealing with the problems arising from the interference by man with the regimen of a silt-carrying river, is perhaps unique in the United States. Important facets of the problems which should have been investigated may have been missed and false starts have been inevitable in the remedial work. But it should be kept in mind that river engineering is not as yet a precise science such as, for instance, bridge building and dam construction. No specific remedy to a situation as complex as the one here considered can be expected to be completely successful. River control is largely a problem of unceasing vigilance and continued maintenance. Those responsible for the control measures must be prepared for disappointments, while those whose responsibility it is to make funds available must be prepared to meet continued needs.

DISCUSSION

In leading the discussion Mr. Boyer complimented the author and the Bureau on the forthright and intensive manner in which they have conducted their investigations of the several phases of sediment movement in the Colorado River. He expressed particular interest in the armoring of the bed through removal of the finer
particles. This same phenomenon was observed along the Schuylkill River in Pennsylvania, where the sediment is a mixture of several materials, including anthracite coal, shale, clays, silts, and quartz sands and gravels. The river bed was found to have become effectively armored by a shingling of the slate particles and the gravels and that a considerable increase in discharge was required to produce movement. When movement did begin, the finer materials under the shingling were carried off in a rush.

Reference to the armoring of the river bed evoked considerable comment. Several photographs were shown by Mr. A. S. Harrison of the process by which a pavement or armored layer developed, taken during experiments on river-bed degradation at the University of California in 1950. The nucleus of a pavement probably is always present even in an equilibrium bed where no degradation has taken place. In a normal river bed, particles which are too large to be transported at ordinary discharges tend to segregate out of the bed material near the surface and accumulate in a layer beneath that part of the bed which actively participates in the transport. Figure 15 shows the movable bed in a flume after the establishment of an equilibrium rate of transport; 1.6 percent of the bed mixture, consisting of particles too large to be transported, segregated from the moving material and accumulated in a layer beneath the bars. Part of this layer is exposed at the foot of the bar in the foreground. Figure 16 shows a portion of the top of this layer exposed by removing very carefully the bar material which covered it.

**Fig. 15. Movable Bed in a Flume After Establishment of Equilibrium Rate of Transport.**
If the bed is allowed to degrade, an increasing number of non-moving particles will accumulate in the coarse layer which begins to inhibit the transport of movable bed material and the bars will begin to disappear as in Fig. 17. Finally, enough non-moving particles will accumulate on the bed surface to prevent entirely the scouring from the bed and the transport of the movable bed material beneath. A typical pavement or armored layer is shown in Fig. 17.

**Fig. 16. Part of the Movable Bed with Bar Material Removed.**

**Fig. 17. Movable Bed in a Flume after Bars Have Begun to Disappear.**

http://ir.uiowa.edu/uisie/34
Mr. Lane stated that the Colorado River Project was one of his first introductions to sediment work and it was one of the most complex. He also commented on shingling, pointing out that while it was realized that shingling would take place, no one was sure how long it would take or what would be its extent. They had no way of predicting how fast the finer material would be removed or to what depth, or what would be the size and distribution of the coarser materials which would be left behind.

Mr. Mitchell raised the question as to the effect of floods entering the Mohave Valley from the side, carrying large quantities of very heavy detritus with them. He was particularly interested in determining if these side flows were the cause of the gradual raising of the river through this valley. He made reference also to the Sacramento Wash, which enters the lower end of Needles Valley.

Mr. Baines wished to know if the river in the region just below Hoover Dam, which has degraded approximately 24 feet, widened appreciably. Secondly, he was interested in the shingling, inquiring whether it occurred on a smooth bed or on a bed where there were dunes. It had been his experience that if dunes form shingling is likely to occur.
In reply to Mr. Mitchell's inquiry, Mr. Vetter stated that the Sacramento Wash, which flows into the river at the lower end of the valley, has a fan of debris in the river at its outlet, but there is no riffle over this fan and it was doubted that this debris fan contributed much to the valley's rise. There is another wash which enters the valley, and gravel deposits some distance downstream in the river have undoubtedly come from that wash. There is historical evidence of floods in the first of the washes referred to, but no very good records of the second. There is some doubt that it has contributed.

In reply to Mr. Baines, Mr. Vetter stated that the river did not widen below Hoover Dam as it is in a canyon section. With regard to the shingling, it was not observed where there were sand bars. Shingling was found mainly on surfaces which have been relatively untouched by flow for some time. Once shingling has formed, it will remain untouched until a cloudburst or large flood passes over it.

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