The Rapids and the Pools—Grand Canyon

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THE COLORADO RIVER REGION AND JOHN WESLEY POWELL

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The rapids and the profile of
the Colorado River

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THE COLORADO RIVER REGION AND JOHN WESLEY POWELL

THE RAPIDS AND THE POOLS—GRAND CANYON

By Luna B. Leopold

Abstract

Through the Grand Canyon the Colorado drops in elevation about 2,200 feet in 280 miles; most of this drop occurs in rapids that account for only 10 percent of the distance. Despite the importance of rapids, there are no waterfalls. Depth measurements made at $\frac{1}{10}$-mile intervals show that the bed profile is highly irregular, but the apparent randomness masks an organized alternation of deeps and shallows. Measurement of the age of a lava flow that once blocked the canyon near Toroweap shows that no appreciable deepening of the canyon has taken place during the last million years. It is reasoned that the river has had both the time and the ability to eliminate the rapids. The long-continued existence and the relative straightness of the longitudinal profile indicate that the river maintains a state of quasi-equilibrium which provides the hydraulic requirements for carrying the debris load brought in from upstream without continued erosion of the canyon bed. The maintenance of the alternating pools and rapids seems to be a necessary part of this poised or equilibrium condition.

GENERAL STATEMENT

In the dry glare of a sun-drenched afternoon, in the bitter chill of a thunderstorm wind, or in the purple evening, there is no respite from the incessant boom of the great river. One finds at times he has forgotten the ever-present roar of the rapids and, as if suddenly awakened, he hears it again. So persistent is the sound that I often wonder how the mind can put away the noise into some recess, even momentarily.

The river's boom is associated with a pervasive uneasiness which never leaves a man while he is clamped within the cliffs of the canyon. This uneasiness is not the reflection of a queasy stomach for, in fact, the dry air, the sun-dappled water, and the intense color tend to give a sense of exhilaration. Rather, the uneasiness is a subdued but undeniable cold fear which never departs.

To anyone who has been down the big river, the words in Powell's journals convey clearly the fact that even those courageous men had the same constant unrest. They had more reason than we for a deep and troubled fear. On that first trip, no one knew whether high and vertical waterfalls might block completely any passage by boat. Clearly, there was no return upstream.

Powell (1875, p. 62), halfway through his trip, expressed his feelings this way: "* * * there are great descents yet to be made, but, if they are distributed in rapids and short falls, as they have been heretofore, we will be able to overcome them. But, may be, we shall come to a fall in these canyons which we cannot pass, where the walls rise from the water's edge, so that we cannot land, and where the water is so swift that we cannot return. Such places have been found, except that the falls were not so great but that we could run them with safety. How will it be in the future!"

In the hundreds of miles through which the river flows in a canyon section, the channel consists of an alternation of flat pools and steep rapids. Yet there are no waterfalls in the usual sense of the word. What John Wesley Powell feared the most does not exist. Why not? This seems a simple enough question, yet the answer is neither simple nor obvious.

This chapter is an attempt to explain, albeit incompletely, why rivers characteristically develop a uniform profile downstream, gradually decreasing in steepness. Despite this progressive flattening of slope, they tend to maintain an alternation of low-gradient deep pools and higher gradient riffles or rapid reaches. The general explanation will then be applied to the Colorado River in the Grand Canyon section to inquire in what ways, if any, a canyon alters a river's characteristic bed profile.

CONCEPT OF QUASI-EQUILIBRIUM

A river is both the route and the transporting agent by which rock and soil eroded off the continent are carried to the sea. The necessity for such movement lies merely in the energy possessed by any object as a result of its elevation. Water falling on mountains as precipitation will flow downhill because of the pull of gravity, and in the course of its movement it will carry along bits of rock and soil. The water moving downhill is constantly replenished by more falling as precipitation, and therefore, through the action of the hydrologic cycle, the continents are gradually worn down. Though the water falls over a widespread area, it does not long remain so dispersed and gathers in the well-defined ribbons of a channel network.

No aspect of the work of rivers can be discussed without some reference to the concept of quasi-equilibrium and least work. The pool-and-rapid sequence, which is the major concern of this essay is integrally related to the concept.

Power is expended—that is, energy is mechanically converted into heat—throughout the natural world. Water converts its energy of elevation into heat as it flows downhill. A rolling rock does the same as it moves down a slope. Wind dissipates its energy as it blows from a high-pressure area to one of low pressure. The work done during such energy conversion tends to be uniformly distributed because any nonuniformity causes a concentration of work on the dissident or anomalous feature.

For example, a carpenter sawing a board strikes a nail. All the work of the saw is concentrated on the nail and little on the wood until the nail is eliminated. So also in planing a board. Any slight prominence or bump on the surface is reduced by the plane faster than the surrounding uniform surface.

These examples are analogous to the work done by flowing water in a river channel. The channel bed—considered over some miles of length—tends toward a uniform down-channel slope. If some unusual feature exists, such as a ledge of especially hard rock, a very large boulder, or a waterfall, the flowing water being locally blocked will flow over and around the obstacle with higher than usual velocity, undercutting the downstream edge and eroding the sides of the obstacle. Therefore, in accord with the general tendency referred to above, energy expenditure concentrates on the bumps of the streambed, tending to reduce them and to make the whole streambed uniform.

Such a tendency toward uniformity is, in the physical world, usually counterbalanced by other tendencies arising from other conditions that must be met. The tendency of the flowing water to erode and lower the streambed is counteracted first by the resistance of the rock or other riverbed materials. This is one of the simpler balances operating in the river system. There are others more complex. The river derives from tributaries and from its bed and banks a debris load of silt, sand, or gravel. This debris will accumulate anywhere along the river where the flow conditions make the capacity to transport less than the load brought in from upstream. The factors governing transport capacity, especially width, depth, velocity, and slope, adjust among themselves to keep in balance the transport capacity and the load to be carried. The ubiquitous form of the river profile—steep in the headwaters and gradually decreasing in gradient downstream—results from the internal adjustments among the hydraulic factors as tributaries introduce additional water and their debris load.

There is another constraint on the tendency for uniform river gradient which is of controlling importance in the present discussion of pools and rapids. Coarse debris, especially gravel, will not move downstream in a uniform sheet but will tend to bunch up in mounds separated by troughs. This concentration of coarse particles at some places on the riverbed, separated by zones of relative scarcity of similar rocks, results from the effect of one rock on another in close proximity. The closer rocks are spaced, the greater is the water flow required to move them. Gravel bars in rivers, then, are the result of the tendency for rocks to accumulate in groups. The phenomenon is strikingly similar to the tendency for automobiles on a highway to accumulate in groups separated by stretches of open road nearly devoid of cars, even though the highway is free of obstructions or causes for local slowdown.

The river channel, then, is a result of complicated interactions among many factors that tend to reinforce or oppose each other. The net result of their interaction is a more or less stable and self-adjusting system, having overall characteristics of uniformity, and, within restraints, of minimization of work. This stable but self-adjusting condition is often described as quasi-equilibrium.

RESPONSE OF A RIVER IN A ROCK CANYON

The question examined here is the extent to which confinement in a rock canyon alters the usual response of a river to the mechanical laws. Are the pools and rapids of a river in a great canyon analogous to the pools and riffles of a small trout stream, or are they of a different origin and nature? The question might best be approached by first describing the nature of the pools or flat reaches and the various kinds of rapids in the Grand Canyon.

Until the U.S. Geological Survey expedition down the Grand Canyon in 1965, there existed no measurements of water depth in any great canyon of the world except at isolated cross sections where a cable has been constructed for water-flow measurements or where a dam or bridge has been constructed. No continuous profile of any canyon riverbed had ever been taken. One reason for this is that a reliable depth measurement cannot be obtained in a swift current by sounding with a lead weight attached to a line. Where the water is deep the weight is swept downstream, and a vertical measurement is impossible. The modern sonic sounder is the only practical way of measuring depth. Such instruments, now widely used in boats, large and small, measure the length of time required for an energy pulse to reach the bed and return upward to the boat. This time lag is automatically converted into depth in feet. Even the sonic equipment fails at times to work satisfactorily in fast rapids, for reasons not known. I presume that air bubbles under the energy-transmitting transducer interrupt the signal.

A recording sounder like those used in oceangoing hydrographic vessels is of no use in a river because the boat proceeds downstream at a varying speed, so that the location at any particular moment must be separately determined. The simple scheme we have used requires merely that aerial photographs be taken beforehand. The photographs are printed on semimatte paper in an unbroken roll, so that as the party progresses downstream, the pictures are unrolled successively. One man reads the depth dial and calls out the depth at about 5-second intervals. Another keeps collating the aerial photograph with identifiable features of the canyon, so that he knows where the boat is at any moment. He writes the depth directly on the photograph at the boat location. In the Grand Canyon and associated canyons of the Colorado River, these measurements were made through about 500 miles of river distance and totaled more than 6,000 separate readings of water depth.

In addition to the large number of depth readings made by echo sounding, a few cross sections were measured with a 100-pound lead weight in connection with current-meter measurements of water velocity (fig. 86).

The water-depth data discussed here were measured in June 1965, before the bypass tunnels at Glen Canyon Dam were closed. They represent, therefore, the conditions in the Grand Canyon essentially unaltered by major dams, though many dams were in operation in upper tributaries. The flow at the time of these measurements was 48,500 cfs (cubic feet per second) at Lees Ferry, though some losses occurred to bank storage, making the discharge decrease slightly downstream.

In order to get a broad picture of the Colorado River channel at this flow, the median values of width and depth in lower Marble Canyon and middle Granite Gorge (mile 113 to mile 149) were 220 feet and 40 feet. The average velocity for these dimensions is computed to be 6.2 fps (feet per second) or 4.2 mph (miles per hour). The mean velocity through the rapids was generally 11 to 15 fps, or 7.5 to 10 mph.

The range of values of width and depth for selected river segments is shown in figure 87. The depth data represent values taken at 1/10-mile intervals in the first 139 miles below Lees Ferry, when the discharge was 48,500 cfs. The width data are measured from aerial photographs taken in the spring of 1965. The maximum depth measured in the Grand Canyon was 110 feet at mile 114.3.

The river flows alternately in long, relatively smooth pools and short, steep, and violent rapids (fig. 88). What constitutes a rapid is a matter of definition, but there are 93 steep reaches of various lengths between Lees Ferry and middle Granite Gorge, a distance of about 150 miles. In this reach, rapids average about 1.6 miles apart.

The water-surface gradient in the pools is less than 2 feet per thousand (0.002) and typically is about 5 feet in 10,000 (0.0005). In the rapids, on the other hand, the water surface falls from 5 to 17 feet per thousand (0.005–0.017). For example, in Badger Creek Rapids, the water surface falls 14 feet in 860 feet. The surface velocity above the rapids was measured at 7.0 fps and in the rapids, 11.0 fps, when the discharge was 48,500 cfs.

These figures may be made more meaningful by inspection of the profile of water surface and bed through part of Marble Canyon (fig. 89). The profile represents 6 miles of river and includes the rapids near the mouth of Unkar Creek. Upstream and down are pool reaches of relatively flat gradient (fig. 90).

The first impression transmitted by such a profile is the large variation in water depth. In the pool reach from mile 71 to Unkar Rapid, through which the water-surface slope remains essentially constant at 0.0008 foot per foot, the variation in water depth ranged from 6 to 74 feet, a change which occurred within a distance of 0.3 mile. The median value was 20 feet. Two-thirds of the individual readings were in the depth range from 13 to 30 feet.

The data suggest that long pools having low water-surface gradients tend to be deeper than other parts of the river. Nearly every rapid includes an unusually shallow section, but not all equally shallow places are a high-gradient rapid. Also, some deep holes occur in the rapids, but these generally are at or near the foot.

FIGURE 86.—Flow-measurement gear being readied for observations of velocity and depth. The 100-pound weight hangs below the current meter from a cable on the winch.

Types of Waves and Causes of Rapids

In attempting to ascertain the causes of rapids, it would be helpful if one knew the details of the sizes and types of boulders or the configuration of bedrock making up the riverbed through the rapids. As only depth soundings are available, one must infer what he can about the bed from other evidence. The character of the shoreline and the distribution of wave forms at the water surface provide some indication of what is hidden under water. To aid in drawing inferences about the causes of rapids, it is useful to categorize the forms seen on the surface, especially the relation of waves to the shoreline and to what is known about water depth.

Four types of waves can be distinguished in rapids. This fourfold classification is descriptive of the hydraulic form rather than the geomorphic cause of the rapids. It is a classification based on the origin of large waves or wave trains in rapids rather than an explanation of why rapids occur at a given place in a canyon. Each type of wave is shown diagrammatically in figure 91.

Waves below large rocks or outcrops.—A common cause of large waves is the chance occurrence of extremely large boulders or rock outcrops in the channel. These rock masses or blocks force water to pass over and around the obstruction. The water speeds up on the downstream side, causing a hole or deep trough in

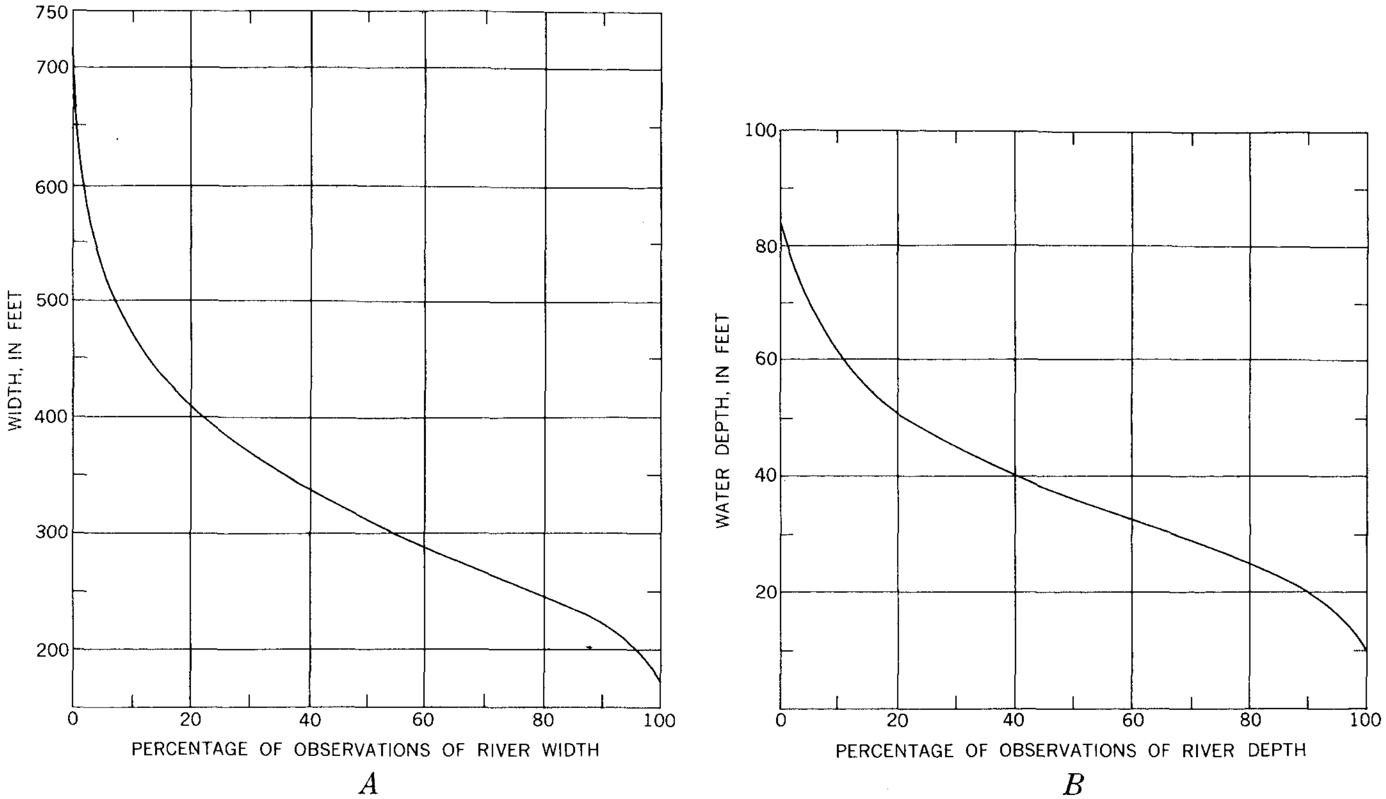


FIGURE 87.—Data on width and depth of Colorado River in Grand Canyon presented as smoothed frequency-distribution graphs. *A*, River widths. The graph shows, for example, that 20 percent of the width observations equaled or exceeded 410 feet, and that 50 percent of the observations equaled or exceeded 320 feet. Widths were measured at 1/10-mile intervals from aerial photographs of an 82-mile segment from mile 28 to mile 110 (miles measured as distances below Lees Ferry, Ariz.). *B*, River depth. The graph shows that 20 percent of the depth observations equaled or exceeded 51 feet, and that 50 percent of the observations equaled or exceeded 36 feet. Data represent values at 1/10-mile intervals in the 139 miles below Lees Ferry.

the water surface. Immediately below that, a standing wave occurs characterized by water leaping upward at the wave crest and continually breaking toward the upstream side.

Deep-water waves caused by convergences.—Convergence seems to be the most common cause of wave trains consisting of individual waves of large magnitude. As shown in figure 91, a narrowing of the channel forces water from along the side of the channel toward the center, often simultaneously from both banks, resulting in a pileup of water near the channel centerline and a train of waves (fig. 92) having wavelengths and amplitudes dependent upon the amount of flow and the amount of convergence.

Waves and riffles in shallow water.—The ordinary riffle seen in small streams generally results from shallow water. Often the shallow water is caused by a gravel bar (fig. 93) and sometimes by a low-angle fan being deposited in the channel from an entering tributary (fig. 90). The form of the bar or channel obstruction, in large rivers as well as small, is a topographic hump on the streambed. There will usually be a deep pool immediately upstream, but over the obstructing bar the water will flow in a shallow and more or less uniform sheet at higher than usual velocities owing to the steep water slope on the downstream side of the obstructing bar.

Waves in deep but high-velocity water.—When large waves occur in a rapid, it is usually not possible to tell whether the water is shallow or deep. We have enough measurements to show that large waves can occur even in very deep water, but not associated with convergence, as described above.

Categorizing the surface features of rapids, as suggested above, leads to the conclusion that the typical alternation of pools and fast water is not the result of random occurrence of rock outcrops in the channel, tributary fans, or talus falls from adjoining cliffs. These causes of rapids are relatively obvious, but only a few

FIGURE 88.—Hance Rapids, caused principally by the debris cone from a tributary entering on the left bank.

of the rapids in the Grand Canyon can be explained by these, as will now be shown.

A channel obstruction causing a rapid can be formed by large blocks of rock falling into the river from adjacent high cliffs. In many places along the Colorado, one sees bedrock blocks whose dimensions are in hundreds rather than tens of feet. Sometimes these are seen as great blocks protruding from the river, but more often, their size can be appreciated when they are on the river margin or on the slopes beneath the enclosing cliffs. The depth soundings through some rapids show that the depth changes instantly from very deep to very shallow and just as quickly increases again. This strongly suggests that the boat has just passed a large block of cliff rock which fell into the river and is completely submerged. Even some of the big rapids seem to be caused primarily from rockfalls from the cliffs. Many rapids are so far from adjoining cliffs, however, that this explanation is improbable.

The second obvious reason for rapids in the great canyons is the occurrence of a fan of rock debris debouched from an entering tributary and partly blocking the river. Many tributaries, however, do not cause a rapid at all, although they are apparently equal in size to those that do.

Some rapids must be the result of outcrops of especially hard rock locally, but because such outcrops are submerged, the cause must be inferred. Lava Falls, one of the largest and most dangerous rapids in the Grand Canyon, seems to be of this sort. In middle Pleistocene time, basalt from a lava eruption partly filled the canyon. This lava flow later was eroded away. Its occurrence suggests such a cause for this steep and violent rapid.

Many rapids, however, do not seem to be explained by the three types of circumstances mentioned. Rather, they are associated with what seems at first glance to be a random occurrence of gravel accumulations, either as a central bar across the channel or as the channelward extension of a lateral gravel bar. In fact, these gravel accumulations are not random when viewed in terms of a long reach of channel. They have a roughly regular spacing as has long been observed in the occurrence of gravel riffles in small streams. Some support for this inference comes from the data on the number of rapids per unit distance mentioned earlier. In the first 150 miles below Lees Ferry, a reach dominated by the sedimentary rock in Marble Canyon, rapids average 1.6 miles apart. In the next 178 miles downstream, a reach dominated by the metamorphic rock of Granite Gorge,

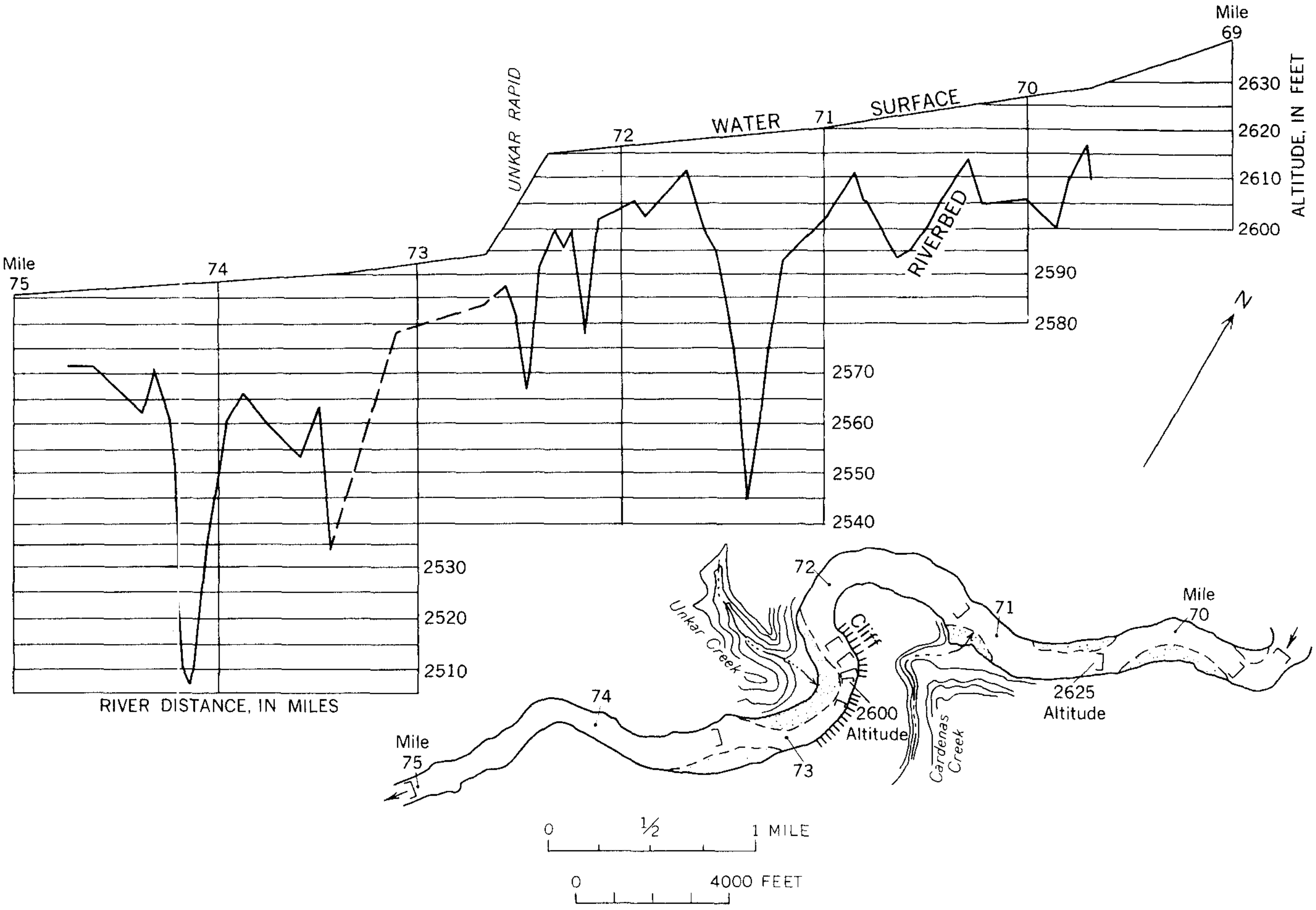


FIGURE 89.—Profile of water surface and riverbed in a 6-mile segment of the Grand Canyon near Unkar Rapid. Below is a sketch map of same reach showing position of 5-foot contours on the water surface and the location of mile points below Lees Ferry.

the spacing also averages 1.6 miles. The above data refer only to spacing of steep zones in the profile. Spacing of bars or shallow places not observable at the surface is a shorter distance.

Thus, the occurrence in canyon rivers of rapids separated by deeper pools, despite the seeming irregularity in any given locality, is apparently independent of the major bedrock type and the valley characteristics associated with different bedrock types. The alternation appears to be one aspect of channel adjustment toward maintaining stability or quasi-equilibrium and is typical in canyon rivers as well as in small streams on a wide and unconfined valley flat.

Another fact that suggests the existence of a quasi-equilibrium state is the long period of time that the Colorado River has maintained its present bed. It was mentioned above that in Pleistocene time, part of the canyon in the lower Granite Gorge was partly filled by the outpouring of lava. By using a radioactive-decay method, McKee, Hamblin, and Damon (1968) determined the age of lava cropping out near the present river level in the vicinity of Toroweap as 1.16 m.y. (million years). They stated (p. 133), "This represents a minimum age of Grand Canyon, for at the time the lava formed, the Canyon was essentially as deep as it is today. Since that time the Colorado River has cut through the 550-foot lava dam at the mouth of Toroweap Valley * * *" plus certain additional strata. These authors go on to say (p. 135), "The negligible amount of canyon deepening during the last million years or more can scarcely be attributed to the hardness of the rock * * *. Probably the most important factor involved in the apparently retarded downcutting, however, is the stream gradient which is controlled by elevation above sea level."

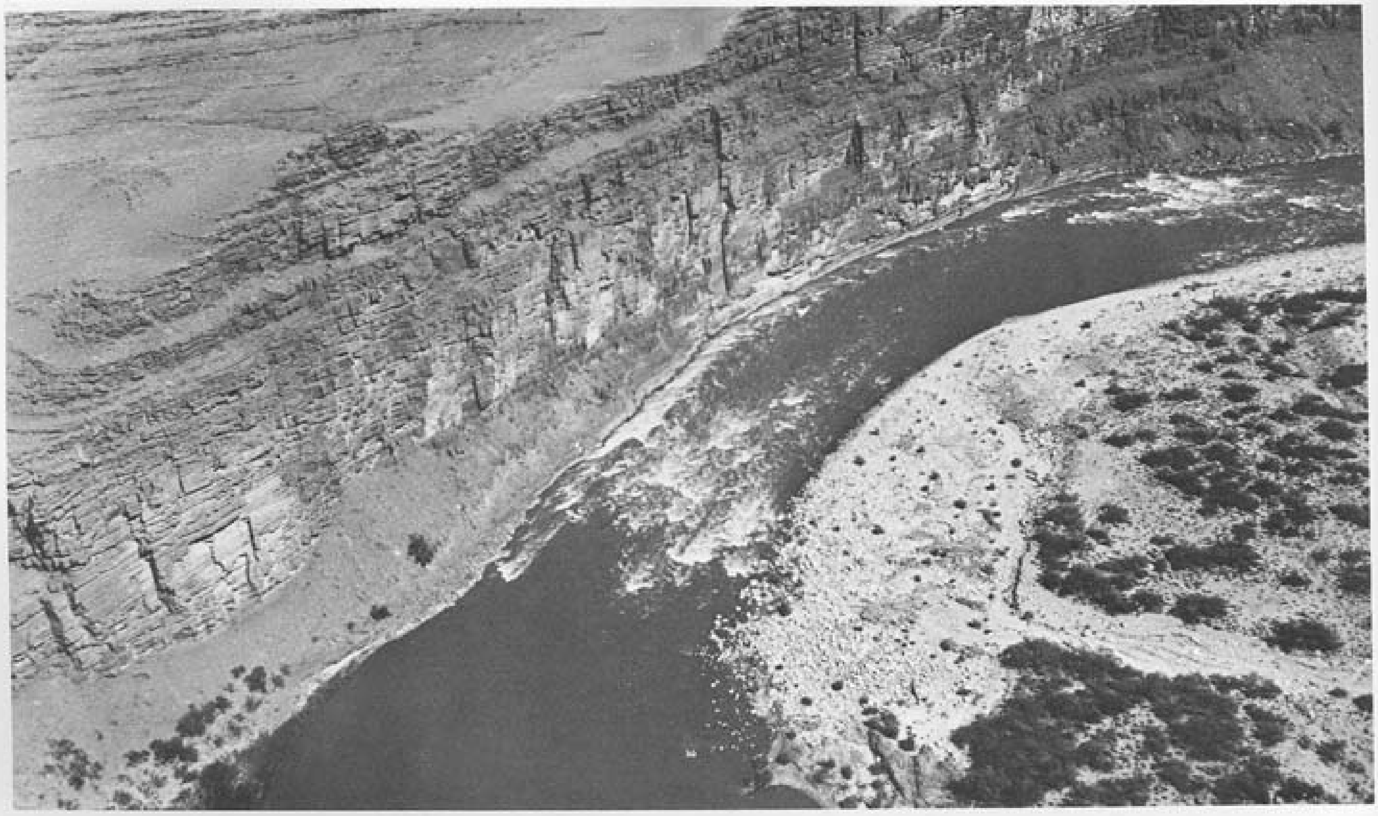


FIGURE 90.—Looking downstream at Unkar Rapid, which was caused by tributary fan forcing river against cliff on the left bank.

To explain in different words the importance of this age determination: the river has had a long time to smooth out breaks in gradient resulting from outcrops of hard rock and from tributary fans or big rockfalls. The erosion of more than 500 feet of hard basalt would require more time and the expenditure of more stream power than would be necessary to dispose of even the largest tributary fan or rockfall observed anywhere in the canyon. Accordingly, one finds it difficult to avoid the conclusion that the river profile is essentially graded and that the alternation of smooth pools and steep rapids is a natural habit of the river, related to the achievement of an equilibrium condition probably equatable to a tendency toward minimum work.

The rapids in the Grand Canyon constitute the most important element in the river's approach to sea level. Considering the whole length of the Grand Canyon, the decrease in elevation of the water flowing through all the pools is small compared with the decrease resulting from even a few of the principal rapids. Figure 94 is a graph showing the proportion of the total elevation attributable to various distances. It can be seen that 50 percent of the total decrease in elevation takes place in only 9 percent of the total river distance. In half the total river length, 86 percent of the total elevation decrease is achieved. The asymmetry of this curve demonstrates the importance of the rapids in accounting for a large proportion of the total elevation drop. For example, in those rapids that have a slope of .01 or more (1 foot drop in 100 feet), 28 percent of the total elevation drop is accounted for.

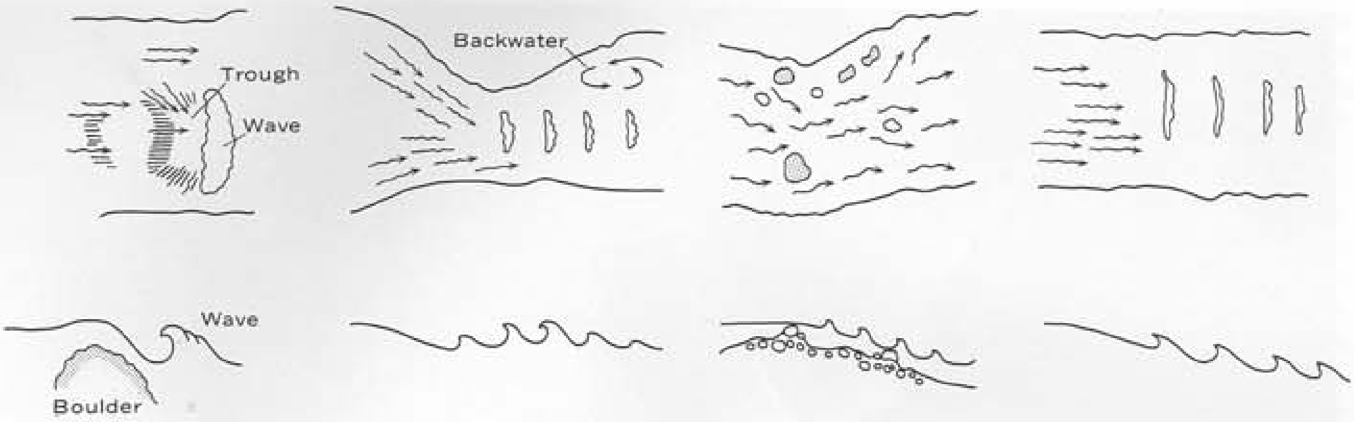
The 10 largest rapids are listed below in order of decreasing water-surface gradient; these alone account for 19 percent of the total fall in the 150-mile river reach used as a sample.

List of steepest rapids, Lees Ferry to mile 150, Grand Canyon

	Slope in feet	*Length in miles*
House Rock Rapid	0. 0170	0. 3
Horn Creek Rapid	. 0168	. 4
75-Mile Rapid	. 0164	. 2
Badger Creek Rapid	. 0162	. 2
Zoroaster Creek Rapid	. 0150	. 2
76-Mile Rapid	. 0130	. 3
Unkar Rapid	. 0130	. 4
Tuna Creek Rapid	. 0130	. 2
Sockdologer Rapid	. 0126	. 4
Grapevine Rapid	. 0120	. 7
Total		[1] 3. 3

[1] Or 2.2 percent of 150 miles.

NOTE.—Total drop through 10 steepest rapids is 246 feet or 19.3 percent of total drop in 150 miles.



Wave over submerged boulder

Deep-water waves of convergence

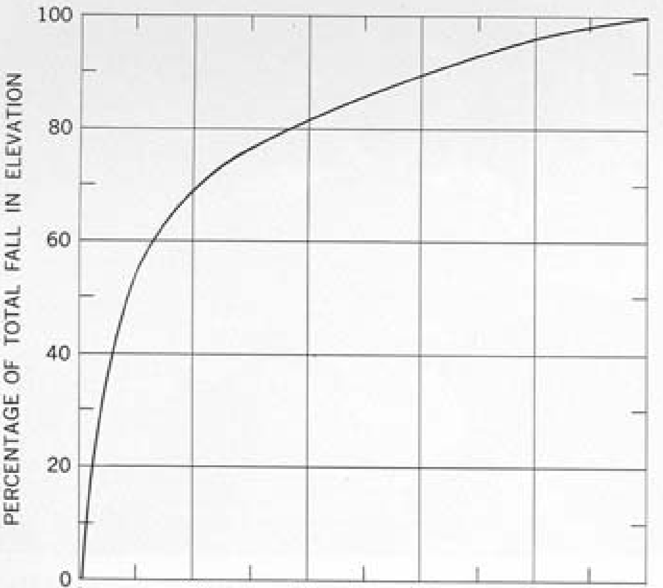
Shallow-water waves over riffle or bar of gravel or boulders

Deep-water waves in high-velocity water

FIGURE 91.—Diagrams showing four types of water waves in rapids. Upper sketches show a plan view of the river; lower sketches indicate the inferred relation of waves to the bed configuration.

FIGURE 92.—A rapid due primarily to convergence where rockbound channel narrows in a part of Granite Gorge.

FIGURE 93.—Rapids unrelated to any tributary entrance and presumably caused by large gravel bar deposited on streambed.



The direction and speed of water through and below a rapid in the Grand Canyon illuminates some aspects of the bed form and profile. Commonly, immediately below a very steep rapid, a large part of the downstream flow will be thrown against one bank, particularly if that bank is a vertical cliff. When this occurs, the opposite side of the stream will invariably have a strong upstream current at the water surface, often forming half the total stream width. Between the downstream and upstream surface currents, then, a strong shear zone exists that will be characterized by boils or round domes of upwelling water. These boils are sporadic in size and intensity, as would be expected of turbulent eddies. The boils in the Grand Canyon may be as small as 3 feet in diameter or as large as 40 feet in diameter. The vertical component of upwelling water is distinctly shown by the dome-shaped topography of the water surface over the eddy. The amount of surface elevation or vertical superelevation of the water surface over the boil is a direct indication of the strength of the vertically directed upward current. We estimated that this vertical superelevation was as much as 1 foot, indicating a vertical velocity of 8 fps.

The presence of vertically directed water in the shear zone requires for continuity that there also be downward-directed motions. These seems to take the form of deep vortexes at the foot of the rapids, especially in the lee of large rocks that are partly submerged. Vortexes are also common in deep slow pools below rapids. The other source of downward vertical motion seems to be the diving of large amounts of water at the foot of a rapid; this water, because of the steep slope through the rapid, already has a downward component. The deep hole at the foot of many rapids, then, must represent scour by downwardly directed water, much of which must flow along the bed at high velocities downstream, later to appear broken into upwelling filaments that cause the described boils. Some indication of the intensity of the downward motion and the speed of water movement downstream at the bed is indicated by two types of observation.

On several occasions I put a fluorescein-dye marker in the river close to the shear zone at the foot of a large rapid. The bag enclosing the dye was buoyant, for it was the type designed for the use of pilots shot down at sea. In several of these trials, the dye bag immediately disappeared, and was dragged below the surface by the downward component. We circled in the pool for a considerable time, waiting to see where the dye marker would appear. In one instance it did not reach the surface again until it had been taken downstream nearly a quarter of a mile. The amount of time required for the marker to reappear provided an estimate of mean downstream velocity of the transporting filament, approximately 8 fps.

Current-meter velocity measurements in a reach just upstream of Unkar Rapid give another indication of the strength of the current near the bed. The cross sections and some velocity measurements are given in figure 95. Near the deepest part of cross section 3, where the depth was about 45 feet, the measured surface velocity was 11.4 fps, and an equal velocity was measured 1 foot above the bed.

It seems, then, that large amounts of water dive at the foot of a rapid to the bottom of the succeeding pool. Some of this water moves swiftly downstream near the bed, and filaments of it are projected to the surface in large boils having a high vertical velocity. This motion in the vertical plane is a part of another large-scale circulation in which most of the flow is confined to one-half of the river channel, whereas water in the other half of the channel is flowing upstream simultaneously at a velocity of as much as 10 or 12 fps. Such an eddy occurs downstream from the area shown in figure 95.

It is interesting that even the most experienced river boatmen greatly underestimate the depth of water in the Grand Canyon and the variability of depth. The extent of the downward and upward motions also was a surprise even to the most experienced.

One may well inquire whether the position and magnitude of the pools and the rapids change with time. Obviously, the period of observation of individual rapids is so short that an answer by direct observation is impossible. Certain inferences, however, may be drawn.

Those rapids caused by the accumulation of debris fans at the mouths of tributary canyons clearly cannot migrate away from the tributary mouth. Therefore, their position must be essentially fixed in geologic time.

A few rapids probably result from a sill or outcrop of especially hard rock upon which an overfall forms as the water cuts into less competent beds downstream. Lava Falls might well be attributed to such a cause, but no other major rapid. Therefore, the upstream migration of knickpoints caused initially by the occurrence of a local body of hard rock cannot account for the succession of rapids throughout the canyon length.

Rapids formed by local accumulation of large blocks falling directly into the river from adjacent cliffs would be expected to decrease in magnitude as these rocks gradually eroded away, but the position of such a rapid should not migrate upstream.

The great age of the lava that once dammed the river at Toroweap strengthens the conjecture that the river has had ample time to eliminate the sections having steep rapids. The rapids, therefore, must be relatively stable features.

Nature and Transport of Material on the Riverbed

The nature of the material on the riverbed can be inferred primarily from three kinds of observations. The bed was exposed to direct observation when the foundations were excavated for both Hoover and Glen Canyon Dams. In the foundation excavation for Hoover Dam, a sawed plank was found imbedded in sand and gravel 55 feet below the normal streambed elevation. This implies that the sand and gravel found in the canyon bottom moves to considerable depths during floods.

Most channel bars exposed at low flow consist of sand and cobbles. Large boulders occur primarily on fans directly attributable to debris from tributary canyons.

Though the streambed includes in places extremely large blocks of rock, for the most part the variation in water depth, typified by the bed profile shown in figure

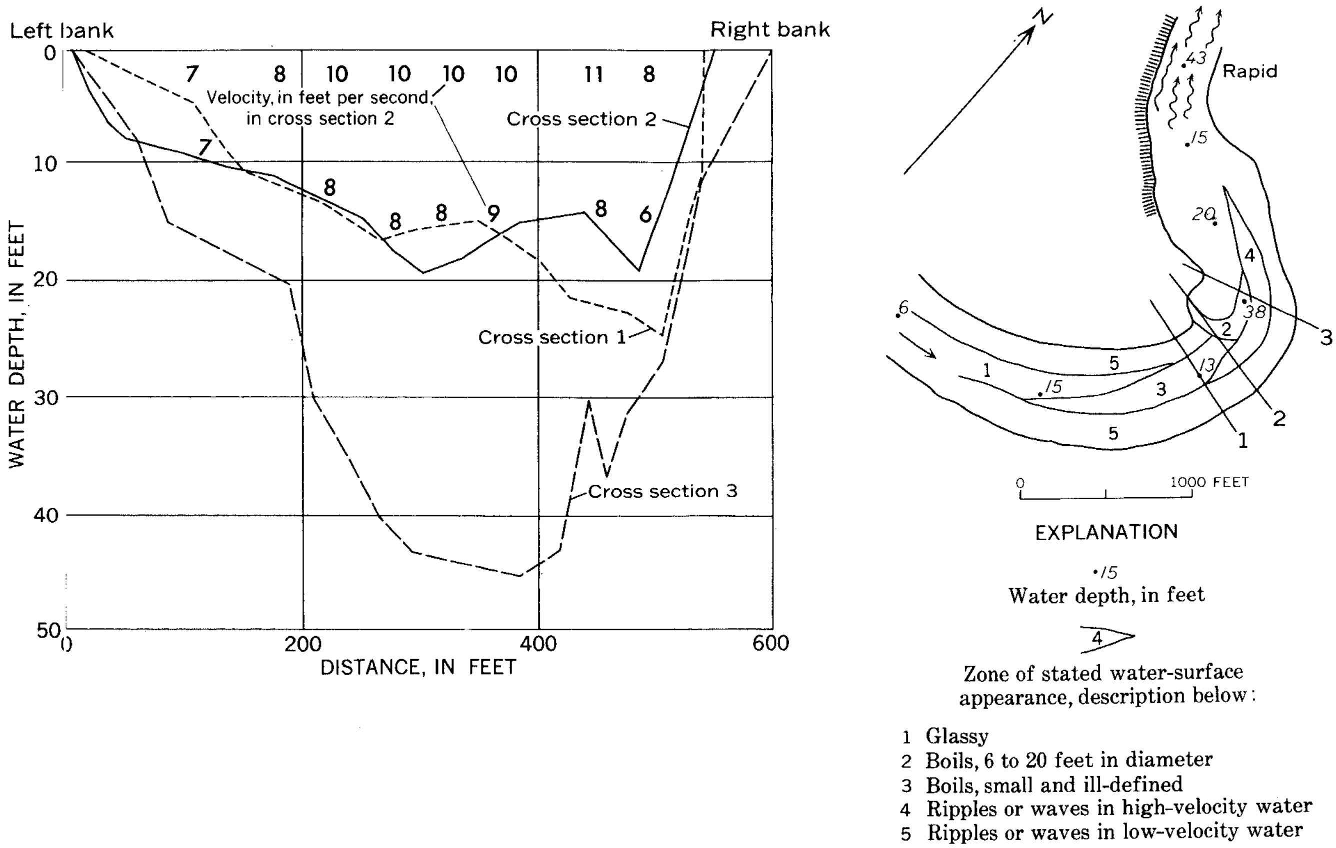


FIGURE 95.—Channel cross sections and sketch map, showing appearance of water surface near Unkar Rapid. Velocity measurements (fps) near the river surface and near the bed are shown for cross section 2.

89, seems to be caused by local scour in a bed composed primarily of sand and gravel. This is supported also by the particle sizes of sediment deposited at the head of Lake Mead; this sediment consisted of 45 percent sand and 55 percent silt and clay (Smith and others, 1960). The relatively fine texture of the bed material is perhaps most persuasively demonstrated by the fact that the riverbed is scoured deeply during floods in all observed sections of the river that were or are still unaffected by dams in the reaches immediately upstream. Data on the depth of riverbed scour during the spring run-off peak have been described previously at some length (Leopold and Maddock, 1953, p. 30–35). However, the previous discussions have, for the most part, omitted the changes throughout the nonflood season, which are important to the present discussion.

Figure 96 shows the changes in some of the principal hydraulic factors at Lees Ferry during a 10-month period from December 1947 to September 1948. These data represent conditions in the Grand Canyon prior to the construction of Glen Canyon Dam and several other dams farther upstream. The spring flood in 1948 was moderately high but far below the maximum of record. The discharge was 92,100 second-feet on May 25. During this season, as the discharge increased progressively from about 10,000 second-feet, the water-surface elevation rose 11 feet, but simultaneously the mean elevation of the riverbed fell 16 feet. In other words, the accommodation of the river channel to the increased flow consisted of an increase in cross-sectional area achieved somewhat more by riverbed scour than increase in water-surface elevation. After the 1948 flood, the water-surface elevation returned to approximately its preflood value, but for several months after the flood recession, the average bed elevation remained 2 to 3 feet lower than in the preflood conditions. In the fall and winter months, the average elevation of the streambed rose gradually to its average springtime condition.

The hydraulic relations during such riverbed scour were discussed in detail by Leopold and Maddock (1953). The scour at Lees Ferry was shown to be associated with high suspended-load concentrations, and for a given discharge, during the recession side of the flood, the sediment load was smaller and the streambed elevation was lower than on the rising flood stage. The scour cannot be attributed merely to high velocity be-

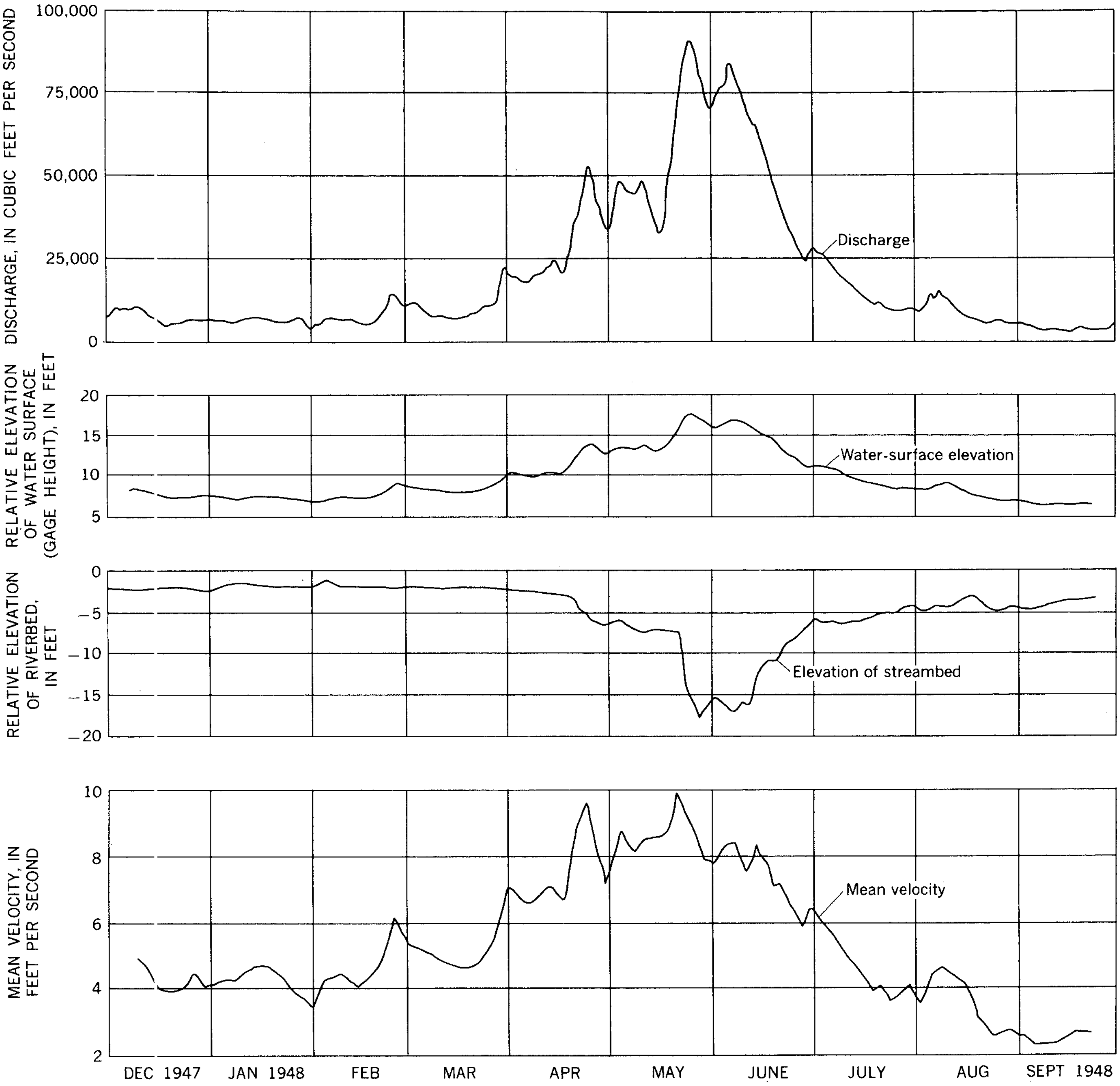


FIGURE 96.—Changes in discharge, water-surface elevation, bed elevation, and mean velocity during a 10-month period at the Lees Ferry measuring station, Colorado River. Note that the streambed had been scoured 16 feet between mid-April and late May as the discharge increased.

cause, as shown in figure 96, the most rapid rise of discharge was associated with deepening of the riverbed which was also coincident with a decrease in the mean water velocity. At the end of August 1948, when the discharge was the same as the preflood values of the preceding January, the mean velocity was lower than had typified the January conditions.

The stations at Grand Canyon and San Juan River at Bluff filled and then scoured on the rising flood stage; the bed changed but little on the falling stage. Thus, during a snowmelt flood, the Colorado River had a large variation in sediment load and changed the elevation of its streambed and the cross-sectional area of its flow as it simultaneously changed its mean water velocity.

These hydraulic adjustments were associated with a changed bed roughness in response to changes in sediment transport.

We see, then, a complicated adjustment of the riverbed roughness, cross-sectional area, and bed forms brought about by different conditions of water and sediment inflow.

Before the dams were built, the sediment transported through the Grand Canyon averaged about 143 million tons per year, as indicated by sediment accumulated in Lake Mead during the first 14 years of the reservoir's existence. The year-to-year variation in the amount of sediment transported through the canyon in the predam condition was large. For example, in the year 1927, the measurements show that 480 million tons were transported past Grand Canyon station.

As the spring flood passed, not all the sand and gravel that was temporarily cut out of the streambed moved completely through the canyon into the lower reaches of the river. The interrupted motion of individual grains of sand or gravel cobbles was an alternation between transport and resting or waiting in a dune or bar for extended periods of time. The average downstream speed of a cobble was very much slower than the average speed of any water particle. For this reason, the total volume of riverbed scour during a flood is large compared with the volume of sediment accumulated in a downstream reservoir as a result of the same flood passage.

The low-gradient pools of a canyon river are visualized as local basins of semipermanent character cut into a bed consisting primarily of sand and gravel. These sections of the riverbed are scoured deeply during flood passage, and after the flood has passed they slowly regain their original topography.

I hypothesize that the areas of rapids, on the other hand, are nearly fixed features, consisting of heavy gravel, only the surface rocks of which move during flood periods. As in other smaller rivers in which we have made observations of marked rocks placed on river bars and riffles, the usual flood moves only rocks lying at or near the surface. These are immediately replaced, however, by similar rocks derived from upstream. Scour of the material of the rapids during a flood is, therefore, nearly inconsequential compared with the deep scour that occurs in the finer grained material of the pools or deeps nearby. Despite the ability of the river to transport the gravel and boulders that form the bulk of any given rapid, the flow mechanics require, for long-term stability, that the riverbed not be a smooth sloping plain, but consist of alternating deeps and shallows which, even through long periods of time, remain in a consistent geographic position.

The main difference between the bed topography in a deep narrow gorge like the Grand Canyon and the common gravel-bedded stream of less mountainous areas is a matter of scale. A river develops a profile connect-

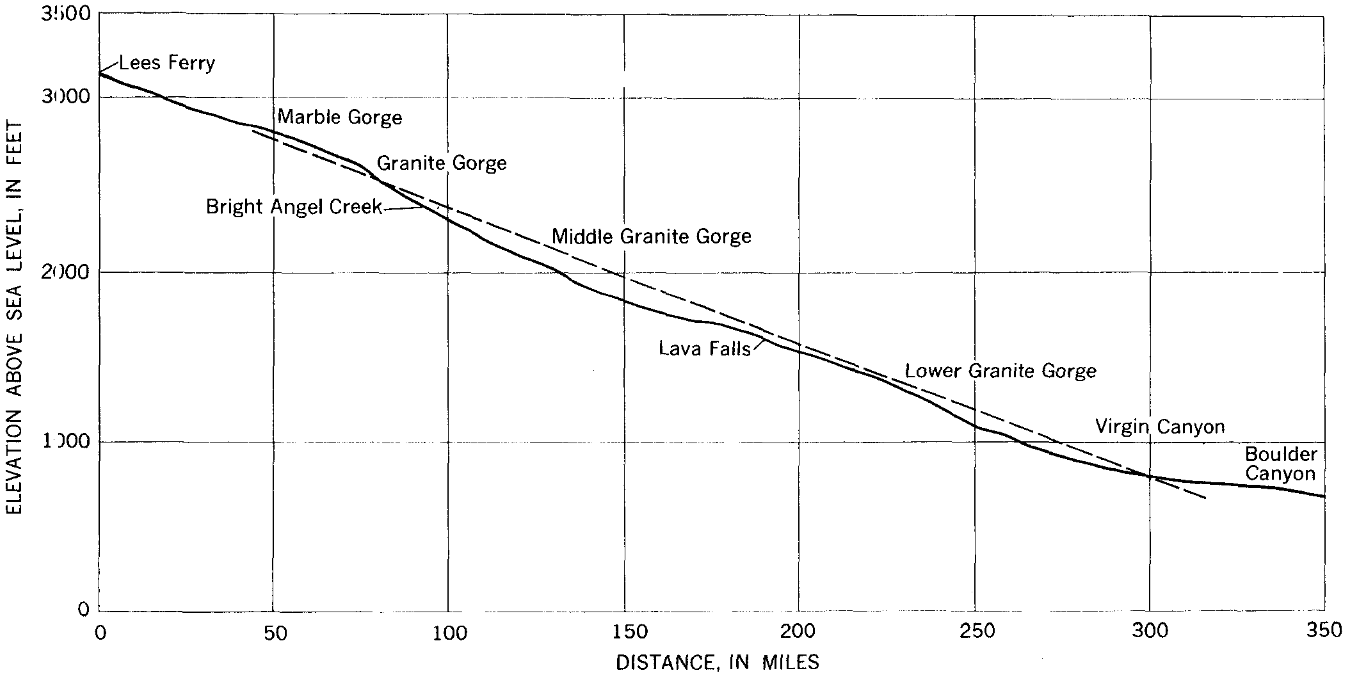


FIGURE 97.—Longitudinal profile of the Colorado River through the Grand Canyon. A straight dashed line drawn at the average gradient shows that the river profile, though somewhat irregular, is nearly straight.

ing the high-elevation headwaters with its mouth or base level by a channel which along its length represents a quickly attained quasi-equilibrium, constantly adjusted through geologic time as the elevation difference between headwaters and mouth is gradually reduced. The concavity of the profile in most rivers is primarily the result of increased discharge as tributaries enter along the river length. Along the Colorado River through the Grand Canyon, the addition of water from tributaries is negligible. The river profile through the Grand Canyon, when drawn at such a scale that the pool and rapids alternation is obscured, is nearly a straight line, as can be seen in figure 97.

SUMMARY

The Colorado River flows several hundreds of miles through a series of canyons, some of which are of very hard and resistant rock. The river seems encased in a vise so confining and limiting that any freedom of action or movement seems to be foreclosed. In fact, however, the river has nearly all the characteristics of an unconfined channel flowing in a broad flood plain, save one, the tendency to move laterally. The Colorado adjusts its depth and velocity by scour and fill of the bed in response to changes of debris load. It formed and maintains bed alternations of deep pool and shallow rapid by the construction of gravel bars, which maintain their size and position despite the trading of rocks on the bar surface. The river profile, except for the alternation of pool and rapid, is smooth and nearly straight.

Only in the lack of lateral migration as a result of the confining rock walls does the canyon river seem markedly different from a free or unconfined one. Yet the perfect form of some meanders entrenched in hard rock indicates that the river has no proclivity for lateral movement, for it has cut nearly vertically hundreds of feet, at least in some places, for periods of several millions of years. Why the canyon river does not erode laterally more than it does is simply not known.

The Grand Canyon section of the Colorado River, despite its impressive rapids, has the characteristics of a river in balance, maintaining its quasi-equilibrium poise by self-adjustment.

The great age and stability of the rapids do not result in all rapids being equal in size or declivity. Their magnitude ranges from small to great. Random variation alone might well have produced one or more rapids so steep or so nearly approaching a real waterfall that the Powell party would have been blocked. Powell took a long chance and was lucky as well as capable.

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