SEDIMENT PROBLEMS
OF THE
LOWER COLORADO RIVER

By Whitney M. Borland and Carl R. Miller
Hydraulic Engineers, Commissioner's Office
Bureau of Reclamation
Denver, Colorado

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by
Whitney M. Borland, M. ASCE
Carl R. Miller, A.M. ASCE

SYNOPSIS

The control of a river to serve the purposes of man alters the river regime and thereby creates a number of varied problems. Closure of Hoover Dam on the Lower Colorado River and subsequent construction of other major structures downstream instigated a series of river adjustments that have required corrective or protective measures. In this paper some of the major problems that have been encountered are pointed out, methods of rectification and design considerations are discussed, and some of the results that have been obtained are given. Also some probable future river problems are briefly examined.

Introduction

There are many interests to be considered in any river control work in the Lower Colorado River basin. State and Federal fish and wildlife agencies, boundary commissions, recreation advocates, adjoining property owners, and others have a vital interest in the river and its use. In this paper we will not attempt to elaborate on the ramifications of each of the interested agencies, but rather we will restrict the material to the technical considerations involved in the carrying out of river control operations by the Bureau of Reclamation. In the planning of river control work, all factors and interests involved are duly considered, and the plan, when evolved, is one that includes the various river uses and the best engineering plan for present and future river operation.

Engineers associated with the planning of the Boulder Canyon Project, of which Hoover Dam is a major feature, realized that extensive changes in river regime would occur in the more than 300 miles of river channel, reaching to the Gulf of California, with closure of Hoover Dam. (Figure 1.) However, the details of these changes and the introduction of new problems could not have been fully anticipated.

Estimates based on available information and data collected prior to closure of Hoover Dam indicated that the average sediment load being transported past the dam site was in excess of 160,000,000 tons or 103,000 acre-feet annually. A resurvey of Lake Mead, in 1948, and subsequent

1/Head, Sedimentation Section, Hydrology Branch, Division of Project Investigations, Bureau of Reclamation, Denver, Colorado.

2/Assistant Head, Sedimentation Section, Hydrology Branch, Division of Project Investigations, Bureau of Reclamation, Denver, Colorado.
sediment measurements at the Grand Canyon gaging station, have confirmed this estimate. Trapping this amount of material in Lake Mead and releasing reregulated clear water to the channel downstream was certain to mark the initiation of a cycle of river channel alterations. These alterations, assisted by the later completion of Davis (1950), Parker (1938), and Imperial (1943) Dams, have extended from Hoover Dam to the Gulf of California. Public Law No. 469 enacted by Congress in 1946, established the framework, under which the study, planning, and control of the Lower Colorado could be accomplished.

History

Prior to construction of Hoover Dam, the river moved uncontrolled through deep canyons and wide alluvial valleys. Rampaging floods occurred in the springtime as the mountains gave up their snow mantle, but the river became a relative trickle in the late fall months. The sands and silts in the canyon bed and alluvial fill in flood plains were alternately shifted, washed out, and replenished as the millions of tons of material moved on to the gulf. It is significant to note that the bulk of the water and sediment carried by the Colorado River is derived from the drainage area above Hoover Dam. Below Hoover, the river flows through desert terrain where the only water and sediment reaching the river is derived from erratic, high intensity summer storms. In the valley flood plains, the river meandered and changed course frequently, destroying a parcel of land in one place and creating new land in another. During low runoff years, the valley areas suffered from lack of water, while during channel flushing high runoff years, the suffering resulted from floods. Historical accounts of the fickle nature of the untamed Colorado River are numerous. (1). Figure 2 illustrates the control of the Lower Colorado River effected by Hoover Dam.

Lake Mead Sedimentation

As mentioned previously, the sediment load of the Colorado River, as it enters Lake Mead, averages about 103,000 acre-feet annually. This extremely large sediment inflow has given rise to the belief by many that Lake Mead would lose its usefulness in a relatively short period of time. This is certainly far from the truth. Although the sediment inflow is large, the reservoir capacity is also large, and therefore, the annual capacity loss is not abnormal. At the present rate of sediment inflow, the 31,250,000 acre-foot original capacity of Lake Mead would be reduced to a negligible amount in about 300 years, not considering additional life which may be added due to compaction of deposits and deposition above spillway crest elevation. However, with closure of Glen Canyon Dam, now under construction upstream, studies indicate the future sediment inflow to Lake Mead will be only one fourth of the present rate, and the life of Lake Mead will be extended beyond 1,000 years. The life of Lake Mead can be expected to be prolonged even further with construction of additional dams and reservoirs between Glen Canyon Dam and Lake Mead on the main stem of the Colorado River and on the sediment carrying tributaries, such as the Little Colorado and Paria Rivers.
Available Data

Data available in the Lower Colorado River basin that can be utilized in the determination of existing conditions, and in planning of river rectification work include:

a. River cross sections extending from Hoover Dam to the International Boundary. These are spaced approximately 1.2 miles apart and have been rerun at regular intervals since Hoover Dam closure. Results of these sections are summarized in Table 1. Cross sectioning is now being done by use of echo-sounding equipment where feasible.

b. Sediment sampling at several locations. Suspended sampling was initiated at Yuma in 1911, and at Imperial Dam and Red Cloud (near Taylor's Ferry) in 1933. A detailed periodic total load sampling program was initiated in 1955 to aid in the design of river channelization work. Total sediment load is presently being determined by the Modified Einstein Procedure (2). Sampling under the current program is being accomplished by the Equal-transit-rate method (ETR). This type of sampling gives a better evaluation of the movement taking place, since it involves the collection of a sample at 25 verticals, which are composited for analysis. The results of these samples are shown on Table 2. Average size analysis of suspended and bed materials for the total load stations are shown in Figure 3. Information obtained includes the sediment load at Needles, California, the inflow to Topock Gorge and Lake Havasu, and the movement into and through the Cibola Valley. Whereas the river cross sectioning gives information on general river aggradation and degradation, the detailed sampling gives information on the movement past a specific point, and values that can be used in river shape determination equations and relationships.

c. Bed material samples have been collected in conjunction with the river cross sectioning and with the total transport determinations. (Figure 3.)

d. Water discharge records are available at several strategic locations throughout the river reach involved.

For details on the sediment sampling, bed material sampling, river cross sectioning, and river discharge, reference is made to publications such as the U. S. Geological Survey Water Supply papers, and reports on River Control Work and Investigations (3)(4).

Scope of Current River Rectification

Until recent years, the river rectification work carried out was of an emergency nature to alleviate the immediate problems. Examples are the channelization below Needles, California, in 1943, to lower the rising river level; channel cutoffs in the Cibola Valley below Blythe, California, to lower river water surface at the Palo Verde Irrigation District outfall drain; and a cutoff above Yuma to move the flow of the river away from an airstrip that
was being damaged by bank erosion. Current and proposed river channelization and control work is now more comprehensive in nature. Conditions are analyzed between major channel structures and the work plan between these structures includes an evaluation of all current and future conditions in that river reach. There are three basic reaches involved in this comprehensive study approach:

a. Davis Dam to Parker Dam (Lake Havasu)

b. Parker Dam to Imperial Dam

c. Imperial Dam to the International Boundary

Note that the reach between Hoover Dam and Davis Dam (Lake Mohave) is not included, since Davis Dam backs water to Hoover Dam and the whole reach is in a canyon. For purpose of economic evaluation, the Parker to Imperial Dams reach has been broken in two subreaches (1) Parker to Palo Verde Dam, and (2) Palo Verde to Imperial Dam.

Aggradation and Degradation

The clear water released from Hoover, Davis, and Parker Dams has resulted in scour of the riverbed and bank materials in the channel below the dam with resultant aggradation in the backwater reaches of the next structure downstream. General degradation and aggradation are illustrated in Figure 4.

This scour and fill of the river alluvium results in a lowering of water surface in one location and a rise in water surface in another location. In intermediate reaches an unstable, braided-type channel develops, which attacks the vulnerable banks. Degradation introduces a continual supply of sediment to the downstream aggradation areas, and results in deterioration of riverbanks and bed. Aggradation results in a rise in river water surface and ground water surface, growth of phreatophytes, and wide alluvial deposit areas. As has been discussed previously, the bulk of the sediment movement in the Lower Colorado River (since closure of Hoover Dam) is derived from the riverbed and banks. This is important in the planning of river rectification work because if this attack on the bed and banks can be brought under control, a stable condition will eventually develop. This is the aim of the present river control and rectification work and planning program being carried out by the Bureau of Reclamation.

River Control and Rectification Program

Probably the best way to discuss the program for river control and rectification in the Lower Colorado River is to begin at Hoover Dam and work downstream, examining each problem area in turn, pointing out the studies and analysis made, the design considerations, construction program, and
results obtained. The discussion is confined to the major problems and problem areas. Many localized-type problems, associated with the operation of the river, are continually developing within the major problem reaches.

Davis Dam to Lake Havasu

With closure of Hoover Dam in 1935, and subsequent closure of Davis Dam in 1950, a degradation cycle began in the river downstream. Much of the material scoured from the river channel deposited in the lower Mohave Valley near Needles. This lower valley was historically an aggrading reach, caused in part by the constriction as the river entered the Topock Gorge. The conditions were aggravated by the closure of Parker Dam in 1938, and subsequent filling of Lake Havasu which created a backwater extending through the Topock Gorge. The aggradation in the area above Topock raised the river water surface elevation and ground water elevation to a point that endangered the town of Needles. In 1946, emergency legislation by the Congress enabled the Bureau of Reclamation to purchase a dredge for the purpose of constructing a channel that would lower the water surface in the Needles area. The dredge purchased was a 20-inch cutter head type and has a design capacity of 500 cubic yards per hour and can move 1,300 cubic yards per hour under favorable conditions. The emergency channel constructed was 200 to 400 feet wide and banks were riprapped as necessary. This channel was completed in 1953 and an immediate lowering in water surface of 5 feet was realized in the Needles area.

Although this emergency channel work alleviated the situation, it was realized that the effect would be only temporary because the source of materials, the broad Mohave Valley, was still contributing material to the Needles-Topock reach at an unabated rate. Further, the supply of material in the Mohave Valley, estimated at 112,000,000 cubic yards, was sufficient to continue the sediment inflow for many years. The permanent solution became obvious. The river had to be confined in a controlled channel from Davis Dam to the mouth of Topock Gorge, a distance of about 43 river miles. Actually, because the river is confined in a well armored channel from Davis Dam to Big Bend, a distance of about 10 miles, channelization length requirement was reduced to 33 river miles. To arrive at a comprehensive plan for a stable controlled channel some specific information and data on existing conditions had to be obtained. Deep bed material sampling was accomplished by use of a "sand-bucket" and/or auger which were driven 10 feet maximum depth or to refusal. Samples were retained for various depths and the variation in material size with depth was established. The total sediment load above Needles, at Needles, and in the Topock Gorge was determined by use of the Modified Einstein Procedure (2). A dominant discharge of 15,000 cfs was determined from an analysis of Hoover and Davis Dam releases and a flood potential of 50,000 cfs from Davis Dam to Piute Wash and 70,000 from there to Topock was computed for use in levee design.

Since the sediment load in this reach of the river would, with channel control, decrease with time from an existing value of about 18,000 tons daily to a negligible amount, this factor had to be considered in the channel
design. It is interesting to note that although the sediment concentration at Needles is only about 400 parts per million (mostly fine to medium sand), the tonnage carried is high because of the high discharge. When the channel has been established at design width, and banks have been riprapped as necessary, vertical degradation within the controlled channel can be anticipated. This degradation will cause a turnover of the bed material until a sufficient layer of armoring material is established. Further complicating the design is the daily fluctuation in releases from Davis Dam, which is used for peaking power, and the relatively high stage of Lake Havasu.

With the available data and the above factors in mind the most compatible channel shape and alinement was established. Several available methods were used in the channel design, including relationships and equations developed by Leopold and Maddock (5), Schoklitsch (6), Blench (7), and Lane (8). The results of these relationships and equations as applied to the available data, are shown on Figure 5. Computed roughness values for the channel vary from 0.025 to 0.030. The amount of degradation that could be expected in the design channel width was determined by use of the Schoklitsch equation, competent bottom velocity, and tractive force as applied to the deep bed material sampling results. Through the process of turnover of the bed material, the transportable sizes are scoured and the general channel gradient is flattened. At a certain combination of bed material size, channel gradient, and other hydraulic factors, stability is reached. It was determined that bed stability would occur when a 6-inch armor layer of 4 to 10 mm material was obtained. Scour of 7 to 10 feet was determined for the upper end of the controlled reach reducing to a few feet near Needles. (Figure 6.) The final channel design shape, profile, and alinement is shown in Figure 7. The overall plan, including work accomplished to date, involves the dredging of over 20,000,000 cubic yards of material and placing of about 236,000 cubic yards of riprap. The dredged channel length is about 30 miles and is on a sinuous alinement with average bend radius of 10,000 feet. Radii limitations are 5,700 feet minimum and 16,000 feet maximum.

Construction of the design channel has now progressed to the lower end of Big Bend. The dredge is working upstream on the established alinement with dredge material being used for levee building as required. A channel width of 170 to 400 feet is cut, depending upon material needed for levee construction. One pass of the dredge will create a channel 170 feet wide. Additional widening to design width is accomplished by river action. Riprap is placed on the outside of the bends only, except in reaches with large radii or where other conditions warrant riprapping on both banks. Generally, the riprap is placed on the bank at design width and it falls in place as the channel widens. Riprap gradation is shown in Figure 8. The dredge is moving material at the rate of 14,000 cubic yards daily, working 3 shifts. Channel completion is scheduled for early 1960. Recently the proposed termination point for the channelization was moved downstream a short distance to accommodate objections of local property owners in the vicinity of Bullhead City.

Because the sediment inflow to the Needles area will continue for many years, though at a decreasing rate, it was deemed advisable to acquire
a smaller dredge to maintain the Needles to Topock Channel while the up-
stream channel was being completed and to maintain the completed channel
in future years. A 12-inch cutter head dredge, with a capacity of 300 cubic
yards per hour, was purchased in 1957 for this purpose and is currently
operating in the area above Topock Gorge. This has resulted in some sta-
bilization of the river stage in the gorge and water surface is being main-
tained fairly constant at Needles. A greater length of time will be required
to determine the full results of this program.

During the past year above normal sustained high flows (20,000 to
25,000 cfs) were experienced in the Davis to Lake Havasu reach and designed
channel, where completed, functioned very well. It is anticipated that the
most troublesome factors, under future operation, will probably be gravel
and cobble bars extending into the channel because of flash floods on tribu-
tary arroyos and bar building at cross-overs within the sinuous channel.

A resurvey of the active capacity of Lake Havasu was carried out
in 1956 and results indicate 58,100 acre-feet of capacity has been lost to
sediment between operating elevations of 430 and 450. This represents 15
percent of the original capacity within these elevations. This loss is pri-
marily due to delta development at the upper end of the reservoir. Water
is pumped from Lake Havasu into the Colorado River Aqueduct for the Met-
ropolitan Water District.

With completion of the Davis to Topock channelization a rapid re-
duction in the sediment transport of the river will be realized, thereby de-
creasing the sediment inflow to Lake Havasu to a negligible amount and creat-
ing a controlled water surface in the river at Needles. In addition to these
benefits from the channelization work, a significant amount of water salvage
is accomplished, flood protection is provided, and recreational facilities
are enhanced.

Parker Dam to Palo Verde Diversion Dam

No critical channel problems have developed between Parker Dam
and Palo Verde Diversion Dam--a distance of 65 river miles. However,
river cross sectioning and total sediment transport determinations indicate
that a considerable tonnage of sediment is being derived from this reach.
Preliminary investigations have been carried out to determine type of sur-
fase and deep bed material and general river channel conditions. Indica-
tions are that no immediate channel rectification work is necessary, but it
is evident that because of the sediment contributed by this stretch of the
river to downstream reaches, future work will probably become necessary.
Headgate Rock Diversion Dam, which supplies water to Indian lands, is lo-
cated about 15 miles below Parker Dam.

The first major problem to develop below Parker Dam was at the
headworks of the Palo Verde irrigation works, which is located about 10
miles upstream from the city of Blythe, California. River bed scour at
the canal headworks continued until diversions could not be satisfactorily
made. This lowering of water surface was arrested in 1945 by the construction of a temporary rock weir. Maintaining this weir proved to be a continuous problem. New rock had to be added to replace rock moved on downstream during high river stages. Approximately 190,000 cubic yards of rock were placed in the temporary weir between 1945 and 1956. Authorization was made by Congress in 1954 for construction of a permanent structure a short distance downstream from the temporary weir. This structure, the Palo Verde Diversion Dam, has been completed and has been in operation during the past irrigation season. The temporary rock weir was modified in accordance with the congressional authorization. This requirement for nullification of the effects of the temporary weir involved some detailed study to determine what section should be established and how much rock removal was required to obtain this section. Removal of the rock also constituted a unique problem but the work was accomplished satisfactorily by the contractor.

Associated with the scour problem at the Palo Verde Diversion Headworks was a sediment inflow problem. Sediment diversion to the canal has been heavy over the years—even before construction of upstream storage structures. A desilting basin and dredge have been maintained by the Irrigation District just below the canal. Because the new diversion dam gates and canal headworks can now be manipulated to minimize the sediment intake to the canal, the desilting operations can be curtailed.

Studies made in connection with the permanent diversion structure included water surface profiles upstream and downstream and expected degradation in the downstream channel. Degradation was determined by extension of the trend that was occurring to an ultimate river slope of 1.0 foot per mile at which the bed would stabilize. The upstream water surface profiles were required to determine levee elevation along the Indian lands on the east side of the river. The downstream profiles and degradation studies were required for tailwater determinations and structure design. Ultimate channel degradation of 8 feet, beyond that existing at time of construction of the new structure, is expected.

Palo Verde Diversion Dam to Imperial Diversion Dam

The river channel problems in this reach of the Lower Colorado River are currently being investigated and studied in detail by the Bureau of Reclamation. Problems include bank erosion and channel deterioration between Palo Verde Diversion Dam and Ehrenburg Bridge near Blythe, California; channel aggradation with accompanying drainage, water loss, and channel capacity problems in the Cibola Valley which extends from below Taylor's Ferry to the headwaters of Imperial Reservoir, and aggradation and sediment inflow to Imperial Diversion Dam and headworks. An approximate balance point between aggradation and degradation occurs near the Palo Verde outfall drain in the Cibola Valley. Between Ehrenburg Bridge and Taylor's Ferry, the river is in a relatively stable reach which holds against the east side bluff and has a surface gravel bed in several locations.
Current planning for this stretch of the river is for channel straightening and bank protection in the upper reach and construction of a new channel in the Cibola Valley. In the upper reach, some of the local land owners are placing protective works now to stop bank scour. In the Cibola Valley, several plans are being studied for river rectification. The primary objective of rectification in the Cibola Valley is to create a stable controlled river channel that will require a minimum of future maintenance. Other benefits, such as losses to nonproductive phreatophytes, lowering of water surface at Palo Verde outfall drain, and recreational and fish and wildlife improvement may result incident to this work.

Severe drainage problems were reported in the lower Palo Verde Irrigation District lands because of the aggrading type channel in the Cibola Valley. As was the case upstream at Topock, there is a natural constriction of the river at the lower end of the Cibola Valley near Adobe Ruin. In 1947 a pilot cutoff was made just upstream from the outfall drain to ease the drainage situation. This cut was 1-1/2 miles long and 40 feet wide, and was accomplished by dragline operation. Additional widening was by river action. The work resulted in a lowering of water surface of 1 foot at the mouth of the outfall drain. However, poor drainage and channel deterioration continued. It was concluded that major rectification in the Cibola Valley was needed. The first plan for such rectification was prepared in 1951 (9). Since then, data acquisition has been carried out to aid in correctly evaluating the existing conditions and to aid in formation of a comprehensive plan for rectification.

One of the most interesting and challenging aspects of the river planning and design in the Cibola Valley is the proposed cutoff of 8 to 15 miles in length, depending upon the plan finally selected. A cutoff in the alluvial Cibola Valley deposits must be designed to remain stable with minimum scour upstream and aggradation downstream under existing and future sediment inflow and dominant channel discharge. A dominant discharge of 10,000 cfs has been established from analysis of past and probable future river operation. The sediment inflow to the reach is 10,000 tons daily, as determined from Modified Einstein computations at Taylor's Ferry. Gravel bed elevation below Taylor's Ferry and estimated maximum bed aggradation elevation at Adobe Ruin at the lower end of Cibola Valley must be met.

For the existing bed material and sediment load, it was determined that a channel gradient of 1.2 to 1.3 feet per mile should be used to obtain stability. Since the straight line slope between stations would be considerably more than the 1.2 to 1.3 feet per mile limit, it was evident that a sinuous type of cutoff channel had to be constructed to meet the slope limitations. Previous experience by the Bureau of Reclamation, Corps of Engineers, (10) and others, indicates that the radius for the hydraulic conditions in the sinuous channel should not be less than 5,000 feet.

The design width for the new channel in the Cibola Valley has been tentatively determined as 450 feet maximum by applying the acquired data and information to the Maddock-Leopold (5) and Tractive Force (8) relationships. The results were checked against data from actual field measurements.
at selected stable reaches in the valley. As in the Needles area, the outside of the bends of the constructed sinuous channel would be riprapped. It is interesting to note that unlike the channelization in the Topock to Davis Dam reach, there will be a continuous sediment inflow to the Cibola Valley until channelization is carried out in the Parker Dam to Palo Verde Diversion Dam reach, which presently is not planned. A report is currently in preparation which will present a comprehensive plan, and show benefits to be derived, by river rectification in the river reach between Palo Verde Diversion Dam and Imperial Reservoir.

One of the most widely known and referred to desilting operations is the one at the intake to the All-American Canal at Imperial Diversion Dam. At the right of Imperial Dam, the majority of the river flow is diverted into the All-American Canal which has an initial capacity of 15,150 cfs. Water is also diverted at the left side of the dam to the Gila Gravity Main Canal which has an initial capacity of 2,200 cfs. Water passing the dam is for purposes of river regulation, which is discussed subsequently, and for Mexican Treaty requirements. At the time of construction of Imperial Dam, it was realized that large tonnages of sediment, primarily sand, would be taken into the All-American Canal. Detailed studies, including laboratory models, were undertaken to devise a desilting works that would remove the sediment and return it to the river below the dam. The final desilting work plan consisted of 6 settling basins, arranged in pairs, equipped with 12 rotating vanes or scrapers per basin that flushed the deposited material, as it settled, into sludge pipes that dumped into the Imperial Dam sluiceway channel (11). To date, the desilting has been completely satisfactory as illustrated in Figure 9. Sediment concentrations at Station 60 on the All-American Canal are a very small fraction of the concentrations entering the desilting basins.

The reservoir above Imperial Dam, at the time of closure in 1938, had a capacity of 85,000 acre-feet. This capacity filled with sediment at a rapid rate thereby reducing the reservoir trap efficiency and allowing more sediment to reach the All-American Canal headworks. The present reservoir capacity is only 1,000 acre-feet. The sediment inflow to Imperial Reservoir, will decrease in coming years with upstream river rectification.

In addition to the desilting works, sluicing operations are carried out periodically at Imperial Dam to remove sediment deposits upstream from the All-American Canal headworks structure. Detailed sediment sampling and discharge measurements are made during these sluices to aid in evaluation of the operation and for use in planning downstream river regulation. A desilting and sluice arrangement is also provided at the Gila Gravity Main Canal headworks, but because of the relatively small amount of water diverted, the sediment problem is minor at this point.

The sediment problem will continue at Imperial Dam for many years to come because it is the terminal point for material carried down the river from upstream sources. Data collection and study will continue
by the Bureau of Reclamation to keep a check on conditions and to assist in planning of any future rectification work should such work become necessary.

**Imperial Dam to International Boundary**

Below Imperial Dam, the major problem at present is that of river regulation. River regulation, as referred to here, is the maintaining of a suitable channel that will transport the sediments introduced at Imperial Dam without creating channel deterioration. This is accomplished by the release to the channel downstream of a certain percentage of the water flowing into Imperial Reservoir. Water is released at Hoover Dam in accordance with a weekly master schedule based on requirements of all water users. This schedule can be fluctuated within set limits to meet varying demands throughout the year. Based on studies of sediment data collected at Imperial Dam and at Yuma, some relationships have been established for use in predicting the amount of water needed for river regulation. Typical relationships are shown in Figure 10. These curves are periodically revised to reflect latest data. The water used for river regulation can be the same water released from Imperial Dam to meet Mexican Treaty requirements. When the Imperial Irrigation District so requests, the water not required for river regulation is put into the All-American Canal and returned to the river at the Pilot Knob Powerplant.

With initial closure of Imperial Dam, degradation occurred downstream. This scouring action reverted to aggradation as Imperial Reservoir filled with sediment. Generally, the river channel has not yet recovered to the condition existing upon Imperial Dam closure. With continued demands on the Colorado River water and development of the water uses above Hoover Dam, the water available for river regulation below Imperial Dam will become less and maintaining a suitable river channel will become more difficult. For this reason, new methods of silt control may become necessary, as was predicted in the studies and analyses made of the situation when planning for Imperial Dam and desilting work (11).

It is interesting to note that the total sediment load now passing the Yuma gaging station is only a fraction of that which passed the same point prior to construction of Imperial and Hoover Dams (Figure 11).

About 5 miles below Imperial Dam, there is an old irrigation diversion structure, Laguna Dam, which was built in 1909. The only purpose this structure serves at present, is to provide reregulation of releases from Imperial Dam. Considerable sediment deposition has taken place in the wide river area between the Imperial and Laguna structures.

Below Laguna Dam, the interests of the Bureau of Reclamation and those of the International Boundary Commission, are closely allied. Therefore, the problems in the reach from Laguna Dam to San Luis, Mexico, which is the lower boundary in the limitrophe reach, will not be discussed in any detail. The Bureau of Reclamation's furthest downstream river work has been the rehabilitation of the existing levee system above and below Yuma (12). This levee rehabilitation was necessary to provide adequate protection
against probable floods and raise in water surface resulting from construction of Morelos Diversion Dam, below Yuma, by Mexico. Part of the expense of this levee rehabilitation was borne by Mexico. The work consisted of placing 1,700,000 cubic yards of levee embankment, including riprap as necessary, over a total length of 41 miles. The levees were designed for a flood of 140,000 cfs, which considers Painted Rock Dam controlling much of the Gila River flood potential. Riprap having a usual thickness of 5 feet, was placed at critical locations. Riprap limitations were a maximum size of 1/2 cubic yard and a minimum of 1/10 of a cubic foot in volume.

Two interesting problems near the city of Yuma have resulted in rectification work by the Bureau of Reclamation. At Yuma, another natural constriction of the Colorado River exists. Here, the river is narrowed from a wide valley into a gorge-type opening about 300 feet in width. The area above this constriction is a natural depository for sediment, particularly during high flows when a backwater effect is created. The river course through this depositional area is subject to considerable shifting. The river channel in the early 1950's moved in against the left bank attacking existing low-lying airport lands, immediately north of Yuma. To correct this condition, a pilot cutoff was constructed to change the river course and give it a direct approach to the constricted section. This cutoff involved excavation of 200,000 cubic yards of material, riprapping at the upstream end, and placing of a structure across the old channel to obstruct flow and force it into the pilot cut. Shortly after completion of the cutoff in 1954, the entire flow of the river was flowing through the new channel. This relocated section of channel is continuing to function satisfactorily. Just below the constriction near Yuma, part of the city water supply is pumped from the left bank of the river. During low river flows, considerable difficulty has been experienced in maintaining an open channel from which the water could be pumped. This resulted from the manner in which the low flow channel entered the constricted reach and from bar buildup where the water treatment plant effluent is discharged into the river. To alleviate this situation, some deflection fencing was placed by the Bureau in 1957 under special appropriation by Congress. Immediate improvement was noted, and the severity of the problem was reduced during 1958 by the relatively high flows passing the Yuma area.

Requirements for river rectification and control work in the Imperial Dam to International Boundary reach are likely to continue for many years to come. Collection and analysis of data will continue and a constant vigil will be kept to foresee the development of critical conditions and thereby provide ample opportunity to take necessary action. Exchange of data and cooperation in analyzing conditions will continue with the International Boundary and Water Commission as has been done in the past.

SUMMARY

The construction of Hoover Dam and other structures on the Lower Colorado River has essentially solved the flood problems, created a firm irrigation water supply, and provided a large block of hydro-electro power.
However, these structures did not eliminate the problems of river control, but only changed their character. The channel aggradation and degradation that have occurred with the construction of water diversion and storage facilities have created a series of varied river control problems that require rectification. These river alterations are continuing and rectification needs will continue as long as sediment contributing reaches of the river remain uncontrolled.

Rectification work, and planning for such work, is in various stages of development. In the river reach between Davis Dam and Topock, channel dredging is underway to create a new fully controlled channel. Work in this reach is 85 percent completed. The channel has been designed to be compatible with existing and future sediment load, bed material, discharge, and hydraulic factors. In the Palo Verde Diversion Dam to Imperial Diversion Dam reach, studies are currently underway and a report will be made soon presenting a plan for river rectification. The plan will probably involve bank control, channel straightening and realignment, and a substantial cutoff channel in the Cibola Valley. Downstream from Imperial Dam, sediment and hydraulic data are being collected and studies and analyses carried out for the purpose of determining river regulation water requirements and to provide a constant check on river channel developments. Various items of river rectification work are carried out as required within these major river reaches to correct a localized channel problem.

Sediment movement and hydraulic data are collected on a regular basis at strategic locations throughout the lower Colorado River basin. Results and analysis of these data are published by the Bureau of Reclamation (3)(4). Total sediment transport sampling stations are established or dropped as required by the detailed study program.

Since the river channel aggradation and degradation results from a shuffling and reshuffling of river bed and bank materials above and below major structures, planning and design for river rectification is aimed at obtaining eventual complete control between these major control points. Since any work must be justified on the basis of benefits to be received, it is not possible to carry out a complete construction program between major structures, but rather work must be concentrated on reaches or sections where benefits will justify the rectification costs. However, this intermediate type work is planned as an integral part of the overall river control program.

River rectification work generally involves straightening, realignment, cutoffs, riprapping, training structures, and levees, the method used in each case being decided on the basis of existing and probable future conditions. Improvement in methods of control are constantly being made on the basis of experience gained on work accomplished so far and analysis of newly collected sediment, hydraulic, and hydrologic data. Present indications are that future needs for river rectification will be in the Palo Verde Diversion Dam to International Boundary reach, the most urgent need at present being in the Cibola Valley.
Looking into the future it is conceivable that the Colorado River will eventually become fully controlled from Hoover Dam to the International Boundary. With increased population trends in this region of the United States, it can be expected that the water resource, including the recreational potential along this 300 miles of river, will be utilized at an ever increasing rate. A fully controlled river will allow the most complete use of the available water for the combined benefit of all interests in the lower Colorado River Basin.

ACKNOWLEDGEMENTS

The authors wish to express their appreciation to Mr. A. L. Mitchell, River Control Engineer, Boulder City, Nevada, and Mr. Paul Oliver, Project Manager, Needles, California, both of the Bureau of Reclamation, for their cooperation and contributions to this paper.
REFERENCES


<table>
<thead>
<tr>
<th>River Reach</th>
<th>Period</th>
<th>River Miles</th>
<th>Quantities (1000 cu yds)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>2/</td>
<td></td>
</tr>
<tr>
<td>Hoover Dam to Lake</td>
<td>1935</td>
<td>0 - 12.2</td>
<td>- 10,402</td>
</tr>
<tr>
<td>Havasu</td>
<td>to 1951</td>
<td>12.2 - 25.6</td>
<td>- 13,671</td>
</tr>
<tr>
<td></td>
<td></td>
<td>25.6 - 42.7</td>
<td>- 25,716</td>
</tr>
<tr>
<td></td>
<td></td>
<td>42.7 - 64.2</td>
<td>- 48,125</td>
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<td>64.2 - 82.9</td>
<td>- 39,515</td>
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<td>82.9 - 91.8</td>
<td>- 14,401</td>
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<td></td>
<td>91.8 - 98.0</td>
<td>+ 8,281</td>
</tr>
<tr>
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<td>98.0 - 111.8</td>
<td>+ 94,737</td>
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<td>111.8 - 119.4</td>
<td>+ 4,304</td>
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<tr>
<td>Davis Dam to Lake</td>
<td>1951</td>
<td>0 - 5.7</td>
<td>- 2,597</td>
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<tr>
<td>Havasu</td>
<td>to 1956</td>
<td>5.7 - 10.9</td>
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<td>10.9 - 25.3</td>
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<td>25.3 - 30.6</td>
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<td>30.6 - 42.7</td>
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<td>42.7 - 53.9</td>
<td>+ 4,495</td>
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<tr>
<td>Parker Dam to Imperial Dam</td>
<td>1937</td>
<td>0 - 86</td>
<td>- 190,100</td>
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<tr>
<td>to Imperial Dam</td>
<td>1956</td>
<td>86 - 147</td>
<td>+ 148,970</td>
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</tbody>
</table>

2/ River miles below Hoover Dam.
3/ River miles below Davis Dam.
4/ River miles below Parker Dam.
5/ Determined from river cross sections and total sediment transport computations.
### TABLE 2

**SUMMARY OF AVERAGE YEARLY TOTAL SEDIMENT LOAD SINCE CLOSURE OF DAVIS DAM**

<table>
<thead>
<tr>
<th>River Reach</th>
<th>Station</th>
<th>Average Yearly Total Sediment Load (Tons)</th>
<th>Average Yearly Water Discharge (Ac. Ft.)</th>
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</thead>
<tbody>
<tr>
<td>Davis Dam to Parker Dam</td>
<td>R. S. 33</td>
<td>7,234,000</td>
<td>10,319,000</td>
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<tr>
<td></td>
<td>Below Needles Bridge</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>R. S. 41</td>
<td>6,804,000</td>
<td>10,319,000</td>
</tr>
<tr>
<td></td>
<td>R. S. 43</td>
<td>4,791,000</td>
<td>10,319,000</td>
</tr>
<tr>
<td>Parker Dam to Imperial Dam</td>
<td>Below Palo Verde Weir</td>
<td>2,867,000</td>
<td>8,882,000</td>
</tr>
<tr>
<td></td>
<td>Taylor's Ferry</td>
<td>3,646,000</td>
<td>8,882,000</td>
</tr>
</tbody>
</table>

1/ Based on flow-duration, sediment rating curve analysis.
3/ Davis to Parker reach based on flow-duration curve for U. S. G. S. station near Topock, Arizona, for calendar years 1950-56. Parker to Imperial reach based on flow-duration curve for U. S. B. R. station estimated daily flows at Taylor's Ferry for calendar years 1951-56.
MONTHLY HYDROGRAPH OF COLORADO RIVER FLOWS AT TOPOCK, ARIZ.

1920-1949
NOTE - Degradation below Hoover Dam at Willow Beach was about 14 feet between 1935 and 1949.

REF. - Report of river control and investigations, Nov. 1957.

- Near Picacho above Imperial Dam (125.2 Mi. below Parker Dam)
- Between Palo Verde weir and Blythe Calif. (64.5 Mi. below Parker Dam)
- Topoc bridge above Lake Havasu
- -0.9 Mi. below Davis Dam
- 28.5 Mi. below Imperial Dam
- 17.4 Mi. below Parker Dam

AGGRADATION - DEGRADATION AT VARIOUS LOCATIONS LOWER COLORADO RIVER

DAM CLOSURE DATES
- Hoover - 1935
- Davis - 1950
- Parker - 1938
- Imperial - 1943

FIGURE 4
Note:
Widths shown are for Negligible Sediment in Transport

Maddock-Leopold with Tractive Force

Schoklitsch

q = 15,000 c.f.s.
n = 0.03
s = 0.00025

COLORADO RIVER CHANNEL STUDIES

FIGURE 5
COLORADO RIVER CHANNELIZATION
BIG BEND TO NEEDLES

NOTE: Probable limit of channel degradation below dredged channel grade as indicated by armor of stabilizing material.
Depth of scour estimated at D.H. No. 4

TRANITION

S = 0.00028 (1.5 ft./mi.)

S = 0.0002 (1.0 ft./mi.)

- 6 Inch armor - 4 mm size
- 6 Inch armor - 10 mm size

Approximate ultimate channel grade after degradation

Proposed dredge channel grade

Drill Holes

M.W.D. Gage - Needles

ELEVATION - FEET

CHANNEL STATION

2000 1900 1800 1700 1600 1500 1400 1300 1200 1100 1000 900 800 700

5 7 11 13 14 16 18 20 21A 23 22 2 3 4 1

6 9 12 15 17 19 21A 24 25 2 3 4 1
COLORADO RIVER CHANNELIZATION
BIG BEND TO TOPOCK, ARIZ.

ARIZONA
L.B.

CALIF.
R.B.

FLOW

10' = 70,000 c.f.s.
6' = 50,000 c.f.s.

n = 0.025
s = .00025

Ave. Bed Material

D_50 = 0.3 mm (Initial)
D_50 = 4.0 mm (Ultimate)

n = 0.025
s = .00025

625'

Rock Protection
where needed

Mohave City

NEVADA \\

NEVADA
CALIFORNIA

MOHAVE VALLEY

NEEDLES

Rectified
Channel
Alinement

CALIFORNIA

TOPOCK BRIDGE

ST A 264+00

ST A 228+00

ST A 205+00

ST A 173+00

FIGURE 7
NOTE
Based on 1/4 cu. yd. max. size and 1/10 cu. ft. min. size mean diameter computed from $4/3 \pi r^3$
Graduation fluctuates with quarry type and operation.

5% Rock fragments and dust allowable
Min. size limit (Approx. 7 in.)
Max. size limit (Approx. 28 in.)

APPROXIMATE GRADATION RIPRAP
COLORADO RIVER CHANNELIZATION
BIG BEND TO NEEDLES

FIGURE 8
NOTE: Lag time between Taylors Ferry and diversion to All American Canal considered as two days.

Data for days of total load sampling at Taylors Ferry 1955-1958

RELATIONSHIP BETWEEN TOTAL SEDIMENT CONCENTRATION FOR INFLOW TO IMPERIAL DAM AND AT STATION 60 ON ALL AMERICAN CANAL

FIGURE 9
DATA FROM SLUICING MEASUREMENTS AT IMPERIAL DAM AND AT YUMA 1955-57

MONTHLY DISCHARGE ENTERING IMPERIAL (1000 A.F.)

MONhLY DISCHARGE PASSING YUMA (1000 A.F.)

+ Indicates degradation
- Indicates aggradation

Plotted values in 1000 tons of sediment aggraded or degraded from channel.
ANNUAL SUSPENDED SEDIMENT LOAD
YUMA GAGING STATION
LOWER COLORADO RIVER CALENDER YEARS-1911-1954

Since closure of Hoover and Imperial Dams

Prior to closure of Hoover and Imperial Dams.

Hoover Dam closed 1935
Imperial Dam closed 1938