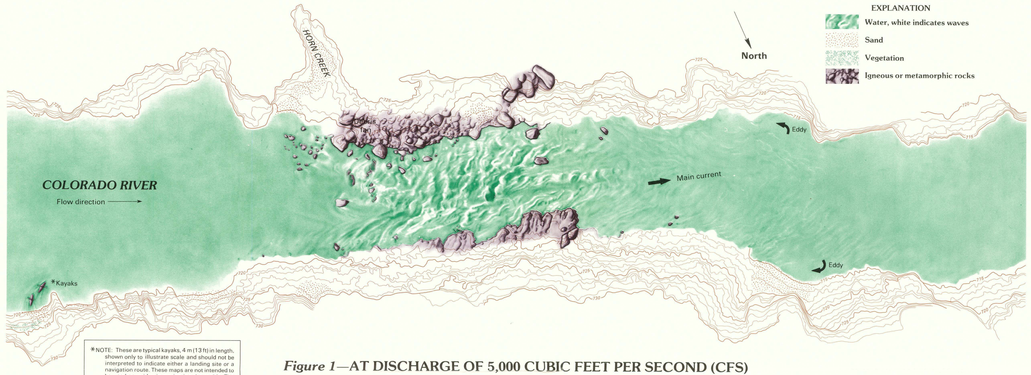


Figure 1—AT DISCHARGE OF 5,000 CUBIC FEET PER SECOND (CFS)

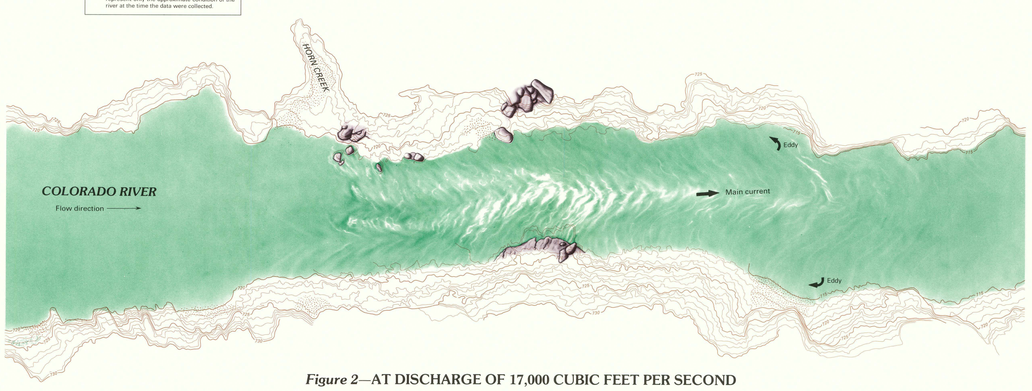


Figure 2—AT DISCHARGE OF 17,000 CUBIC FEET PER SECOND

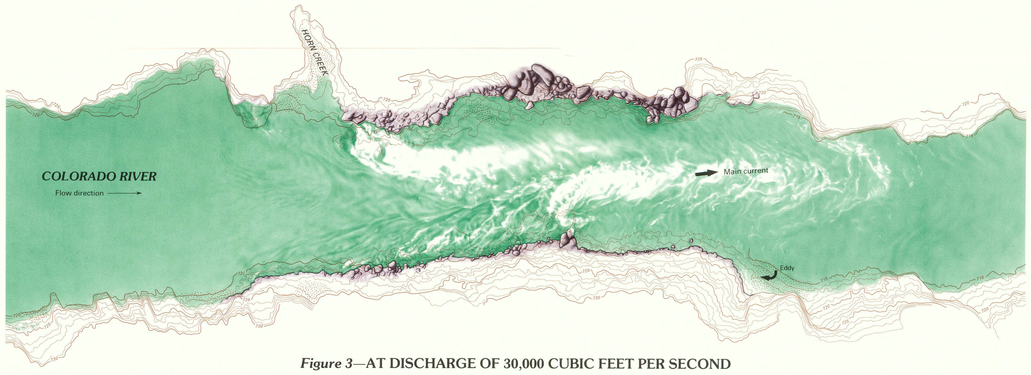


Figure 3—AT DISCHARGE OF 30,000 CUBIC FEET PER SECOND

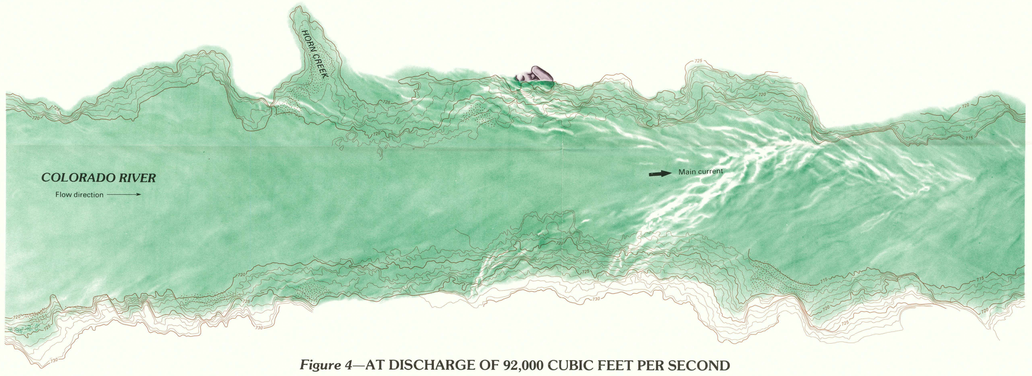


Figure 4—AT DISCHARGE OF 92,000 CUBIC FEET PER SECOND

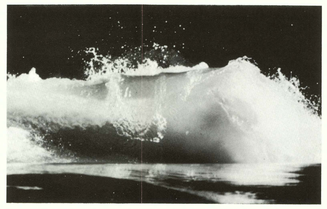
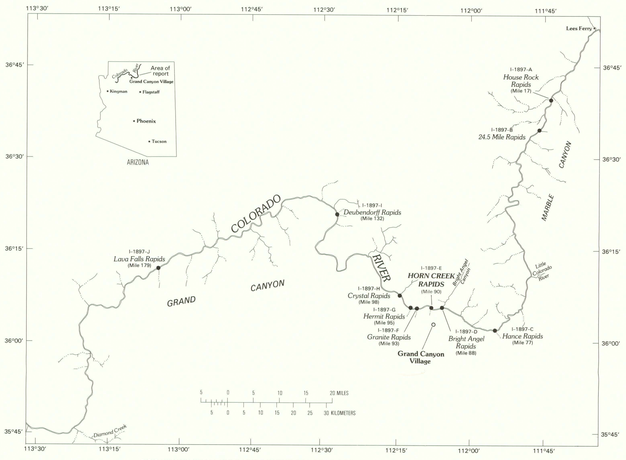


Figure 5—THE CURLING WAVE AT TOP CENTER OF HORN CREEK RAPIDS
(Viewed from northeast shore)



LOCATIONS OF MAJOR RAPIDS IN THE COLORADO RIVER, GRAND CANYON, ARIZONA
I–1897–A indicates series number of map for each rapids.

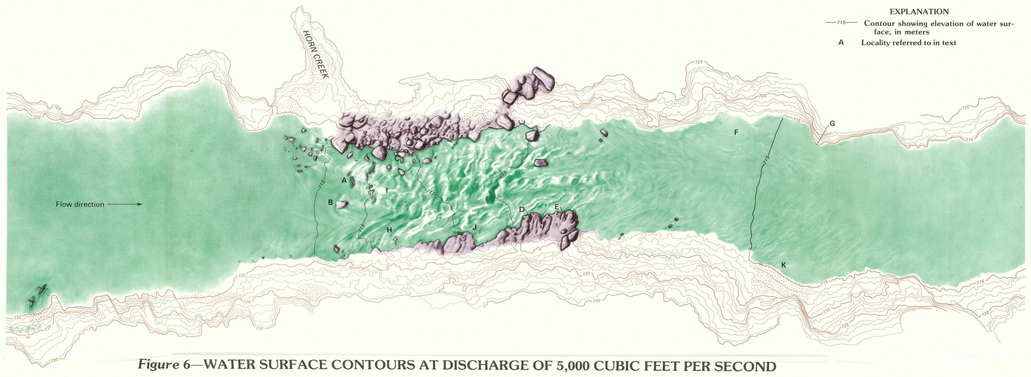


Figure 6—WATER SURFACE CONTOURS AT DISCHARGE OF 5,000 CUBIC FEET PER SECOND

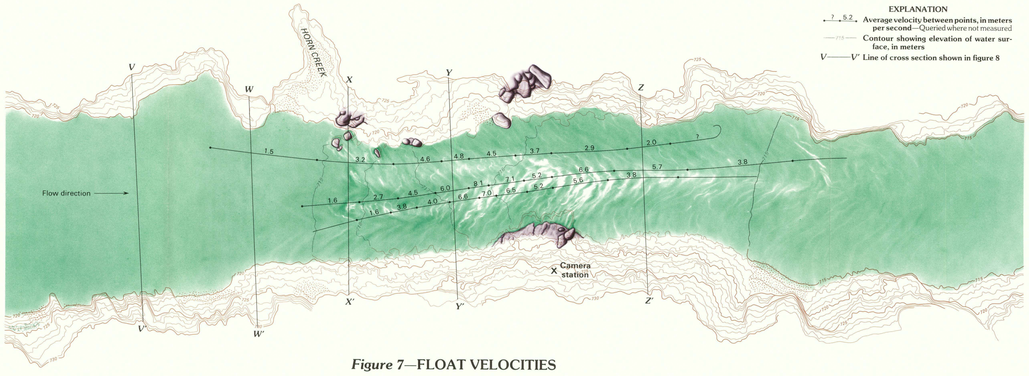


Figure 7—FLOAT VELOCITIES

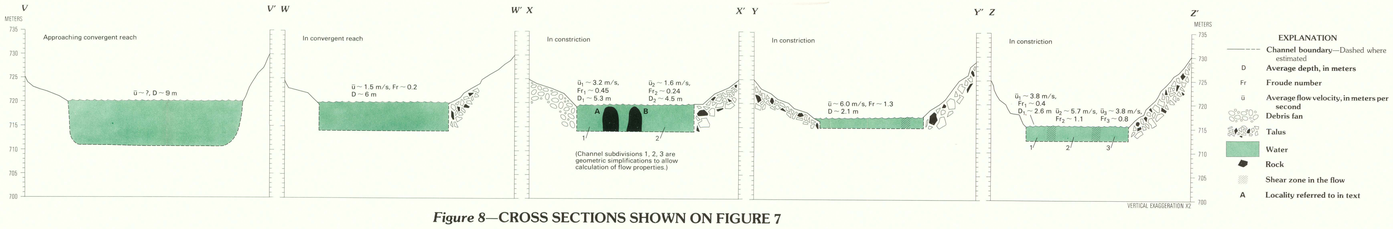


Figure 8—CROSS SECTIONS SHOWN ON FIGURE 7

DISCUSSION

Whereas most of the rapids of the Colorado River are caused by debris flows from tributary canyons, the debris flow that has come down Horn Creek (a minor tributary on the southwest side of the Grand Canyon) is only one of the contributing factors to the existence of Horn Creek Rapids. The bedrock at Horn Creek Rapids consists of mica schists and quartzo-feldspathic schists of the Vishnu Schist and intrusive pegmatite-granite dikes, both providing very resistant rocks that are obstacles in the river channel throughout the rapid. In addition to the debris from Horn Creek and the boulders and bedrock protuberances, a third cause of roughness and constriction of the river channel at Horn Creek Rapids is rockfalls from a large talus slope on the northeast side of the river. This particular combination of the debris from Horn Creek, the bedrock obstacles, and the talus rockfalls causes Horn Creek Rapids to be dramatically different in hydraulic character than the rapids where large debris fans cause a strongly convergent-divergent nozzle shape of the Colorado River channel (for example, at House Rock (Map I–1897–A) and Crystal Rapids (Map I–1897–H)).

The hydraulic features of Horn Creek Rapids change dramatically with changing discharge, and the changes are severe enough to affect boating navigability. At low discharges, especially lower than the 5,000 cubic feet per second (cfs) conditions shown in figure 1, the rapid is navigable only by small boats (in general less than 6 m long) because rocks littering the channel prevent passage of larger boats. At 5,000 cfs, as well as at the higher discharges of 17,000 and 30,000 cfs shown in figures 2 and 3, large waves are present at the top and bottom of the rapid. At the flood-level discharge of 92,000 cfs in 1983, these waves were not prominent, but rather, a large lateral wave emanated from the northeast shore at the bottom of the rapid (fig. 4). The shift of the lateral waves from the top of the rapid at low and moderate discharges (figs. 1–3) to the bottom of the rapid at high discharges (fig. 4) reflects a change in the location of the controlling constriction within the rapid, an effect not seen in general at rapids with strong converging-diverging geometries. This shift in constriction can be seen by comparing the topographic contours at the shorelines on figures 1–4. (This phenomenon is discussed in more detail below.)

Many of the important waves in Horn Creek Rapids are associated with large boulders (fig. 5). Two large boulders at the top of the rapid (**A** and **B** in fig. 6) form the "horns", visible to approaching boating parties as humps in the water's surface (the boulders are visible at discharges less than about 10,000 cfs and cause large waves at higher discharges). The southwest side of the rapid downstream from the mouth of Horn Creek is strewn with medium to large boulders (for example, **C** in fig. 6), and boulders (or bedrock outcrops) as much as 10 m in diameter are found along the northeast shore (for example, at **D** and **E**, fig. 6). The channel bottom under Horn Creek Rapids is probably comparable in roughness to that at Lava Falls Rapids (Map I–1897–J) because of these large boulders.

At a discharge of 5,000 cfs, the water surface through the rapid drops at least 4 m (from approximately 719 m to 715 m elevation; fig. 6); at least 3 m of this drop in elevation occurs over a distance of 80 m at the top of the rapid. The slope of the water surface through the rapid decreases as the discharge increases, as can be seen by a comparison of the water-surface elevations above and below the rapid in figures 1 through 4.

Streamlines (paths of floats) and velocities of floats were determined from Super-8 motion pictures taken from the camera station shown (fig. 7). The floats and experimental technique are described in Kieffer (1987). The floats were launched upstream of the rapid, approximately at the place where the streamlines begin on figure 7. Each velocity numeral (in units of meters/second, m/s) refers to the section of streamline between large dots. The floats were launched when the discharge at Horn Creek Rapids was approximately 17,000 cfs. The hydraulic conditions at this discharge were so different from the conditions at 5,000 and 30,000 cfs, for which the standard illustrations in this series of hydraulic maps are made (figs. 1 and 3), that a special base map on which to portray the streamlines was created from photographs from the camera station indicated in figure 7. This map (fig. 2; also used as the base map for fig. 7) is therefore more schematic in character than the maps at 5,000 and 30,000 cfs, which were prepared from stereographic low-altitude aerial photography.

In order to demonstrate the complexity of the flow in the rapid, a perspective of vertical, as well as horizontal, relations is shown in the cross sections of figure 8. Discharge in all cross sections is 17,000 cfs. Depths were not measured directly in any cross sections. A fathometer traverse was run slightly upstream of cross section *V–V′*, and these data are used in that cross section. In all other cross sections, the depths shown were obtained from the continuity equation as described in Kieffer (1987); errors on the order of 1 m should be expected, since both channel shape and shear zones between different streamlines had to be assumed. The cross sections are simplified to a rectangular shape, an assumption partly justified by the vertical slope of some of the bedrock walls and partly made because of a lack of data to justify a more complex model. The cross-sectional characteristics and depths so obtained are roughly consistent with a fathometer tracing through the rapid approximately along the most northeasterly streamline of figure 7 (fathometer tracing obtained by Julie Graf, written commun., 1986).

The cross sections suggest that the bed of the channel rises from an elevation of about 711 m in the backwater above the rapid (*V–V′*) to an elevation of about 715 m where debris from Horn Creek and from the northeast wall constrict the channel (*X–X′* and *Y–Y′*), and drops back to 712 m at the bottom of the rapid (presumably back to the backwater elevation of 711 m below the runout of the rapid in the zone not covered by this map).

The flow pattern at Horn Creek Rapids is determined by (1) a relatively minor horizontal constriction at the top of the rapid (approximately in cross sections *X–X′* and *Y–Y′*), (2) the vertical constriction caused by the elevation of the channel bed under the rapid (this begins as far upstream as cross section *W–W′*, as shown in the cross sections), and (3) the obvious large boulders. The horizontal and lateral constrictions cause the right and left "tongues" (**H** and **I** indicated in fig. 6) at the top of the rapid (the structure of the tongues is complicated by the presence of the horns, **A** and **B** in fig. 6). The large boulders cause individual standing waves, for example, at **D**, **E**, **A**, and **B** (see fig. 6). At discharges greater than about 15,000 cfs, there is no visible wave associated with **A**, but there continues to be a large wave at **B**. For a general discussion of the flow patterns in rapids, see Kieffer (1985, 1987).

Although the data from which figure 4 was constructed are limited, they show unequivocally that at the high discharge of 92,000 cfs, the main constriction point in the channel at Horn Creek Rapids was not at the top of the rapid, but at the bottom (approximately at the location of cross section *Z–Z′*). Thus, the tongue and oblique waves that are normally characteristic of the entrance at the top of the rapid move downstream at Horn Creek, in effect, forming a new, "lower" Horn Creek Rapids at high discharges.

Water accelerates from a very low flow velocity—probably a few tenths of a meter per second—from the backwater above the rapid (on the left of the map areas) to velocities exceeding 7 m/s (fig. 7). The backwater is caused by the constriction of the channel by boulders and debris. The moderately high velocity of 1.5 m/s measured at cross section *W–W′* is in a zone where convergence and acceleration into the rapid has already begun.

The water accelerates from the backwater into the constriction. Velocities in a narrow chute of water on the southwest side of the river, near the Horn Creek debris fan, were measured to be 3.2 m/s at *X–X′* and to increase to 4.8 m/s along the southwest streamline (fig. 7). The velocities along this streamline decrease between *Y–Y′* and *Z–Z′* as the flow interacts with a narrow eddy zone along the southwest shore (location **F**, fig. 6). On the northeast side of the river, the float velocities increase more slowly (to 1.6 m/s by cross section *X–X′*), probably because of fairly strong eddies along the shore in this region. However, the velocities then accelerate dramatically toward 7 m/s (or greater) past cross section *Y–Y′*.

In the runout of the rapid, near section *Z–Z′*, the flow velocities depend dramatically on lateral position in the river. On the southwest side, the velocities are low, and a small eddy near **F** contains recirculating flow. Even floats launched near the center of the rapid (for example, the center streamline in fig. 7) are influenced by the shear zone between the main current and this eddy and can be dragged toward impact with the southwest wall near point **G**.

An important parameter in characterizing the state of the flow is the Froude number, $Fr = \bar{u}/(gD)^{1/2}$ (where $\bar{u}$ is an average flow velocity, g is the acceleration of gravity, and D is the average depth of the flow). The Froude number is a dimensionless measure of the relative importances of inertial versus potential energy, and it was calculated for each cross section from the measured and inferred depths and velocities. Froude numbers less than 1 indicate subcritical flow dominated by potential energy, and Froude numbers greater than 1 indicate supercritical flow dominated by kinetic energy. Standing waves are stable features in the flow if the Froude number exceeds 1. At 17,000 cfs, the following values were obtained for Horn Creek Rapids: Fr=0.2 at *W–W′*; Fr=0.24 to Fr=0.45 at *X–X′* depending on location in the cross section; Fr=1.3 in the main channel at *Y–Y′*; and Fr=1.1 in the tailwaves at *Z–Z′*. Uncertainties of these values are on the order of 30 percent. Nevertheless, these Froude numbers indicate that the flow changes from subcritical conditions (Fr<1) upstream of the constriction (*V–V′*, *W–W′*, *X–X′*) to supercritical conditions (Fr>1) in the convergence and constriction (*Y–Y′*), back to critical (Fr=1) in the tail waves (*Z–Z′*), and then subcritical (Fr<1) in the diverging section (below *Z–Z′*).

The standing waves of Horn Creek Rapids are features of supercritical flow, and they become particularly strong when the flow becomes highly supercritical as it flows over the tops of large obstacles (see Kieffer, 1985 and 1987 for details). At the top of the rapid, in *X–X′* the flow is subcritical across most of the channel, but the two rocks in this cross section (**A** and **B**) cause the flow to become locally supercritical. The unusual geometry of these rocks, particularly at **B**, causes a beautiful curling standing wave (fig. 5) under certain flow conditions.

The runout from the rapid (the main current passing through *Z–Z′*) consists of a train of gently breaking waves and swells. The Froude number is about 1 at *Z–Z′*; a similar condition has been found in the tailwaves at both House Rock and Lava Falls Rapids. In contrast to the rapids that have strong constrictions formed by large debris fans, there are almost no eddies at the bottom of Horn Creek Rapids (note the small size of the eddies at **F** and **K** in fig. 6). Although small sand deposits can be found among the boulders at Horn Creek, at the time of preparation of this map there are no significant camping beaches at Horn Creek Rapids because there are no large eddies below the rapid.

To summarize, the most significant hydraulic features in Horn Creek Rapids are local hydraulic jumps and standing waves caused by bedrock and rockfall debris (for example, the horns **A** and **B** and their waves at the top of the rapid; a large wave caused by a rock at **J**; or waves at **D** and **E** at high discharges); lateral waves (oblique hydraulic jumps, such as **J** in fig. 6) caused by the constriction of the channel both by convergence of the walls laterally and by the underwater presence of debris; and the boulder debris from Horn Creek on the southwest side of the rapid (for example at **C**). At 92,000 cfs, a large lateral wave appears at the bottom right of the rapid (fig. 4). Because waves are present at all discharges documented, Horn Creek Rapids appears to maintain supercritical flow through all of these discharges. The displacement of the oblique hydraulic jumps downstream with increasing discharge (compare figs. 1 and 4) is a noteworthy hydraulic feature in this rapid.

The hydraulic features of Horn Creek Rapids reflect a dynamic equilibrium between the flow in the Colorado River channel, bedrock protrusions (particularly on the northeast side near the middle of the rapid), rockfalls from the north channel wall, and flooding events from Horn Creek. The configuration of the channel bottom depends not only on the bedrock topography and the contribution from the catastrophic rockfalls and tributary floods, but also probably to some extent on the transient sediment load of the river. The channel configuration changes with time, both gradually and catastrophically.

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Kieffer, Susan Werner, 1987, The rapids and waves of the Colorado River, Grand Canyon, Arizona, U.S. Geological Survey Open-File Report 87–096.

SCALE 1:1 000
100 0 100 200 300 FEET
10 0 10 20 30 40 50 60 70 80 90 METERS
CONTOUR INTERVAL 1 METER

HYDRAULIC MAP OF HORN CREEK RAPIDS, GRAND CANYON, ARIZONA

By
Susan Werner Kieffer
1988

INTERIOR—GEOLOGICAL SURVEY, RESTON, VA—1988

Hydraulic data collected in October–November 1985 by Susan Werner Kieffer, assisted by Margie Marley.

Contour lines compiled on analytical stereoplotters at the U.S. Geological Survey, Flagstaff, Arizona, from aerial photographs flown in 1984 by the Bureau of Reclamation, Series 6023.

Airbrush portrayal of hydraulic features by Patricia Hagerty Gray, U.S. Geological Survey.

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