HYDRAULIC MAP OF DEUBENDORFF RAPIDS, GRAND CANYON, ARIZONA By

VERTICAL EXAGGERATION X2

CONTOUR INTERVAL 1 METER LONG-DASHED LINES REPRESENT 0.5-METER CONTOURS



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Survey, Flagstaff, Arizona, from aerial photographs flown in 1984 by the Bureau of Reclamation, Series GCES Airbrush portrayal of hydraulic features by Patricia Hagerty Gray, U.S. Prepared on behalf of the Bureau of Reclamation under Interagency Acquisition No. 6-AA-40-04190

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

1–1897–B 24.5 Mile Rapids 5 0 5 10 15 20 MILES 5 0 5 10 15 20 25 30 KILOMETERS LOCATIONS OF MAJOR RAPIDS IN THE COLORADO RIVER, GRAND CANYON, ARIZONA I-1897-A indicates series number of map for each rapids.

Canyon debris fan underwater. In this same short distance, the water-surface elevation drops Kieffer, Susan Werner, 1987, The rapids and waves of the Colorado River, Grand Canyon, about 0.5 m, but the water velocity increases to about 4 m/s to accommodate the discharge in the constricted channel. An arbitrary assumption was made that 80 percent of the discharge Arizona, U.S. Geological Survey Open-File Report 87-096.

Rock Rapids; upstream from the debris fans that cause each rapid, there seems to be an eddy so topography and the contribution from the catastrophic rockfalls and tributary floods, but also weak at low discharges that one could call it a "pond" (Kieffer, 1987). The channel is shown as on the transient sediment load of the river. The channel configuration changes with time, both having a flat bottom or rectangular shape in figure 4; the reader should recognize that this is an gradually and catastrophically. idealization used for flow calculations, and that the channel is covered with large boulders **REFERENCES** Flow accelerates from the backwater into the constriction. At Deubendorff Rapids, from Kieffer, Susan Werner, 1985, The 1983 hydraulic jump in Crystal Rapid: Implications for cross section V-V' to cross section W-W', the channel narrows, and the channel bottom rises from an elevation of 596.5 m to about 600 m where it meets the upstream part of the Galloway river-running and geomorphic evolution in the Grand Canyon: Journal of Geology, v. 93,

rapid (L, the strongest eddy on the west, and M, on the east, fig. 3). Both eddies can produce sandy beaches (D, N, fig. 3) during high flows if sediment is available. The shearing between the eddies and main jet produces pronounced vortices and small whirlpools in the region of the tailwaves (1). The most significant hydraulic features in Deubendorff Rapids are the rock fields A and B at the top of the rapid, the so-called "Table Rock" or "Alligator Rock" (F), the wave G, and the rocks and waves at H. The rock fields A and B become submerged by 30,000-cfs discharge (fig. 2), but the other hydraulic features remain significant at all discharges to 30,000 cfs, the highest discharge for which conditions were documented at this rapid. Waves are present at all The area above Deubendorff Rapids shown on these maps is a backwater caused by the discharges documented because Deubendorff Rapids appears to maintain supercritical flow constriction of the channel by the Galloway Canyon debris fan. Because this region is a through this range of discharges. backwater, flow velocities are very low (approximately 0.3 m/s at 5,000 cfs at cross section The hydraulic features of Deubendorff Rapids reflect a dynamic equilibrium between the V-V'). In cross section V-V', the east half of the channel has been assumed to be an eddy with flow in the Colorado River channel and flooding or debris flows from Galloway and Stone negligible flow velocity because it is very similar to water in the same configuration at House Canyons. The configuration of the channel bottom depends not only on the bedrock

converging-diverging channels; in contrast, at 5,000 cfs (fig. 1), the effect of the individual boulders is much more pronounced so that the overall standing-wave pattern is more difficult to interpret. For a general discussion of the flow patterns in rapids, see Kieffer (1985, 1987). Velocities of floats were determined from Super-8 motion pictures taken from the camera station shown (fig. 5), as were flow streamlines (paths of floats such as the one shown in 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 trajectories shown are those of floats launched when the discharge was about 7,000 cfs and water conditions were very similar to those portrayed by the airbrush illustration. The trajectories shown all lie in the western part of the channel, the so-called "left run" alluded by river-runners; it is the only navigable route at low discharges (even though it begins on the river-left side of the channel, the navigable route ends toward the right side of the channel because of the boulders and waves at H that must be avoided). A second group of floats was launched when the discharge was 12,000 cfs. Their trajectories and velocities (not shown) were similar on the west side of the channel. However, one float was able to follow a trajectory east of rocks A and **B**—the so-called "right run" that opens up for navigation at higher discharges (note in fig. 2 how rocks near A and B are covered by water at 30,000 cfs).

fathometer traverse and was arbitrarily lowered 0.5 m to make the water-surface elevation agree with that shown (601.5 m) on the topographic map (fig. 1). Depths in other cross sections were calculated from the mass-continuity equation as described in Kieffer (1987). The flow pattern at Deubendorff Rapids is determined by two factors described above: (1) the overall geometry of constriction and divergence of the channel, and (2) individual boulders. The constriction and divergence occurs both laterally (map view, fig. 1) and vertically (cross sections, fig. 4). At 30,000 cfs, the waves are typical of standing waves associated with

In order to demonstrate the complexity of the flow in the rapids, a perspective of vertical, as well as horizontal, relations is shown in the cross sections of figure 4. Discharge in all cross sections is 5,000 cfs. The depth in cross section V-V' was measured at 7,000 cfs during a

large uncertainties, the water-surface contours give a general idea of where the elevation drop occurs within the rapid. The surface slope of the water 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 and 2.

boulder F has been informally called "Table Rock" or "Alligator Rock" by river runners. There is a prominent wave at G (fig. 3), but the major hazard of the rapid is the continuously rocky bottom and rocks and the waves formed by boulders, for example, particularly at **H** (fig. 3). At a discharge of 5,000 cfs, the water surface through the rapid drops 6 m (from about 601 m to 595 m) in elevation (fig. 3). Because of the extreme rockiness of the channel of Deubendorff Rapids, the water-surface contours shown are very generalized: it is estimated that at any specific point the elevation error could be ± 1 m (because of rocks and waves) and, within the channel, the location of a contour could be uncertain by as much as \pm 10 m (because of the difficulty of doing stereographic contouring across turbulent water). In spite of these relatively

INTRODUCTION The general configuration of Deubendorff Rapids (figs. 1 and 2) is caused by a debris fan emerging from Galloway Canyon that has forced the Colorado River against the west wall of the river channel. As shown in figure 1, much of the debris fan is exposed when the discharge of the Colorado River is below 5,000 cubic feet per second (cfs), including prominent groups of rocks near the center of the channel (A and B in fig. 3). At present, only a small debris fan (C, fig. 3) exists at the mouth of Stone Canyon (just downstream from Galloway Canyon), but the carved reentrant (extending in bedrock above D-D₁, fig. 3) across from this canyon suggests that in the past Stone Canyon has influenced the course of the river more than it does at the present time. Bedrock at river level is a diabase sill that intruded into the Bass Limestone of the Unkar difficult. The large boulder E (fig. 3) is from the Supai Group, and the large boulder under the water at F (fig. 3) is Bass Limestone; because of its position directly in the center of the main flow,

m/s. The channel bottom drops, on average, only about 3.5 m, but because the boulders can be of this order in diameter, the average numbers cited here are highly variable.

Figure 6—Typical float used for measurement of water-surface velocities. Float is approximately 1 m high and contains 800 grams of sand in its base.

flows in the main (west) channel at cross section W-W'.

measurements were made just a short distance upstream.

At low discharges, the channel is tightly constricted from W-W' through Y-Y'. Between

Between Y-Y' and Z-Z', the water surface drops another 2 m from 597.5 m to 595.5 m, and

The Froude number $(Fr=\bar{u}/(gD)^{1/2})$, where \bar{u} is the average flow velocity, g is the acceleration

the channel bottom drops from 596.5 to 594 m. The velocity in cross section Z-Z' was not

measured, but it was assumed to be approximately 5 m/s—the same as that where the last

of gravity, and D is the average depth of the flow) 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. At 5,000 cfs, the following values were obtained:

Fr=0.04 at V-V'; Fr=1.3 at W-W'; Fr=2.3 at X-X'; Fr=1.6 at Y-Y'; and Fr=1.3 in the tailwaves at

Z-Z'. Uncertainties of these values are of the order of 30 percent. 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. Thus, from

cross section W-W' as far downstream as velocity measurements could be made (to the

upstream side of Stone Canyon), the calculations suggest that the flow is supercritical. This

conclusion is consistent with the fact that this region is covered with standing waves, a

characteristic feature in supercritical flow. Critical conditions can be assumed in the tailwaves I

(fig. 3) below Stone Canyon (Kieffer, 1987), and a return to subcritical flow in the main jet occurs

only downstream of the tailwaves (see Maps I-1897-A and J for similar flow in other rapids).

flow. The first type belongs to the class of waves typical of flows in converging channels: undular

waves near Fr=1 conditions and breaking oblique waves at higher Froude numbers. At 5,000

cfs, the flow accelerates down a smooth tongue on the west side of the channel; undular waves,

J (fig. 3), on the tongue probably indicate the location of Fr=1 conditions. At 30,000 cfs, the flow

divides into two channels split by rock piles A and B (fig. 3); the flow in each channel shows a

tongue that ends in a series of strongly breaking oblique waves (K in fig. 3, and analogous places

in fig. 2). These breaking waves are interpreted here as oblique hydraulic jumps. Air is entrained

into the water by these waves. The regular pattern normally formed by standing waves in a

smoother channel of more regular geometry (for example, a laboratory flume) is broken up in

Deubendorff Rapids by the projection of boulders into the flow, for example, at F, G, and H. As

shown by the streamlines in figure 5, most of the flow initially converges toward the west, then is

forced back toward the east bank above Stone Canyon, and finally is forced back to the west

individual obstacles protruding up into the flow (Kieffer, 1987). These cause large standing

waves, for example, F, G, and H in figure 3. 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

sharply breaking waves above Stone Canyon, where the Froude number is calculated to be

greater than 1, and gentler waves and swells below Stone Canyon, where the flow has probably

decelerated to Fr=1 conditions. There are eddies on both sides of the main current below the

The runout from the rapid (I) is unusually long and complex and consists of a train of rather

The second type of waves characteristic of supercritical flow are those associated with

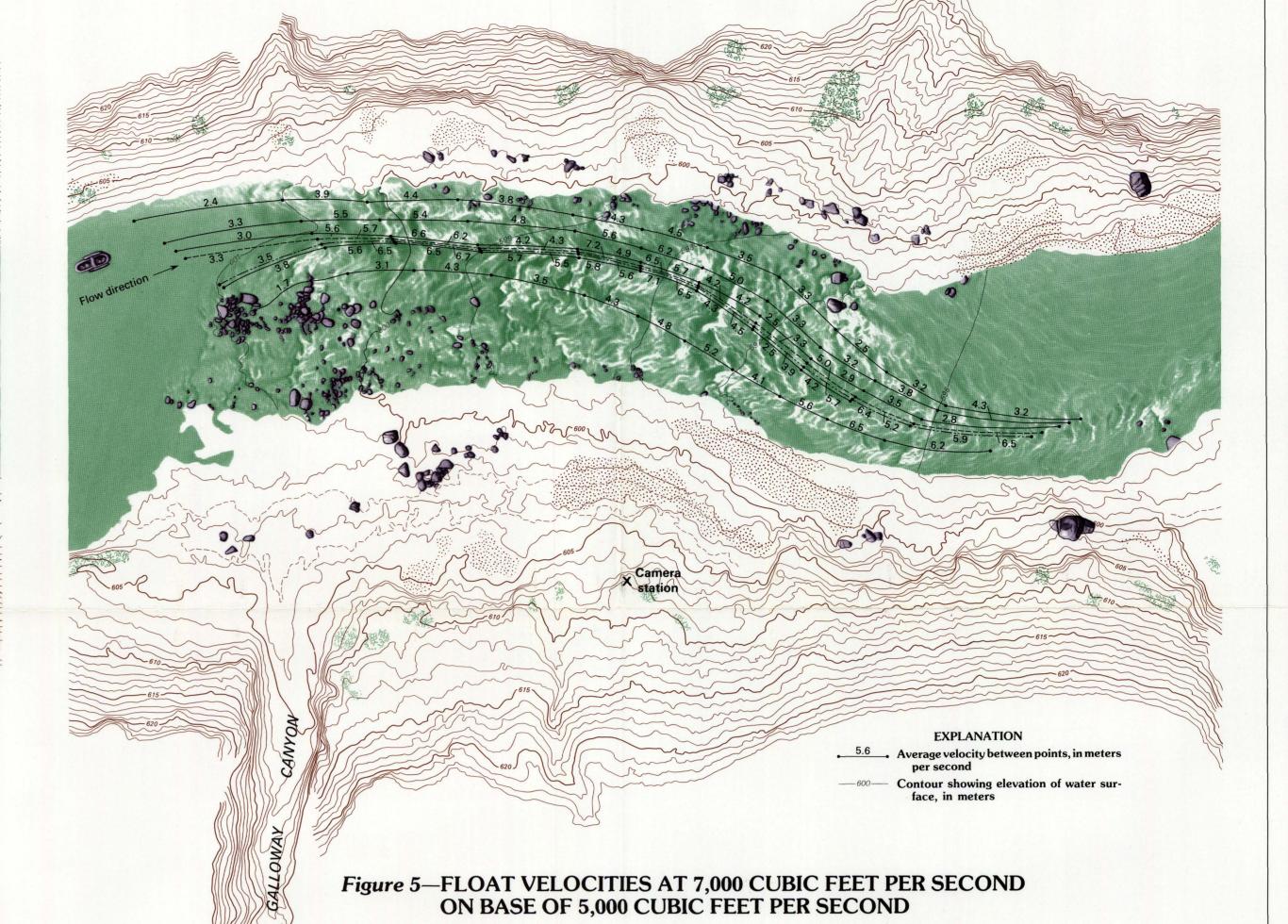
bank in the runout of the tailwaves because of the small debris fan C at Stone Canyon.

response to the large-scale roughness of the bed.

The standing waves of Deubendorff Rapids represent two types of waves in supercritical

these cross sections, the water surface drops about 4.5 m, and water velocities are typically 5-7





HYDRAULIC MAPS OF MAJOR RAPIDS, GRAND CANYON, ARIZONA

DEUBENDORFF RAPIDS

MAP I-1897-I

MISCELLANEOUS INVESTIGATIONS SERIES

DEPARTMENT OF THE INTERIOR U.S. GEOLOGICAL SURVEY

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

EXPLANATION

--- Contour showing elevation of water sur-

face, in meters

A Locality referred to in text

Assume 30 percent of cross section blocked by rocks

In constriction

 $\bar{u} \sim 4$ m/s, Fr ~ 1.3

Y'Z

Figure 4—CROSS SECTIONS SHOWN ON FIGURE 3

V——V' Line of cross section shown in figure 4

*NOTE: This is a typical commercial passenger motor-boat, 10 m (33 ft) in length. It is shown only to

METERS

METERS

At beginning of constriction

 $\bar{u}\sim 0.3$ m/s, Fr ~ 0.04

fathometer tracing)

 \bar{u} \sim 4.5 m/s, Fr \sim 1.6

illustrate scale and should not be interpreted to indicate either a landing site or a navigation route. in navigating the rapids. The illustrations are airbrush renderings of the water structure and of some rocks. As such, they represent only the

Susan Werner Kieffer

 $\bar{u}\sim 5$ m/s, Fr ~ 2.3

EXPLANATION

Shear zone in the flow

- Channel boundary—Dashed where estimated

Average flow velocity, in meters per second

PREPARED IN COOPERATION WITH THE BUREAU OF RECLAMATION AND THE NATIONAL PARK SERVICE