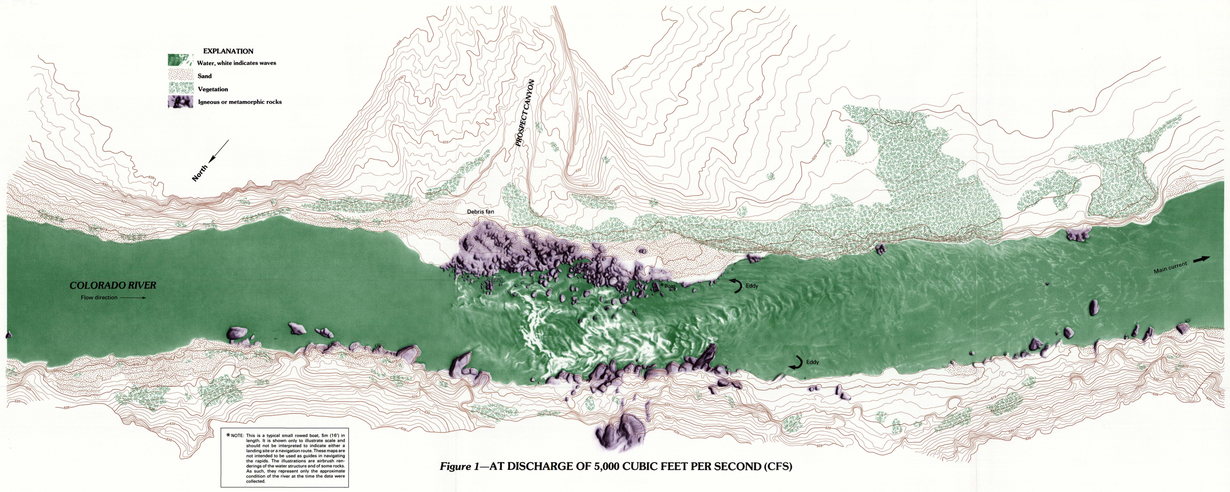


Figure 1—AT DISCHARGE OF 5,000 CUBIC FEET PER SECOND (CFS)

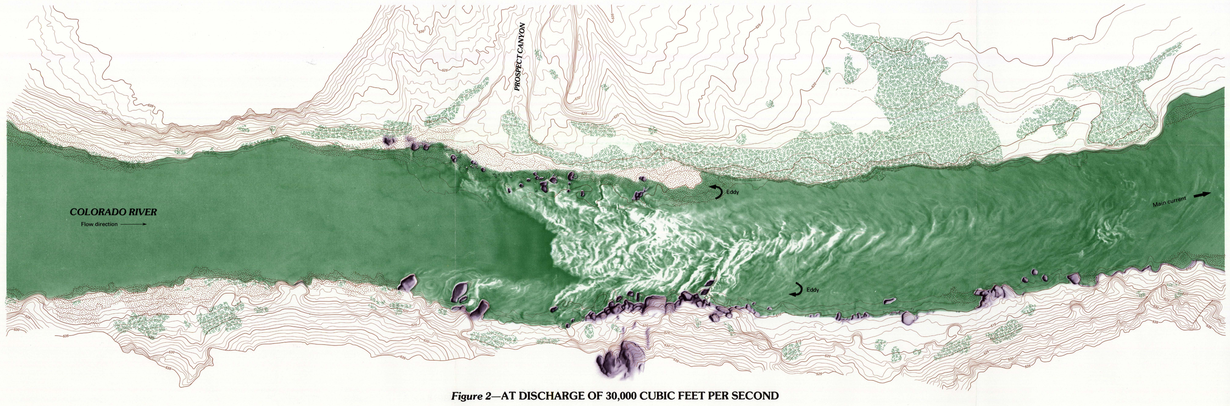


Figure 2—AT DISCHARGE OF 30,000 CUBIC FEET PER SECOND

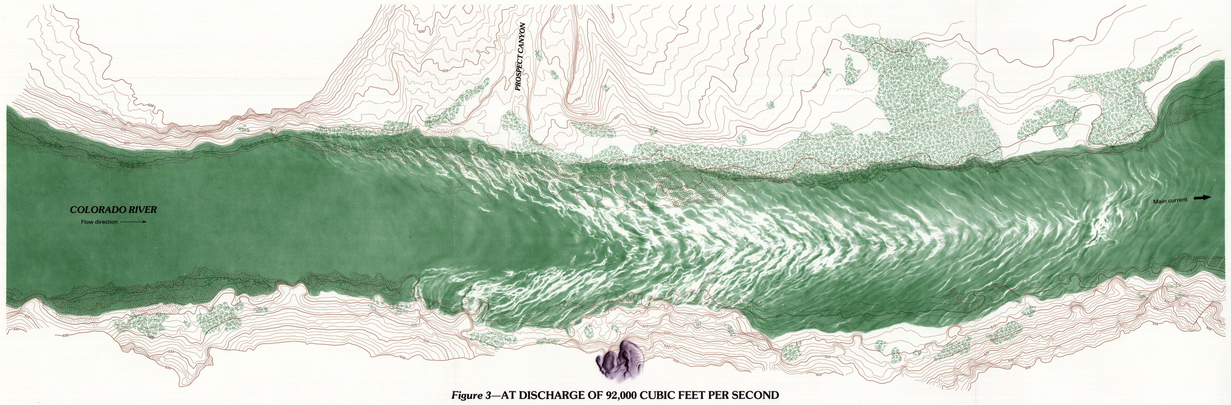


Figure 3—AT DISCHARGE OF 92,000 CUBIC FEET PER SECOND

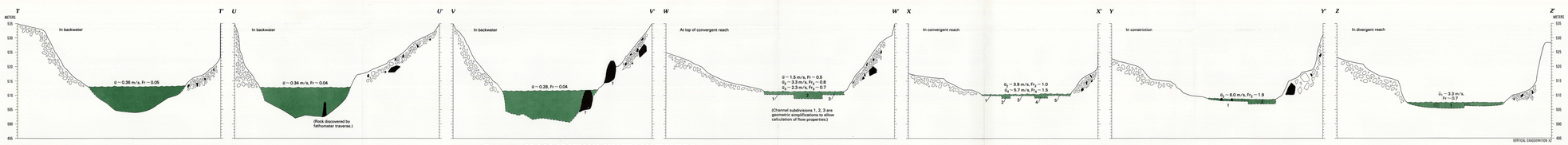


Figure 4—CROSS SECTIONS SHOWN ON FIGURE 5

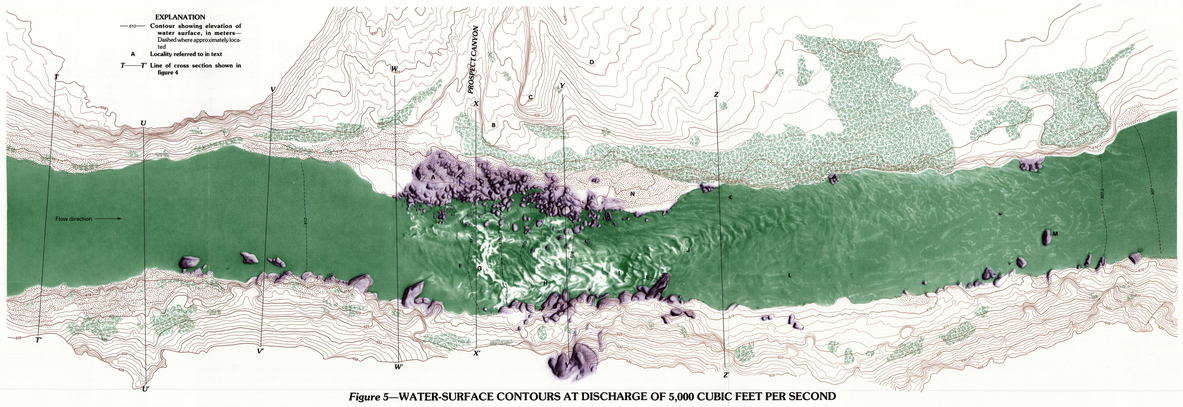


Figure 5—WATER-SURFACE CONTOURS AT DISCHARGE OF 5,000 CUBIC FEET PER SECOND

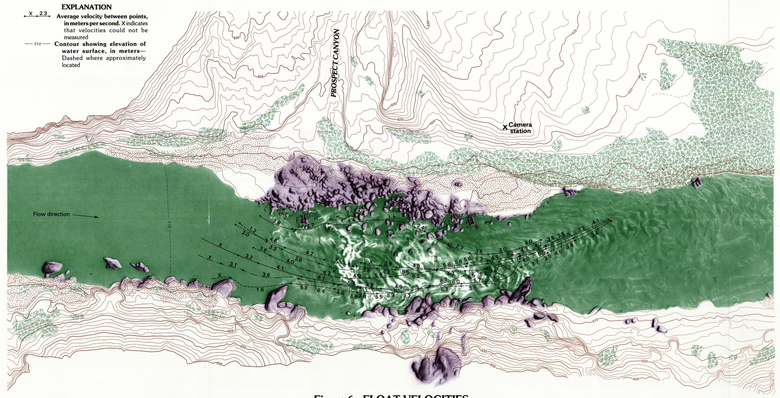
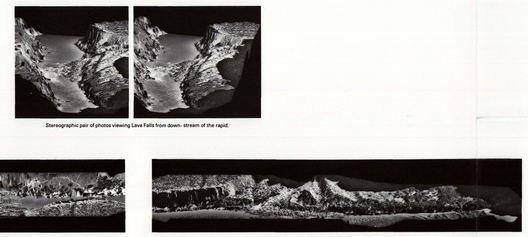


Figure 6—FLOAT VELOCITIES



Stereographic pair of photos viewing Lava Falls from down- stream of the rapid.

View from Prospect Creek north toward the lava cliffs; note the remnants of the old debris fans in the foreground. Vertical relief exaggerated.

View from north looking up Prospect Canyon. The sloping flat surfaces are remnants of old debris fans. Vertical relief exaggerated.

Figure 7—COMPUTER-ENHANCED DIGITAL IMAGES OF LAVA FALLS RAPID AT 5,000 CFS

DISCUSSION

The general configuration of Lava Falls Rapids (figs. 1, 2, 3, and 4) is caused by a debris fan from Prospect Canyon that has forced the Colorado River against the northwest wall of the Grand Canyon. The debris fan that presently extends into the channel is the youngest of a sequence of debris flows that have come down Prospect Canyon; several others form terraces on the canyon walls downstream (figs. 1, 2, 3, and 5; and photo, fig. 7). The most prominent debris fan is exposed when the discharge is below 5,000 cubic feet per second (cfs; fig. 1).

Large boulders that have fallen from lava cliffs on the northwest side of the canyon also cause important waves. Boulders as much as 10 m in diameter are found along the northwest shore (for example, at **E**, fig. 5), and the channel bottom under Lava Falls is probably rougher than under any other rapid in the Grand Canyon. The "ledge" (**F**, fig. 5) that forms the so-called "Ledge Hole" (**G**, fig. 5) appears to be formed of a few large boulders of lava. Some boulders on this shore are not even visible at 5,000 cfs discharge (see cross section *U–U'* fig. 4).

At a discharge of 5,000 cfs the water surface through the rapid drops 4 m (from about 512 m to 508 m elevation; fig. 5). The slope of the water surface through the rapid decreases as the discharge increases, and the water surface through the rapid is approximately horizontal when the rapid in figures 1, 2, and 3. The drop in elevation is quite uniform on the southeast side of the river where shallow water spills across the debris fan, but on the northwest side of the channel the elevation drop is concentrated at a 2.5-m "falls" near the center of the rapid.

Streamlines (the paths of floats) and velocities of floats were determined from Super-8 motion pictures taken from the camera station shown (fig. 6). 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 the map. Each velocity numeral (in units of meters/second, *m/s*) refers to the section of streamline between large dots. The different dash-dot patterns distinguish the different streamlines. The discharge was 10,000 cfs when these floats were launched. Because the bathymetry reflects a discharge of 5,000 cfs or 5,000 cfs is assumed to be the boundary condition for the hydraulic computations from the base map to the streamlines. The only change of significance is that the water at 10,000 cfs covered the southern debris fan to a higher level, so that the southernmost trajectory shown was possible at 10,000 cfs, whereas it would not have been possible at 5,000 cfs. Slight (about 10–15%) differences in velocity between floats launched at 7,000 cfs and 10,000 cfs were noticed in the converging section of the rapid and in the tailwaves (see Kieffer, 1987), but these were judged not significant enough to include in this map.

Discharge in all cross sections (fig. 4) is 5,000 cfs. Depths in cross sections *T–T'*, *U–U'*, and *V–V'* were measured during fathometer traverses; depths in other cross sections were calculated from the measured velocities and continuity (*Q=VA*; fig. 4).

The flow pattern at Lava Falls Rapids is determined not only by the obvious large boulders but also by the constrictions and divergences of the channel; these changes in channel shape occur both laterally (map view, fig. 1) and vertically (cross sections, fig. 4; aerial views, fig. 7). For a general discussion of the flow patterns in rapids, see Kieffer (1985, 1987).

The entire area above Lava Falls Rapids shown on these maps is a backwater caused by the constriction of the channel by the Prospect Canyon debris fan and the rockfalls on the northwest bank. Because this region is a backwater, flow velocities are very low (approximately 0.3 – 0.4 m/s) at 5,000 cfs in cross sections *T–T'*, *U–U'*, and *V–V'*).

Flow accelerates from the backwater into the constriction. Between cross sections *V–V'* and *W–W'*, the channel narrows, and the channel bottom rises from an elevation of 502 m in the section *V–V'* to 504 m in the section *W–W'*. Boulders as much as 2 m in diameter are encountered underwater, and possibly as high as 5.0 m by cross section *X–X'*. In the stretch of the river between *V–V'* and *W–W'*, the water-surface elevation is nearly constant at 512 m, but the water velocity increases to 3.3 m/s to accommodate the discharge in the constricted channel.

The channel becomes tightly constricted at *X–X'* by both the debris fan and the boulders on the lava cliffs. More than half of the water is funneled into the main channel on the northwest side of the river. In this region of the main channel the drop of water surface is about 1 m, and the velocity is about 5.6 m/s.

Between *X–X'* and *Y–Y'* the water surface drops another 2.5 m, whereas the channel bottom drops only about 1 m to 500 m elevation. The velocity increases to about 6 m/s at cross section *Y–Y'*. Although the channel bottom is relatively smooth between *Y–Y'* and the tailwaves (**J**), it is only about 3.5 m/s at cross section *Z–Z'*. At *Z–Z'*, the channel bottom is at approximately 505-m elevation, 2 to 3 m higher than in the backwater upstream of the rapids.

The Froude number ($Fr=\bar{u}/(gD)^{1/2}$, where $\bar{u}$ is the average flow velocity, D is the average depth of the flow, and g is the acceleration of gravity) is a dimensionless measure of the relative importances of inertial vs. 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 5,000 cfs, the following values of Froude number were obtained: Fr=0.05 at *V–V'*; Fr=0.04 at *W–W'*; Fr=0.04 in the main channel (see channel and fig. 5) in the smaller southeast channel at *X–X'*; Fr=2.4 in the main channel at *Y–Y'*; and Fr=0.8 in the tailwaves at *Z–Z'*. Uncertainties of these values are of the order of 30%. Nevertheless, these Froude numbers indicate that the flow changes from subcritical conditions (Fr<1) upstream of the constriction, to supercritical conditions (Fr>1) in the convergence and constriction, and back to critical (Fr=1) and then subcritical (Fr<1) in the diverging section.

The standing waves of Lava Falls Rapids are features of supercritical flow. In the converging part of the channel, the flow accelerates down a smooth tongue on the north side of the channel into a series of strongly breaking right lateral waves (**M**, fig. 5 and analogous places on figs. 2 and 3), interpreted here as oblique hydraulic jumps. Air is entrained into the water by these waves. In the center of the channel, the ledge (**F**, fig. 5) forms a barrier to the flow; water pours over the ledge into the Ledge Hole, a strong eddy (**G**, fig. 5). As shown by the streamlines in figure 6, most of the flow goes down the main-current side of the channel, and strongly breaking waves are formed in the ledge hole and downstream. Because of the constriction and elevation, the flow becomes strongly supercritical. Obstacles within the supercritical flow cause large waves, e.g., the waves by the rocks at **Q**, **H**, and I in figure 6. The excess energy of the flow (stored in the backwater and gained from the 6-m descent) is dissipated in the waves, as well as in turbulent response to the large-scale roughness of the bed.

The runout from the rapid (the tailwaves *J* on both sides of *Z–Z'*) consists of a train of gently breaking waves and swells. The Froude number is about 1 at the upstream end of the tailwaves, and decreases to 0.8 by *Z–Z'*. There are eddies on both sides of the main current below the rapid (**K** and **L**, fig. 5). The south eddy (**K**, fig. 5) produces a sandy beach (**N**) during high flows if sediment is present. At 92,000 cfs, the main current (the main jet produces pronounced vortices and small whirlpools in the region of the tailwaves (*J*).

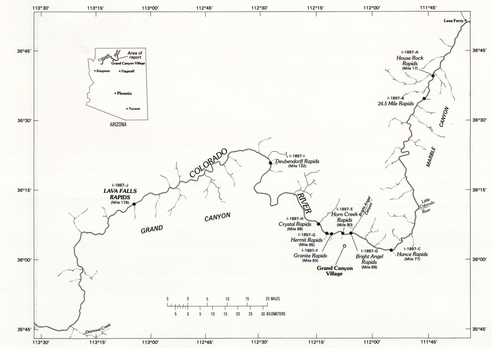
The most significant hydraulic features in Lava Falls Rapids are the Ledge Hole at the top of the rapid (**G**), the right lateral waves (especially the so-called "V-wave hole" at **H**), and the so-called "third hole" (**I**) near the black rock (**E**) at the bottom of the rapid. These three hydraulic features are significant at all discharges up to the highest documented, a flow rate of 92,000 cfs. At 92,000 cfs, an additional strong wave arises downstream in the center of the channel (**M**, fig. 5; wave illustrated in fig. 3). Waves are present at all discharges documented because Lava Falls Rapids appears to maintain supercritical flow through all of these discharges.

The hydraulic features of Lava Falls Rapids reflect a dynamic equilibrium between the flow in the Colorado River and the debris fans from Prospect Canyon. Debris flows come from Prospect Canyon. 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 on the transient sediment load of the river. The channel configuration changes with time, both gradually and catastrophically.

REFERENCES CITED

Kieffer, Susan Werner, 1985, The 1983 hydraulic jump in Crystal Rapid: Implications for river-running and geomorphic evolution in the Grand Canyon: Journal of Geology, v. 93, p. 385–406.

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


EXPLANATION FOR FIGURE 4
Channel boundary—Dashed where estimated
Shear zone in the flow
Fr Froude number
ū Average flow velocity, in meters per second
Debris fan
Talus
Water
Rock
Lava Falls
Area of Grand Canyon Village
Kingman
Flagstaff
Phoenix
Tucson
ARIZONA
House Rock Rapids
24.5 Mile Rapids
CANYON
MARBLE
COLORADO
Deubendorff Rapids
RIVER
LAVA FALLS RAPIDS
GRAND
CANYON
Crystal Rapids
Horn Creek Rapids
Hance Rapids
Granite Rapids
Grand Canyon Village
Bright Angel Rapids
Hance Rapids
Havasu Canyon
Bill Hall Canyon
Pipe Creek
Pipe Creek Rapids
Pipe Creek Rapids
Pipe Creek Rapids