DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

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

HYDRAULIC MAPS OF MAJOR RAPIDS, GRAND CANYON, ARIZONA
BRIGHT ANGEL RAPIDS
MISCELLANEOUS INVESTIGATIONS SERIES
MAP I-1897-D

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

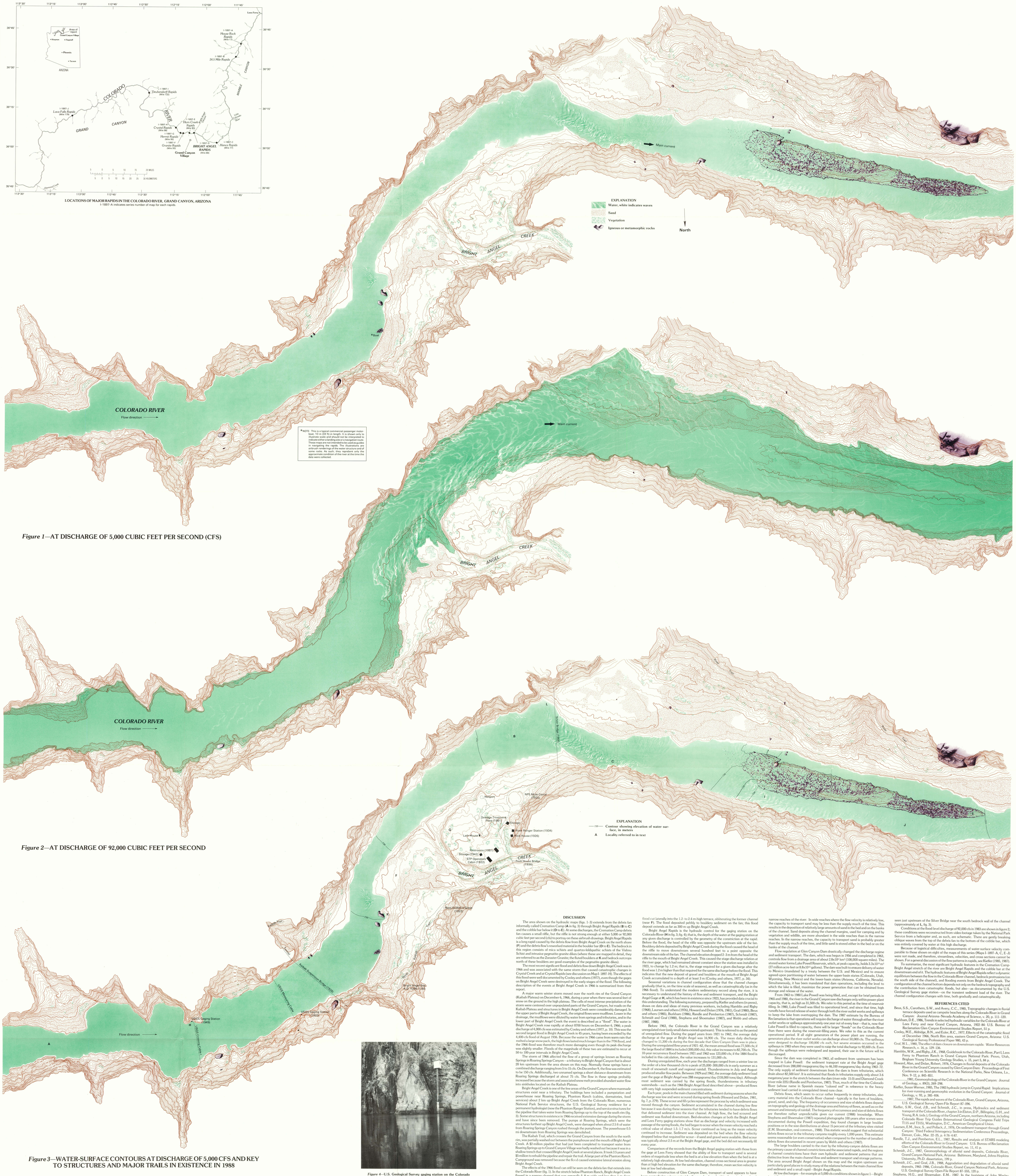

Figure 4—U.S. Geological Survey gaging station on the Colorado River near Bright Angel Creek, with Zoraster Granite and Vishnu Schist bedrock in background.

DISCUSSION

The area shown on the hydraulic maps (figs. 1–3) extends from the debris fan informally called Cremation Camp (**A** in fig. 3) through Bright Angel Rapids (**B** to **C**) and the cobble bar below it (**D** to **E**). At some discharges, the Cremation Camp debris fan causes a small riffle, but the riffle is not strong enough at either 5,000 or 92,000 cubic feet per second (cfs) to portray on these airbrush drawings. Bright Angel Rapids is a long rapid caused by the debris flow from Bright Angel Creek on the north shore (**F**) and the debris flow's reworked material in the boulder bar (**D** to **E**). The bedrock in this region consists of mica schists and quartzo-feldspathic schists of the Vishnu Schist and intrusive pegmatite-granite dikes (where these are mapped in detail, they are referred to as the Zoraster Granite; the fluted boulders at **K** and bedrock outcrops north of these boulders are one good examples of the pegmatite-granite dikes).

The most recent significant flood and debris flow down Bright Angel Creek was in 1966 and was associated with the same storm that caused catastrophic changes in Crystal Creek and at Crystal Rapids (see discussion on Map I-1897-H). The effects of this flood were well documented by Cooley and others (1977), even though the gages on Bright Angel Creek were destroyed in the early stages of the flood. The following description of the events at Bright Angel Creek in 1966 is summarized from their report.

A major warm winter storm moved over the north rim of the Grand Canyon (Kaibab Plateau) on December 6, 1966, during a year when there was several feet of snow on the ground in the high plateau. The cells of most intense precipitation of the storm were centered over unpopulated parts of the Grand Canyon, but roads on the Kaibab Plateau and structures in Bright Angel Creek were considerably damaged. In the upper parts of Bright Angel Creek, the original flows were mudflows. Lower in the drainage, the mudflows were diluted by water from springs and tributaries, and in the lower part of Bright Angel Creek the event is described as a "flood". The water in Bright Angel Creek rose rapidly at about 0700 hours on December 6, 1966; a peak discharge of 4,000 cfs was estimated by Cooley and others (1977, p. 10). This was the second largest flood in Bright Angel Creek in 91 years, having been exceeded by the 4,400-cfs flood of August 1936. Because the water in 1966 came from warm rain that melted a large snow pack, the high flows lasted much longer than in the 1936 flood, and the 1966 flood was therefore much more damaging even though its peak discharge was slightly smaller. Floods of the magnitude of these two are estimated to recur at 50- to 100-year intervals in Bright Angel Creek.

The storm of 1966 affected the flow of a group of springs known as Roaring Springs in Roaring Springs Canyon—a tributary to Bright Angel Canyon that is about 20 km upstream from the area shown on this map. Normally these springs have a combined discharge ranging from 5 to 15 cfs. On December 9, the flow was estimated to be 150 cfs. Additionally, two unnamed springs a short distance downstream from Roaring Springs discharged at about 75 cfs. The flow in these springs probably increased because the storm and associated snow melt provided abundant water flow into sinkholes located on the Kaibab Plateau.

Bright Angel Creek is one of the few areas of the Grand Canyon where manmade structures exist near a tributary. The buildings here included a pumpstation and powerhouse near Roaring Springs, Phantom Ranch (cabins, dormatories, food services) about 2 km up Bright Angel Creek from the Colorado River, numerous National Park Service structures, the U.S. Geological Survey residence for a permanent hydrologist (now the Phantom Ranger Station), and service structures for the pipeline that takes water from Roaring Springs up to the top of the south rim (fig. 3). Some structures in existence in 1966 received extensive damage during the storm and have since been removed. The pumps at Roaring Springs, which were the structures furthest up Bright Angel Creek, were damaged when about 2.5 ft of water from Roaring Springs Canyon rushed through the pumphouse. The powerhouse 0.5 mi downstream from Roaring Springs was demolished.

The Kaibab Trail, which crosses the Grand Canyon from the south to the north rim, was partially washed out between the pumphouse and the mouth of Bright Angel Creek. A $2-million pipeline that had just been completed to transport water from Roaring Springs up to Grand Canyon Village was badly washed out because it was in a shallow trench that crossed Bright Angel Creek at several places. It took 3.5 years and $5 million to rebuild the pipeline and repair the trail. A large part of the Phantom Ranch Campground was removed because the flood caused extensive lateral erosion along Bright Angel Creek.

The effects of the 1966 flood can still be seen on the debris fan that extends into the Colorado River (fig. 1). In the stretch below Phantom Ranch, Bright Angel Creek flowed in a narrow channel that was generally 5–8 m wide and less than 1 m deep before the flood. The flood plain that adjoined the channel was as much as 60 m wide and was bounded by terraces (gravel bars) between 1.2 and 2.4 m above the streambed (such as **G** in fig. 3). The stream channel was bordered by thick brushy and reedy riparian vegetation (note trees near **G**). The flood of 1966 removed some of the vegetation, rearranged or scoured the bars, obliterated the channel, and removed part of the original terrace. Between Phantom Ranch and the Colorado River, the flood cut laterally into the 1.2- to 2.4-m-high terrace, obliterating the former channel (near **F**). The flood deposited pebbly to bouldery sediment on the fan; this flood deposit extends as far as 300 m up Bright Angel Creek.

Bright Angel Rapids is the hydraulic control for the gaging station on the Colorado River (**H** in fig. 3; fig. 4); that is, the depth of the water at the gaging station at any given discharge is controlled by the geometry of the constriction at the rapid. Before the flood, the head of the riffle was opposite the upstream side of the fan. Bouldery debris deposited by Bright Angel Creek during the flood caused the head of the riffle to move downstream several hundred feet to a point opposite the downstream side of the fan. The channel elevation dropped 2–3 m from the head of the riffle to the mouth of Bright Angel Creek. This caused the stage-discharge relation at the river gage, which had remained almost constant since the station was installed in 1923, to change by 1.2 m; that is, the stage required for a given discharge after the flood was 1.2 m higher than that required for the same discharge before the flood. This indicates that the new deposit of gravel and boulders at the mouth of Bright Angel Creek accumulated to a depth of at least 3 m (Cooley and others, 1977, p. 34).

Seasonal variations in channel configuration show that the channel changes gradually (that is, on the time scale of seasons), as well as catastrophically (as in the 1966 flood). To understand the modern sedimentary record along the river, it is necessary to understand the history of flow and sediment transport, and the Bright Angel Gage at **H**, which has been in existence since 1923, has provided data crucial to this understanding. The following summary, prepared by Kieffer and others (in press), draws on data and ideas of many previous workers, including Hamblin and Rigby (1968), Laursen and others (1976), Howard and Dolan (1976, 1981), Graf (1980), Beus and others (1985), Burkham (1986), Randle and Pemberton (1987), Schmidt (1987), Schmidt and Graf (1988), Stephens and Shoemaker (1987), and Webb and others (1987, 1988).

Before 1963, the Colorado River in the Grand Canyon was a relatively unregulated river (only small dams existed upstream). This is referred to as the period of unregulated flow. During the gaged years from 1921 to 1962, the average daily discharge at the gage at Bright Angel was 16,900 cfs. The mean daily discharge changed to 11,300 cfs during the first decade that Glen Canyon Dam was in place. During the unregulated flow years of 1921–62, the mean annual flood was 77,500 cfs; if the large flood of 1884 is included (300,000 cfs), this value increases to 82,700 cfs. The 100-year recurrence flood between 1921 and 1962 was 123,000 cfs; if the 1884 flood is included in this calculation, the value increases to 131,000 cfs.

During unregulated flow, each year the discharges ranged from a winter low on the order of a few thousand cfs to a peak of 25,000–300,000 cfs in early summer as a result of snowmelt runoff and regional rainfall. Thunderstorms in July and August produced smaller flow peaks. Between 1929 and 1962, the average daily sediment load past the gage at Bright Angel was 288 megagrams/day (318,000 tons/day). Although most sediment was carried by the spring floods, thunderstorms in tributary watersheds—such as the 1966 Bright Angel flood described above—produced flows with very high suspended-sediment concentrations.

Each year, pools in the main channel filled with sediment during seasons when the discharge was low and were scoured during spring floods (Howard and Dolan, 1981, fig. 7, p. 279). These scour and fill cycles represent the process by which sediment was moved through the canyon. Sediment accumulated in the channel during low flow because it was during these seasons that the tributaries tended to have debris flows that delivered sediment into the river channel. At high flow, the bed scoured and sediment was flushed downstream. Bed-elevation changes at both the Bright Angel and Lees Ferry gaging stations show that as discharge and velocity increased with passage of the spring floods, the bed began to scour when the mean velocity reached a critical value of about 1.5–1.7 m/s. Scour continued as long as the mean velocity continued to increase. Sediment was deposited on the bed when the flow velocity dropped below that required for scour—if sand and gravel were available. Bed scour was typically about 2.5 m at the Bright Angel gage, and the bed did not necessarily fill every year.

Comparison of the records from the Bright Angel gaging station with those from the gage at Lees Ferry showed that the ability of flow to transport sand is several orders of magnitude less when the bed is at a low elevation than when the bed is at a relatively high elevation. At low bed elevation, channel cross-sectional area is greater than at high bed elevation for the same discharge; therefore, mean section velocity is less at low bed elevation.

Before construction of Glen Canyon Dam, transport of sand appears to have been controlled to a large extent by the supply of sand within the main channel and from tributaries. Even though seemingly large quantities of sand passed through Glen Canyon, sand supply was apparently limited compared to transport capacity much of the time.

The Bright Angel gage is set in a relatively narrow part of the channel; the Lees Ferry gage is in a wider part of the channel. Comparison and contrast of the records from these two gages suggests the following generalization of phenomena in wide and narrow reaches of the river: In wide reaches where the flow velocity is relatively low, the capacity to transport sand may be less than the supply much of the time. This results in the deposition of relatively large amounts of sand in the bed and on the banks of the channel. Sand deposits along the channel margins, used for camping and by vegetation and wildlife, are more abundant in the wide reaches than in the narrow reaches. In the narrow reaches, the capacity to transport sand is probably greater than the supply much of the time, and little sand is stored either in the bed or on the banks of the channel.

Flow regulation at Glen Canyon Dam drastically changed the discharge regime and sediment transport. The dam, which was begun in 1956 and completed in 1963, controls flow from a drainage area of about 2.8×10^5 km² (108,000 square miles). The stored water forms Lake Powell Reservoir, which, at peak capacity, holds 3.3×10^{10} m³ (27 million acre-feet or 8×10^{12} gallons). The dam was built to ensure delivery of water to Mexico (mandated by a treaty between the U.S. and Mexico) and to ensure agreed-upon partitioning of water between the upper-basin states (Colorado, Utah, Wyoming, New Mexico) and the lower-basin states (Arizona, California, Nevada). Simultaneously, it has been mandated that dam operations, including the level to which the lake is filled, maximize the power generation that can be obtained from storage and release of the water.

From 1963 to 1980 Lake Powell was being filled, and, except for brief periods in 1965 and 1980, the river in the Grand Canyon saw discharges only within power-plant capacity, that is, as high as 31,500 cfs. We refer to this period as the time of reservoir filling. In 1980, Lake Powell was filled to operational level, and since that time, high runoffs have forced release of water through both the river outlet works and spillways to keep the lake from overtopping the dam. The 1987 estimate by the Bureau of Reclamation is that operations will require discharge of water through either the river outlet works or spillways approximately one year out of every four—that is, now that Lake Powell is filled to capacity, there will be larger "floods" on the Colorado River than there were during the reservoir-filling years. We refer to this as the current operational period. If all eight generators of the power plant are running, the generators plus the river outlet works can discharge about 50,000 cfs. The spillways were designed to discharge 100,000 cfs each, but severe erosion occurred in the spillways in 1983 when they were used to raise the total discharge to 92,600 cfs. Even though the spillways were redesigned and repaired, their use in the future will be discouraged.

Since the dam was completed in 1963, all sediment from upstream has been trapped in Lake Powell: the sediment transport rate at the Bright Angel gage decreased from 288,000 megagrams/day to 46,100 megagrams/day during 1963–72. The only supply of sediment downstream from the dam is from tributaries, which drain about 82,500 km². It is estimated that floods in tributaries supply only about 3.6 megatons/year in the stretch between the dam (river mile 15.0) and Diamond Creek (river mile 225) (Randle and Pemberton, 1987). Thus, much of the time the Colorado River (whose name in Spanish means "colored red" in reference to the heavy sediment load carried in unregulated times) runs clear.

Debris flows, which seem to occur rather frequently in steep tributaries, also carry material into the Colorado River channel—typically in the form of boulders, gravel, sand, and clay. The frequency of occurrence and size of debris flows depend on topography and geology of the drainage area and history of flows, as well as on the amount and intensity of rainfall. The frequency of occurrence and size of debris flows are therefore rather unpredictable given our current (1988) knowledge. When Stephens and Shoemaker (1987) repeated photographs 100 years after scenes were documented during the Powell expedition, they found changes in large boulder positions or in the size distributions at about 15 percent of the tributary sites visited (E.M. Shoemaker, oral commun., 1988). This statistic would suggest that substantial debris flows occur in the tributary canyons roughly every 1,000 years. This estimate seems reasonable (or even conservative) when compared to the number of (smaller) debris flows documented in recent years by Webb and others (1987).

The large boulders carried to the river by the tributary-canyon debris flows are the primary cause of channel constrictions and the associated rapids, and the regions of channel constrictions have their own hydraulic and sediment patterns that are distinctive from the main channel flow and sediment transport and storage patterns. The area around Bright Angel shown on this map and the region upstream are particularly good places to study many of the relations between the main channel flow and sediment and a small rapid—Bright Angel Rapids.

At low discharges—for example at 5,000-cfs conditions shown in figure 1—Bright Angel Rapids consists of two riffles: **B**–**C** and **I**–**J** in figure 3. The cobble bar **D** is visible at these low discharges and displays wel-developed imbrication. At a discharge of 5,000 cfs, the water surface drops 7 m from nearly 740- to 733-m elevation over the 2.2 km reach of the map, as shown in figure 3. The steepest drops occur in the riffles. 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 and 2. One of the more spectacular small eddies on the river can be seen just upstream of the Silver Bridge near the south bedrock wall of the channel (approximately at **L**, fig. 3).

Conditions at the flood-level discharge of 92,000 cfs in 1983 are shown in figure 2; these conditions were reconstructed from video footage taken by the National Park Service from a helicopter and, as such, are schematic. There are gently breaking oblique waves from the top of the debris fan to the bottom of the cobble bar, which was entirely covered by water at this high discharge.

Because of logistical difficulties, measurements of water-surface velocity comparable to those shown on eight of the maps of this series (Maps I-1897-A, C, E-J) were not made, and therefore, streamlines, velocities, and cross sections cannot be shown. For a general discussion of the flow patterns in rapids, see Kieffer (1985, 1987).

To summarize, the most significant hydraulic features in the Cremation Camp–Bright Angel stretch of the river are Bright Angel Rapids and the cobble bar at the downstream end of it. The hydraulic features of Bright Angel Rapids reflect a dynamic equilibrium between the flow in the Colorado River channel, bedrock protrusions (on the south side of the channel), and flooding events from Bright Angel Creek. The configuration of the channel bottom depends not only on the bedrock topography and the contribution from catastrophic floods, but also—as documented by the U.S. Geological Survey gage station—on the transient sediment load of the river. The channel configuration changes with time, both gradually and catastrophically.

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HYDRAULIC MAP OF BRIGHT ANGEL RAPIDS, GRAND CANYON, ARIZONA

By

Susan Werner Kieffer

1988

PATENTED—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 GCES

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

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