Comprehensive Survey of Sedimentation in Lake Mead, 1948-49

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D. DRAINAGE BASIN TRIBUTARY TO LAKE MEAD

By H. E. Thomas, U.S. Geological Survey

Lake Mead is in the Lower Colorado River Basin, as defined in the Colorado River Compact of 1922.¹ Hoover Dam is about 354 miles downstream from Lee Ferry, which is the Compact point marking the lower limit of the Upper Colorado River Basin. The Lower Basin, however, provides only a very small proportion of the water that flows into Lake Mead; these contributions come from the Little Colorado River, the Virgin River, small perennial or ephemeral creeks, and some fairly large springs in northern Arizona. In an average year about 95 percent of the inflow to Lake Mead comes from the Upper Basin. Thus the water that accumulates in Lake Mead comes from an area that extends far beyond the limits of the area encompassed by the reservoir survey of 1948-49. Basic water data collected by the Geological Survey in cooperation with the States of Arizona, Colorado, Nevada, New Mexico, Utah, and Wyoming constitute a broad general outline of the hydrologic conditions in that large tributary area, but they are far from adequate for comprehensive planning of water-resource development above Lake Mead. This section summarizes these existing data and provides a background of information as to the source of the water and sediment in Lake Mead.

The part of the Colorado River drainage basin tributary to Lake Mead comprises about 168,000 square miles, or 5 percent of the continental area of the United States. If this vast area has one characteristic in common, it is perhaps the lack of hospitality to mankind. Very little of the area is desirable for habitation, and the lands occupied by the basin are accordingly among the least populated parts of Colorado, Wyoming, Utah, New Mexico, and Arizona.

The basin has a greater range in physical characteristics than is to be found in most other areas of comparable size on the North American continent. Physiographically, it includes several of the highest peaks of the Rocky Mountains as well as high mountain valleys and broad upland plains, extensive plateaus and spectacular canyons, broad alluvial valleys, and desert ranges. Climatologically, the basin presents the extremes of year-round snow cover and heavy precipitation on the higher peaks of the Rockies, and desert conditions in which annual precipitation is commonly less than 5 inches. The temperature range is from the temperate—as in the mountain meadows of Colorado and Wyoming, where there is a scanty 90-day growing season—to the semitropical—as near Lake Mead, where only occasional winter frosts occur. Geologically, the rocks in the basin are of a wide variety of types, ranging in age from Precambrian to Recent.

As might be expected in a region of such diverse physical characteristics, there are some areas with very high rates of runoff, and other areas that yield practically no water to the Colorado River; also certain areas in which the streams are generally clear, and other areas that are major contributors of the sediment that enters Lake Mead.

PHYSIOGRAPHY

The drainage basin tributary to Lake Mead includes parts of five physiographic provinces as outlined by Fenneman (1930). The easternmost part of that basin is within the Southern Rocky Mountains province, which comprises high mountain ranges and intermontane valleys. Characteristically, this part of the basin receives heavy precipitation, and most of it is covered by forest and alpine flora. Many of the largest streams of the Colorado River system—the Yampa, White, Colorado, Gunnison, Dolores, and San Juan Rivers—rise in this mountainous province.

The northwestern part of the Colorado River basin lies within the Middle Rocky Mountains province. Like the Southern Rockies, this province is composed of high forested mountain ranges and intermontane valleys. Because of its generally higher latitude, the growing season in these valleys is shorter than in valleys of the Southern Rockies, and the annual evaporation rate is less. In this province are the headwaters of the Green River and many of its important tributaries.

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¹ The agreement concerning the apportionment of the use of the waters of the Colorado River System dated November 24, 1922, executed at Santa Fe, N. Mex., by Commissioners for the States of Arizona, California, Colorado, Nevada, New Mexico, Utah, and Wyoming, approved by Herbert Hoover as representative of the United States of America, and proclaimed effective by the President of the United States of America, June 25, 1929.
Between the Middle and Southern Rocky Mountains is the Wyoming Basin, a physiographic province characterized by elevated plains in various stages of erosion, and isolated low mountains. Precipitation is generally less than 20 inches a year, and the basin is classified as semiarid. Most of the streams draining this area are intermittent; they contribute only small quantities of water to the Colorado River system, chiefly during annual freshets.

The central part of the drainage basin tributary to Lake Mead is within the Colorado Plateau province. Some of these plateaus are high and forested, and they receive a moderate amount of precipitation; others are lower canyoned plateaus of high relief; and large areas are rather thoroughly dissected. The precipitation over most of the plateau country is scant. Sonoran types of vegetation—including piñon, sagebrush, and grasses—provide sparse cover, leaving large areas of bare or thinly mantled rock. The streams rising in the plateau country make relatively small annual contributions to the flow of the Colorado River; the Little Colorado River is the largest of these contributors. In drainage basins where steep, barren or sparsely vegetated slopes are prevalent, rainstorms may produce high runoff for short periods. This is particularly true of the southern part of the drainage basin, where intense summer rainstorms may produce flash floods that constitute a substantial proportion of the annual runoff.

The lowest part of the drainage basin tributary to Lake Mead is in the Basin and Range province; the lake itself is almost entirely within this province. The climate here is arid, and the desert mountains and valleys contribute practically no water to the lake except after exceptional rainstorms. Two perennial streams enter Lake Mead within the province: Muddy Creek, which has a sustained flow from springs, and the Virgin River, which derives most of its water from high plateaus and from the Pine Valley Mountains in southwestern Utah.

GEOLoGY

The geology of the drainage basin tributary to Lake Mead is sufficiently diverse that its problems attract specialists in all phases of the earth sciences. Rocks in the area range in age from Precambrian to Recent and in type through a wide assortment of igneous, sedimentary, and metamorphic. Deposits of economic value in the basin include gold, silver, lead, zinc, copper, molybdenum, antimony, vanadium, and uranium; coal, petroleum, natural gas, oil, shale, and rare hydrocarbons; phosphate rock, potash, salt, gypsum, helium, and carbon dioxide; and construction materials. The broad, simple structures and easily recognized strata of the plateau country attract the hobbyist without formal training in geology; yet the complex structures of many of the mountain ranges are brain teasers for the ablest geologists and geophysicists.

The geologic formations of the tributary drainage basin are significantly related to the water and the dissolved and suspended materials that enter Lake Mead. A negligible proportion of the runoff is derived by direct precipitation upon the stream channels. Somewhat larger quantities may result from overland runoff, particularly from bare rock or impervious mantle rock. Most of the runoff is derived from melting of winter accumulations of snow in the higher mountains, but nearly all this water moves for at least a short distance through the soil or underlying ground-water zones before reaching the streams. The quantity of runoff generally is only a minor fraction of the precipitation upon the region and represents the excess of water beyond the requirements for transpiration by plants and for direct evaporation. Pervious rock materials that absorb a large proportion of the precipitation may subsequently be dewatered by evapotranspiration draft or by discharge of ground water to streams. Thus the geology is a significant factor in the precipitation-runoff relations throughout the tributary basin.

The chemical constituents carried by the river are derived in part by solution of rock materials over which the river and its tributaries flow. Thus the Colorado River in its annual flood stages laps against beds of gypsum in Cataract Canyon in southeastern Utah, and some of that rock is dissolved and carried away in the river. Some tributaries likewise flow directly over soluble bedrock, and as a result their waters have a high mineral content—a fact that is suggested by the names given to several small streams in the basin, such as Onion Creek, Salt Wash, Saleratus Wash, and Gypsum Canyon. However, outcrops of soluble bedrock in stream channels occupy a very small proportion of the total channel area, and the quantity of dissolved materials derived from them is also a small fraction of the total dissolved solids carried into Lake Mead.

Most of the dissolved material in the river is derived from ground water. The most obvious sources are saline springs along the main stem and tributary channels, springs rising from limestones or igneous rocks, fault springs, and return flow of irrigation water. Ground water seeping into the river and its tributaries carries a large proportion of the total dissolved solids of the river. Types of rock that are important contributors of dissolved materials include evaporites, shales, and sandstones. These rocks crop out principally in the Colorado Plateaus and the Wyoming Basin.
The geologic formations cropping out within the drainage basin are also the ultimate sources of the sediment carried by the Colorado River and its tributaries. The formations include a great variety of rock types, ranging from highly indurated to loosely cemented or unconsolidated rocks. Individual sedimentary formations commonly include a wide range in textures, both horizontally and vertically. A thorough appraisal of the sediment-producing characteristics of any part of the basin would require detailed geologic mapping of those formations and, in addition, mapping in corresponding detail of the soil or mantle conditions, the vegetative cover, and the topography. Such mapping has not yet been completed for any major part of the Colorado River basin.

A rough comparison of the sediment-producing capabilities of various parts of the basin may be made on the basis of the generalized outcrop areas as shown on the geologic map of the United States. Extensive areas, especially near the boundaries of the basin, are underlain by indurated rocks that are resistant to erosion. For the most part these rocks form the mountain ranges and are of Paleozoic age or older. However, there are also extensive areas of volcanic rocks, including some that are remote from mountainous areas, which are for the most part of Tertiary or Quaternary age. Generally the streams rising in these areas are fairly free of sediment at all seasons. The rocks most common to the areas that produce relatively clear water are crystalline and metamorphic types, lavas, limestones, and well-cemented sandstones and conglomerates.

Much of the drainage basin in the Colorado Plateau, and nearly all of the Wyoming Basin, is underlain by shale, mudstone, and clay—rocks which upon weathering yield predominantly silt- and clay-sized particles. The silt-producing formations are chiefly of Mesozoic and Tertiary age. The Little Colorado, San Rafael, and Dirty Devil Rivers drain basins in which fine textured materials predominate.

A classification of the drainage basin according to capabilities of producing sediments, as inferred from geologic maps, is presented in figure 4. Although the rock outcrops and the mantle rock formed from them constitute the ultimate source of the sediment load carried by the river, it is likely that only an insignificant part of the load comes directly from those sources. Indeed, the main stream and tributaries rarely come in contact with bedrock except in their headwaters, and instead the bed and banks of the channels are formed of stream-borne sediment, or alluvium. Geologic reconnaissances show that the area covered by alluvium is only a very small proportion of the total area of the basin, but that, rather generally throughout the basin, the river and its tributaries are cutting both downward and laterally into the alluvial deposits of past centuries. These alluvial deposits are believed to constitute the immediate source of much of the sediment now moving toward Lake Mead.

**WATER**

The Colorado River is most impressive in its canyons below the mouth of the San Juan River—in Glen Canyon, or in Marble Canyon or Grand Canyon where tourists most commonly view it. Viewed from the rim of one of these canyons, the river is a thin ribbon of water that is dwarfed by the massiveness of the setting.

The great plateau country of northern Arizona and southeastern Utah provides a scenic environment and much sediment for the river, but little more. Of the water that enters Lake Mead, only slightly more than 5 percent is contributed by the small streams of Arizona, Nevada, New Mexico, and southern Utah. All the rest comes from Colorado, Wyoming, and northern Utah by way of the main stem of the river or its principal tributaries. Indeed, more than three-fourths of the annual inflow to Lake Mead is derived from the high headwater areas of streams that rise in the numerous ranges of the Rocky Mountain chain.

For the most part the arid plateau land contributes only enough water to the river to offset the rather sizable losses from the river due to evaporation and transpiration. Along extended segments of the river there is practically no inflow during most of the year, and because of the evapotranspiration draft the river passes through those reaches with a net loss during most of the year.

The sources of the inflow to Lake Mead during the 1948 water year are shown graphically in figure 5. It is evident from this diagram that the main stem of the Colorado in Utah and Arizona, as well as the channel of the Green River below the Uinta Basin and the channel of the San Juan River below the mouth of the Animas River, serve principally as conduits for water that has originated in headwater areas to the north and east.

The concentration and chemical character of dissolved solids in the streams vary considerably throughout the year. As a rule the concentration is greatest during periods of low flow and least during flood periods. Howard (1948) has shown that there is a progressive downstream increase in concentration of dissolved solids both in the Colorado River and in its principal tributaries. These increases are caused chiefly by natural ground-water inflow and by return water from agricultural and industrial developments. Large increases are recorded, for example, in a short reach of the river near Grand Junction, Colo., where
there is considerable return flow of irrigation water to the stream.

SEDIMENT

Historically the sediment has always been a conspicuous feature of the Colorado River, as indicated by the name "colored river", first applied by the early Spanish explorers. At all times the observer is likely to be impressed by the murkiness of the water of the main stem and its principal tributaries—generally tawny brown, perhaps reddish or grayish, but characteristically muddy.

The rock materials which the streams have transported and deposited during the latest geologic epoch are classified by geologists as Recent alluvium. This alluvium forms the flood plains that flank the main stems and tributaries along many miles of their courses; it constitutes the islands, bars, and shoals in the river and underlies the river channel. In places where the channel is constricted, the alluvium may be as much as 200 feet thick, as shown by test borings at prospective dam sites. And in the broad valley plains the Recent alluvium may form the surficial material in a belt as much as 3 miles wide.

The ultimate source of the Recent alluvium is the older rock formations of the drainage basin, and the fragments that result from their weathering. Where gradients are steepest—chiefly in the small tributary channels—a stream may flow directly over bedrock for some distance; and in other reaches the channel may be bordered by bedrock walls. In these places the stream itself becomes the eroding agent, and acquires some sediment directly from bedrock. Overland flow over bare or impermeable rock material may also carry sediment into the streams.

It is likely that only a negligible proportion of the sediment in Lake Mead has moved continuously from its original source. Generally the process of sediment transportation is a series of short travels, with intervening deposition and reexcavation. Typically a stream that is eroding along a certain reach will carry some of that sediment only to a reach having lesser gradient, and the sediment remains there until a greater volume of water can carry it farther. The tributaries quite generally have higher gradients than do the main stems, and boulders and blocks that can be moved by those tributaries may come to rest opposite their mouths, in the main stems. Practically all of the rapids in the Colorado and Green Rivers in Utah are caused by this accumulation of coarse detritus at the mouths of tributaries.

Climatologic conditions are a factor contributing to the discontinuity and irregularity of sediment transportation. Many of the minor tributaries that drain the Colorado Plateaus have high peak discharges during August, September, and October, following intense rainstorms, and may carry heavy loads of sediment to the Colorado River at that time. That river ordinarily is at relatively low stage during those months and is unable to carry the heavy load; consequently, much of the sediment may be dropped along its channel. Transportation of such debris may not be resumed until the high main-stem flows of the succeeding year. The mechanics of sediment transportation are complex, and there is not necessarily a close correlation between precipitation over the drainage basin, runoff, and sediment load in a designated period.

In its relation to the stream system, the alluvium may be classified as (1) sediment "in transit"—sediment moving either as suspended load or as bed load moving along the channel bottom; (2) sediment in "live storage"—sediment that is temporarily at rest in bars, islands, stream banks, and bottoms, where the annual fluctuations in streamflow may readily place it in transit again; and (3) sediment in "dead storage"—alluvium that has remained in place for a long time beneath flood plains or far beneath the channel bed, where reexcavation and further transportation are unlikely unless there are appreciable changes in runoff, gradient, or other controlling factors.

SUSPENDED LOAD

Data concerning the sediment load during the water year 1948, based on samples collected daily or oftener, have been obtained by the Geological Survey at eight stations in the drainage basin tributary to Lake Mead. During the year records were begun at half a dozen other localities, which permit a more thorough analysis of the transportation of sediment by the river and its tributaries during subsequent years.

The suspended load during 1948 is shown graphically on figure 6. Although the data are inadequate to show how much sediment is carried by several of the tributaries that are suspected of being important contributors, comparison with figure 5 shows that the streams that yield most of the water do not carry a proportionate share of sediment. In 1948 the flow of the Colorado River at Cisco, Utah, plus that of the Green River at Green River, Utah, was more than three-fourths of the total that entered Lake Mead (fig. 5); but the sediment passing those two points was less than a quarter of the amount entering the lake. On the other hand, the records for three tributaries in the southern part of the basin—the Little Colorado, Paria, and San Juan Rivers—show that these streams yield a far greater proportion of the suspended sediment than of the water that reaches Lake Mead. It is inferred from the sediment "pickup" along the main stem in southern Utah and
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EXPLANATION

- Areas contributing few sediments
- Source of sandy sediments
- Source of silt and clay

Boundary of drainage basin

FIGURE 4.—Map of drainage basin tributary to Lake Mead, showing source areas of sediments as inferred from surface geology.
EXPLANATION
Of 14,000,000 acre-feet of water entering Lake Mead—

Each solid line represents 5 percent

Each dashed line represents 2 to 4 percent

Each dotted line represents 1 percent

Stream-gaging station

Outline of Colorado River drainage basin

Figure 5.—Streamflow entering Lake Mead during water year 1948.
there is considerable return flow of irrigation water to the stream.

SEDIMENT

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Of 144,100,000 tons of sediment measured at Grand Canyon—

Each solid line represents 5 percent

Each dashed line represents 2 to 4 percent

Each dotted line represents 1 percent

Sediment-gaging station

Outline of Colorado River drainage basin

Figure 6.—Suspended sediment inflow to Lake Mead during water year 1948.
Arizona that other small tributaries in this area are likewise important contributors of sediment.

The areas from which the bulk of Lake Mead sediment is derived are in the Colorado Plateau province in Arizona, southeastern Utah and New Mexico. These areas are generally remote from the highest parts of the basin and include the areas having least precipitation and least runoff in the drainage basin. If the reservoir sedimentation is to be controlled, it would appear that the control must be in these areas.

Long-term records of suspended sediment are available at four stations in the tributary drainage basin. These records indicate that the sediment transported during the water year 1948 was close to the average annual load in the period 1930–48. Probably more than 95 percent of the sediment entering Lake Mead passes through the Grand Canyon, where records of the suspended load have been obtained since 1925. Beginning with the water year 1930, similar records have been obtained for the Colorado River at Cisco, the Green River at Green River, and the San Juan River at Bluff, all in Utah. The annual variations in suspended load at Grand Canyon and the proportions of that load that pass the three upstream stations are depicted in figure 7.

In the period of record at Grand Canyon, the year of highest runoff (1929) was also the year of greatest sediment contribution, and the year of least runoff (1934) was also the year of least sediment transportation. There are striking variations in the proportions of the load that pass the three upstream stations from year to year, though it is generally true that the San Juan River carries less water and more sediment than either the Green River or the Colorado River above its junction with the Green. There is a noteworthy contrast between 1939 and 1943, two years of approximately equivalent sediment load at Grand Canyon. In 1943 the load measured at the three upstream stations amounted to one-third, but in 1939 to more than two-thirds, of the quantity measured at Grand Canyon.

**BED LOAD**

In many of the canyons of the Colorado and its principal tributaries, the stream bed is composed predominantly of sand and gravel, boulders, and huge blocks

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**Figure 7**—Sediment carried by the Colorado River in water years 1931–50.
and one might conclude that if the river moves such material it must have truly magnificent power. Actually, the water moves around the larger obstacles, and if they are displaced at all it is for a negligible distance. Individual boulders can be identified in the same positions as when they were photographed more than 40 years ago. Other evidence that gravel or larger size fragments are not carried far by the main stem may be deduced from the distribution of rocks of certain distinctive types. As an example, pebbles of trachyte or of basalt in Glen Canyon may be identified in the deposits of the Colorado River, but only a few miles below the lowest tributary that drains the outcrop areas of those rocks, which are, respectively, in the Henry Mountains and on the plateau near Navajo Mountain. Finally, gravel is rare among the river deposits in the lower parts of reaches of low gradient, of which Glen Canyon and the Uinta Basin are good examples. It is concluded that for the most part the gradients along the river are insufficient for large-scale movement of gravel in the bed load.

Although the movement of gravel in the larger streams, expressed in ton-miles, is considered to be small, the total transportation of sediment along the bed may be significant. This bed-load transportation is not included in determinations of suspended load. It is likely that it represents a higher proportion of the total sediment in transit at some gaging stations than at others. For example, along the main stem of the Colorado River suspended load is being measured in the Grand Canyon, where turbulent flow, rapids, and high gradients occur throughout a long reach of the river; at Lees Ferry, where smooth flow and low gradients are characteristic of the river upstream in Glen Canyon, and steeper gradients and turbulent flow are the rule downstream in Marble Canyon; and at Hite, in the upper part of Glen Canyon, where stream gradients are gentle and where the river might be expected to drop some of its suspended load after a turbulent course through Cataract Canyon. Comparing these broad physical characteristics at the three stations, it might appear that the proportion of bed load should be least in the turbulent flow of Grand Canyon, and greatest at Lees Ferry where the velocity is increasing near the head of Marble Canyon. It is likely, however, that the proportion of bed load is determined partly by the changes in gradient and velocity in the immediate vicinity of the sampling points, and data are not available as to these factors at the established gaging stations.

**LIVE STORAGE**

Aerial photographs taken in different years commonly show many changes in the channel during the intervening period: meanders may have enlarged in some places and the channel straightened elsewhere, islands and bars shown on earlier photographs may have disappeared or changed in shape, and new ones may have appeared on the later photographs. Marked changes are noted in comparisons between the topographic maps of 30 or more years ago and aerial photos taken in the 1930's. Channel sections measured during stream-gaging operations showed marked differences from season to season, and sometimes from week to week, particularly in certain reaches of the streams. All these are evidences of the marked changes in live storage of sediment in the stream channel.

It appears that streams on a rising stage carry increased sediment in transit, and on a falling stage they drop the sediment from suspension, thus increasing the live storage. At some places, as for instance along the San Juan River at Shiprock, N. Mex., the channel scour is so great at peak discharge that the gage height may be very little above, or even lower than, the height recorded when discharge of the stream is at minimum.

No quantitative surveys or even detailed reconnaissances have been made to determine the volumes that may be involved in this type of "live" storage along the channel. It is probable, however, that the total volume along the main-stem channels may be many times the average annual deposition of sediment in Lake Mead.

**DEAD STORAGE**

By far the greater part of the Recent alluvium along the Colorado River and its tributaries above Lake Mead is not readily accessible for further movement downstream. This alluvium underlies the channel at depths that are not reached by the normal scouring action of the river but that have been penetrated in test drilling; and it forms the flood plains, which are known to antedate the first visits of white men by many centuries, and which in many places are covered by profuse vegetation. Even this alluvium has by no means reached a permanent resting place, however. Under natural conditions the only resting place for sediment was at the mouth of the river in the Gulf of California; but the creation of Lake Mead above Hoover Dam has afforded a temporary substitute for this resting place. The alluvium upstream from Lake Mead is merely interrupted in its movement downstream, but much of it will not be dislodged until some major change occurs in the basin: a change in climate or vegetative cover resulting in markedly greater seasonal or annual runoff; increased stream gradients due either to diastrophic movements or to further downward cutting of the channels; or modification of the natural conditions by development projects. In con-
sequence of water-resources development, for example, the release of clear water below Hoover Dam caused erosion of the river channel, which had been stable under natural conditions when the river carried a heavy sediment load.

At some places in the Colorado River basin, gradational processes are now at work on sediment that has long been in "dead" storage. Streams are eroding some flood plains that had become fairly stable features of the landscape, but it is not known whether major changes in climate, vegetative cover, or physiography are involved. Detailed analysis of the areas of renewed erosion and their recorded history may result in establishing the date when renewed erosion began, and the causes of that erosion.

REFERENCES CITED