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INSIDE

Floods and Sandbars in the Grand Canyon

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ABSTRACT

Erosion of sandbars and beaches in the Grand Canyon National Park downstream from Glen Canyon Dam has become a major problem that needs to be addressed. Geomorphic and geologic mapping provide a link between sandbar elevations and discharge measurements. This link allows an estimate of discharges that will deposit sand far enough above normal high water to prevent frequent depletions by erosion. The sand is needed to protect habitats and archaeological sites and to maintain beaches used by recreationists. It is proposed that when the Little Colorado is in flood, discharge at Glen Canyon Dam be increased to bring the total discharge to the desired high value. Analysis of the flow records show that such opportunities are presented on the average once in eight years, suggesting that the proposal has a reasonable chance of success.

INTRODUCTION

The Colorado River in the Grand Canyon section in Arizona once fluctuated greatly in its flow. Year-to-year and season-to-season variability was large. Peak discharges ranged from 300 000 cfs (cubic feet per second) to 19 200 cfs, a difference of 16 times. The amount of sediment transported as suspended load was very large. Measurements carried out at the Grand Canyon for the period December 1940 to June 1941 show that, at 50 000 cfs, about 2 000 000 tons were moved per day during the rising stage of the flood,[1] and 500 000 tons during the falling stage, whereas almost 5 000 000 tons per day were moved during the peak of the flood

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Glen Canyon Dam at high discharge during the June 1983 flood. The dam is 710 ft (216 m) high. The four jets of water issuing from near the lower right corner of the dam are from the outlet works. Releases from the right spillway are hidden by the cloud of mist and spray near the lower left corner of the dam. The left spillway, whose exit is visible a short distance downstream from the outlet-work jets, was inactive when the photo was taken. Discharge from the powerplant is below river level and not visible. Photo courtesy of David L. Wegner

[1]Sediment transported during the rising stage of a flood is much greater than that transported during the falling stage (Leopold and Maddock, 1953).

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Grand Canyon *continued from p. 1*

at ~130 000 cfs (Leopold and Maddock, 1953).

The closure of Glen Canyon Dam in 1963 wrought immense changes in the river. The high peaks were eliminated and the maximum controllable discharge—through power-plant and outlet works—is only ~45 000 cfs (1274 m^3/s). The sediment, so characteristic of the river, is now deposited in the reservoir behind the dam, and the releases are clean and cold. All this materially affected the riparian zone[2] in the Grand Canyon, bringing about changes in erosion, vegetation, and the biotic communities (Johnson, 1991; Stephens and Shoemaker, 1987; Stevens et al., 1995, 1997; Webb, 1996). The annual peak discharges now are usually in the range of 25 000 to 35 000 cfs. Only five times in the 35 years since dam closure has the peak flow in the Grand Canyon equaled or exceeded 45 000 cfs. Such discharges come about when water going over the dam spillways is added to the maximum discharge through power-plant and outlet works.

The curtailment of sediment passage in the canyon has resulted in little replenishment of the sandbars, on which the maintenance of the original riparian community depended. The release of water

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[2]The zone along a river that is directly affected by the river and its fluctuations.

ENVIRONMENT MATTERS

Institute for Environmental Education

Enhancing Integrated Science: The Leadership Imperative

Cathleen May, Director, Institute for Environmental Education
Mary Barber, Ecological Society of America
Linda Stanley, U.S. Geological Survey

What factors determine the success or failure of integrated scientific efforts? Are these factors scientific themselves? Social? Cultural? Are they fundamentally dollar-based and administrative? Will collaboration necessarily yield integrated approaches and results? Are there things that organizations can do to enable collaborative efforts among scientists?

The Geological Society of America, the Ecological Society of America (ESA), and the U.S. Geological Survey (USGS) organized a workshop, attended by 24 invited participants and 12 organizers, to investigate these questions. The workshop, "Enhancing Integrated Science" was held November 4–5, 1998, in Reston, Virginia. The participants represented life sciences, earth sciences, economics, social sciences, science administration, and institutional and agency leadership. The results of the workshop illustrate its emergent focus on leadership roles and include a set of "guiding principles" for integrated science, a set of recommendations for the USGS, and a set of recommendations for the larger community of science-enabling organizations and institutions. A summary report, including the results listed above as well as operating definitions, a list of participants, agenda and discussion topics, candid quotes from participants, and an action plan for disseminating the results of the workshop can be found on the USGS Website at: www.usgs.gov/integrated_science/index.html.

The process of organizing the workshop became a microcosm—a real-time illustration of the social and cultural progression by which individuals become a functional collective. A shared vision of the approach to the workshop evolved as individuals came to rely on one another's perspective of the problems we would tackle. Shared responsibility for the products of the workshop evolved as we came to trust each other's contribution during the workshop. These attributes—shared vision, interdependence, and trust—appear to be essential elements of genuine collaboration. Many of the features of the systems in which we work (academic, governmental, or otherwise) are inimical to interdependent, collaborative working relationships. This is not news. Science is a competitive endeavor.

How do we get beyond competition? One of the overarching understandings to emerge from the workshop was that leadership is imperative. If we are to expand the culture of science to include the collaboration so essential to integrated scientific approaches, individuals and institutions alike must embrace the leadership imperative. Only leadership can modify funding structures to remove organizational barriers to collaboration. Only leadership, among the entire scientific community, can expand reward systems to include something other than individual achievement. Leadership is required to ensure that "interdisciplinary" does not come to mean "antidisciplinary." Scientific societies, academic institutions, funding agencies, and federal agencies all share the leadership challenge. Leadership is required to safeguard the pursuit of deep understandings, rigorous methodologies, and technologies of individual disciplines without which we cannot achieve useful understandings of complex natural systems.

N. Metzger and R. N. Zare (*Science,* v. 283, p. 642–643) directly address the leadership imperative by focusing on science policy, "Federal structures . . . strongly militate against interdisciplinary programs cutting across jurisdictional lines." These authors recommend an ambitious interagency approach, funded by Congress through direct appropriations, to bring interdisciplinary research "from belief to reality." In essence, Metzger and Zare challenged Congress and the federal system to actively embrace the leadership imperative.

Even as the Metzger and Zare article reached the community, one federal agency moved to the fore with a bold action to enable interdisciplinary science. In a February 1, 1999, news release, USGS Director Chip Groat proclaimed his agency's "commitment to integrating USGS's scientific disciplines. . ." and announced budget restructuring that includes a line item for integrated science (see www.geosociety.org/science). This action signals, at least in the USGS, federal recognition of the exigencies of organizational leadership to interdisciplinary science.

GSA, ESA, and the USGS will continue their joint efforts to enhance integrated science by following through on the imperatives for organizational leadership we derived through our workshop last November. Some plans for implementation in the near future are contained in the summary report cited above. Long-range planning for collaborative leadership efforts is in the works. If your organization or institution is interested in active leadership to enable interdisciplinary science, please contact us through Cathleen May, (303) 447-2020 ext. 195 or at cmay@geosociety.org.

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from the dam has been governed by demand for electricity from the power plant. This demand fluctuates widely and quickly, so the discharge in the river has changed radically hour by hour and day by day. Not only has the riparian ecosystem been affected, but a decline in recreational use of the canyon has caused significant commercial loss.

These various effects have become so serious that scientific teams studying the issue have recommended various remedies, including the trial release of water at high controllable discharges to test whether such discharges were sufficient to put in motion sand stored in the bed and in side draws and perhaps build back at least some of the sandbars. In 1996, a "test flood" consisted of the release of 45 000 cfs for a week; in 1997, a discharge of 31 000 cfs for 48 h was designed to transfer from channel bottom to channel margins at least some of the 2.2 million tons of sand and 2.7 million tons of silt and clay that had been delivered to the Colorado River by a sequence of floods on the Paria River (Kaplinski et al., 1998). Both flows deposited sand, to the jubilation of all concerned, but an important part of the deposited volume was subsequently washed away (Kaplinski et al., 1998). Several floods on the Little Colorado River in January and February 1993 brought a large amount of new sand into the Colorado

Grand Canyon *continued on p. 4*

Figure 1. The only tributaries shown in this location map are the Paria and the Little Colorado Rivers, which are pertinent to this paper. Rivers are in blue; stream gages are in orange. The Lees Ferry gage measures the discharge from Glen Canyon Dam. The Cameron gage measures the discharge of the Little Colorado River, except for the relatively small flow from a spring near the confluence with the Colorado River. The Grand Canyon gage measures the combined discharges of the Colorado, Little Colorado, and Paria Rivers, plus the contribution of small tributary streams within the Grand Canyon, and minus seepage and evaporation losses. Oak Cave and Tsegi Wash, in green, are the location of Holocene deposits discussed in the text.

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River and built conspicuous beaches throughout the Grand Canyon. A year later, these beaches were largely gone (I. Lucchitta, 1994, personal observation).

This paper offers an additional or alternative plan to rebuild the sandbars utilizing floods on the Little Colorado River. The plan is designed in such a way that important parts of the deposition are above the usual moderate peak discharges, so would be less likely to be eroded away.

THE PROPOSAL

A significant amount of sand is brought into the canyon from tributaries entering downstream of the dam, especially the Little Colorado River, which has a large drainage area, more than 26 000 mi^2 (67 340 km^2). The Paria, with an area of 1570 mi^2 (4082 km^2), is helpful (see Fig. 1).

It is proposed that when the Little Colorado approaches a significant flood discharge, the operators at Glen Canyon Dam open penstocks and outlet works so that a combination of high flow from the tributary added to a maximum release from the dam would produce a discharge in the Grand Canyon sufficiently high that its effects may provide on a small scale what the original undammed river accomplished in sand movement and deposition.

This study uses information and data from several disciplines to examine the feasibility of the proposal. Such analysis involves more than the hydrology and hydraulics of the river basin but must perforce deal with the geomorphology of the canyon bottom, which gives an insight into the long-term functioning of the river. Then, in order to estimate what a flood of any size might deposit, it is necessary to analyze in simplified form the various strandlines and terraces, and determine their dates of deposition or renewal.

THE RECENT GEOLOGIC PAST

Extensive and reliably dated Quaternary deposits of the Colorado River in the Grand Canyon go back about 500 000 yr (Lucchitta et al., 1995, 1999), and perhaps about 750 000 yr (Machette and Rosholt, 1991). There have been nine discrete levels of deposition, datable by modern techniques, that are seen in the canyon varying from 10 to 205 m above the present river. Older and higher levels undoubtedly were once present, but have been eroded.

Most deposits consist of remnants of terraces produced by aggradation and underlain by far-traveled river gravel locally intermixed with coarser and more angular debris of local derivation from nearby tributary washes. Taken as a whole, the gravel terraces indicate overall downcutting through the Quaternary, interrupted periodically by aggradation, probably in glacial or late-glacial times. Cobbles greater than 10 cm are common in the gravel, indicating considerable energy and discharge. Tributary rivers and washes mimicked the activities of the main river.

The data show that the Colorado River has cut down an average rate of ~0.4 m/ka for this time interval, within the 0.4–1.09 m/ka range calculated (Lucchitta, 1988) for carving the Grand Canyon as a whole. In reality, this rate averages intervals of aggradation (negative downcutting) with intervals of downcutting at a faster, but unknown, rate. An estimate of the rate at which erosion occurs following a period of aggradation is given by the most recent deposits.

Near-Stream Terrace Levels

The more recent depositional units and sandbars of immediate concern are those that stand at elevations ~10 m or less above the present river. These deposits

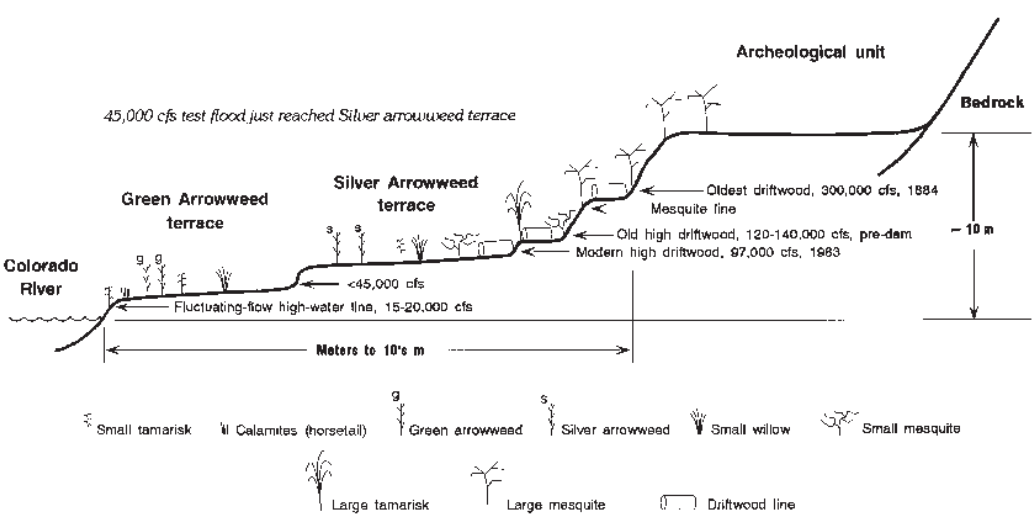

Figure 2. Strandlines and terraces in eastern Grand Canyon. Shown schematically are terrace treads and risers, strandlines marked by driftwood lines, and the vegetation types characteristic of each terrace level.

include the last aggradational terrace, as well as terraces produced during the current period of erosion, which includes the decades since Glen Canyon Dam was built. Geomorphic and geologic studies (Lucchitta and colleagues) provide a general profile of the units in this range, shown in Figure 2.

The archeological unit—the last aggradational terrace—is given this informal name (Lucchitta et al., 1995) because prehistoric Puebloan people lived and farmed on these deposits, leaving abundant evidence of their passage in the form of sites and artifacts of many kinds (Fairley et al., 1994). The unit corresponds in a general way to Hack's (1942, 1945) Tsegi Formation, present in washes tributary to the Colorado River in the southwestern Colorado Plateau. The relation of this formation to Puebloan artifacts and to the present channel is similar to those of the archeological unit, as is the fine grain size. Ages are comparable.

The archeological unit consists of a terrace whose base (strath) is below present river level, and the top (tread) about 10 m above it. The unit is composed predominantly of fine to very fine grained sand. The grain size, excellent rounding, and common frosting of the sand grains suggest derivation from Mesozoic eolian sandstone units abundant on the Colorado Plateau. Far-traveled material is scarce in most places. The sand grades laterally into coarser colluvium derived from local slopes and washes, giving the unit a striped appearance.

The archeological unit commonly is modified by wind action and overlain by resulting eolian deposits. In many places, these deposits bury Pueblo II sites built on top of fluvial material. These relations show that the unit stopped being deposited 800–750 yr B.P., and has been incised ~10 m since that time. The oldest age obtained so far from the unit is 5259–4985 calibrated ^{14}C yr B.P. (Lucchitta et al., USGS data) from a level ~3 m below the top of the unit, and at least 7 m above the base. This suggests that the beginning of deposition may well have been in early Holocene—or even late Pleistocene—time.

Pollen associated with the sediments in Oak Cave, southern Utah (Fig. 1), records the initiation of a regime of heavy summer rains, indicated by the expansion of ponderosa pine, which requires summer rain, and the stripping of interfluve soil mantles, indicated by the waning of sagebrush, which requires deep soil (Lucchitta and others, USGS data). The late Pleistocene to early Holocene age of these sediments either slightly precedes that of the archaeological unit, or corresponds to early deposition of this unit.

These depositional, age, and palynological data are interpreted to indicate regional stripping of soil mantles, with accompanying overloading and aggradation of the regional drainage network resulting in deposition of the archeological unit and correlatives. We prefer the aggradational origin for the unit (the grade of the river increased with time) to the origin proposed by O'Connor et al. (1994), which invokes slackwater deposition from large floods (the grade remained constant), for the following reasons, among others: (1) Deposits correlative with the archeological unit are regionally widespread, and not restricted to the Colorado River and its floods. (2) Deposits of tributaries to the Colorado River are graded to the top of the unit, indicating general aggradation of the drainage network. (3) The unit is present in all types of reaches, not just back-eddy areas downstream from constrictions, where slackwater deposits would be typical.

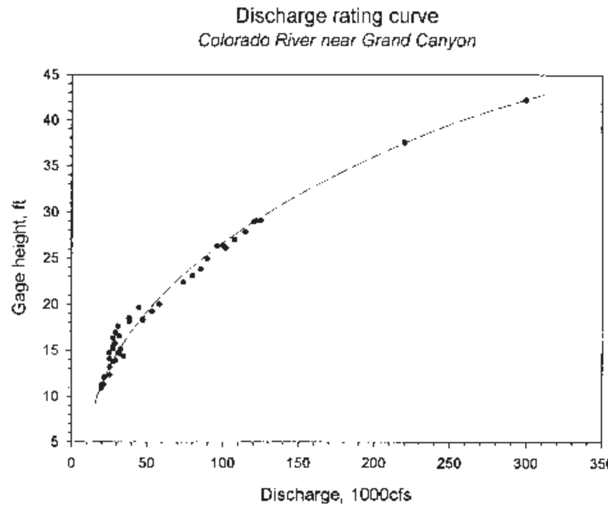

Figure 3. Discharge rating curve, Grand Canyon station. Many of the deviations from the curve are due to measurements being taken on the rising or falling stages of a flood.

The end of alluviation and onset of vigorous downcutting that incised the archeological unit started about 800 yr ago; downcutting has occurred at the high rate of 12.5 m/ka. The significance of these data is that the last period of major aggradation by the Colorado River is represented by the archeological unit, whereas the river has been operating in a regimen of strong downcutting for approximately the past 800 yr, continuing to this day. Glen Canyon dam was built during a strongly erosive regimen.

Among the levels below the archeological unit are two prominent terraces traceable along many reaches of the Grand Canyon. They have been named the Green Arrowweed and the Silver Arrowweed terraces, respectively (Lucchitta et

Grand Canyon *continued on p. 6*

Figure 4. Photo of beach on the Colorado River produced by the 1993 flood of the Little Colorado River. The beach is a short distance downstream from the confluence. The beach must have resulted from the flood on the Little Colorado because no such beaches were present upstream from the confluence, and because the sand contained abundant basaltic detritus. Basalt is common along the course of the Little Colorado River. One year later, the beaches visible in the photograph were virtually gone.

Grand Canyon *continued from p. 5*

al., 1995), from the local flora found there when the studies were carried out (Fig. 2). All levels below the archeological unit have been created and refurbished by floods during the historic period.[3] Lines of flood debris and driftwood are found in consistent relations to treads and risers of the terraces, as shown in Figure 2. The younger (and lower) strandlines of large driftwood include abundant worked wood and artifacts such as cans. Plastic objects are common in the 1983 strandline, but very rare in the pre-dam 120 000–140 000 cfs strandline. In pre-dam time, beaches and strandlines produced by lesser floods tended to be modified or destroyed by the higher floods, so they cannot be recognized easily. Floods greater than 120 000–140 000 cfs were rare; the 1884 flood of 300 000 cfs (8490 m^3/s)[4] is marked locally by deposits and a strandline composed of large rotten logs, scarce worked wood, and a few artifacts that include no plastic items. The 97 300 cfs (2755 m^3/s) flood of 1983, which marks the greatest post-dam discharge, is represented by a sand terrace and a drift line composed chiefly of fresh, relatively small wood and modern artifacts, including abundant plastic items. The various strandlines were surveyed by total station (Lucchitta et al., 1995, and USGS data).

The test flood of 1997 covered only the Green Arrowweed terrace. The 1996 test flood reportedly just reached the lower end of the Silver Arrowweed terrace (various sources, personal communications). Subsequent discharges have removed a considerable volume of the sand deposited by the test floods (personal observations by Lucchitta in 1998; Kaplinski et al., 1998; and Hazel et al., 1999).

Relation of Terraces to Floods

The geomorphic terraces must be placed within a hydrologic context. This is best done by relating the levels of the terraces to the discharge rating curve, which correlates gage height with discharge. The best gaging station to use for this purpose is that at Grand Canyon, near Bright Angel Creek. Measurements by current meter at this station began in 1921, but a reliable estimate of 300 000 cfs at Lees Ferry was also obtained for the flood of July 8, 1884 (see above).

A plot of the rating curve (Fig. 3) shows that there has been no progressive change during the period of record. The rating curve for Grand Canyon is a reasonable approximation of the action of the river in the canyon and, combined with the general cross section provided by geomorphic studies, is used here to represent the relation of terrace heights to discharge.

From Figure 3, it can be seen that a discharge of about 55 000 cfs, corresponding to a gage height of 19 to 20 ft (6 m), is required for water to reach a significant part of the Silver Arrowweed terrace. However, an appreciable deposit of sand probably will require 65 000 to 70 000 cfs and a gage height of about 22 ft (7 m). Such a deposit would be relatively durable because it would be well away from the lower step of the terrace, and thus from the erosive action of the river.

In the 35 years since the dam began controlling the flow, only six events equaled or exceeded the 45 000 cfs of the 1996 “test flood” and of these, only two were significantly higher, 58 400 on June 15, 1965, and 96 200 cfs on June 29, 1983. All events exceeding 45 000 cfs required a contribution from the spillway of the dam.

The Little Colorado River can provide the 10 000 to 25 000 cfs needed to raise the maximum controllable outflow from the dam (45 000 cfs) to the required discharge. The floods of the Little Colorado in January and February 1993 indicate that not only is such a contribution possible, but that such floods also bring much sand into the Grand Canyon. The peak discharge of these floods was 18 200 cfs at Cameron, the sixth largest in the period of record. On March 3, a few weeks after the peak, the magnificent beaches (Fig. 4) produced by these floods lined the length of the river from the Little Colorado River confluence to at least as far as Diamond Creek, Mile 226 (Lucchitta and colleagues, personal observations).

ON THE POSSIBILITY OF RESTOCKING SAND ON THE BEACHES

In contrast to the test “floods,” which essentially mined the sand in the channel of the Colorado River—a depletable resource—or redistributed sediment brought in by floods on the Paria—which are puny compared to the sediment transported by the Colorado River in pre-dam times—the Little Colorado flood introduced enough new sand to form beaches the length of the river below the confluence (Fig. 4), in addition to the sand that remained in the channel or made its way to Lake Mead. Such floods provide an opportunity for restocking beaches in the Grand Canyon downstream from the confluence.

First, one must achieve a combined Colorado–Little Colorado River discharge sufficient to keep sand entrained rather than allowing it to settle in the channel, and this discharge must be maintained long enough to build adequate beaches. Second, the discharges must attain a high enough stage to park the sand where it will not be readily eroded by the river in its normal modern flows.

In the period of record, seven days of the highest peak discharges (> 18 000 cfs) of the Little Colorado at Cameron included four that increased the discharge at Grand Canyon enough to overflow the Silver Arrowweed terrace. These four occurrences in the 50 years of measurement means one occurrence about every 12 years.

Alternatively, one may estimate the possible contribution by counting the number of days when the daily flow near Cameron exceeded 10 000 cfs. The daily flow often is high on two to four successive days, which would mean little attenuation by channel storage. In the 50 years of record, there were six such occurrences, two of which were not identical with the seven analyzed above. Thus, there appears to be the possibility of six useful events in 50 years, or one in eight years on the average.

The concept is that the flow of the Little Colorado River be monitored at the most downstream gaging station at Cameron, Arizona. When the discharge reaches a high enough level, the operator of Glen Canyon Dam would, on short notice, increase the discharge through power-plant and outlet works to the maximum capacity of 45 000 cfs. A direct radio link from gage to dam would make the opportunity practical. Furthermore, advance notice of a possible peak at Cameron could be obtained from careful observation of the gages on the Little Colorado River upstream of Cameron.

Given the potential for useful events to occur on average once in eight years, it is quite within reason that the high flow of the Little Colorado River could be made to coincide with a release of 45 000 cfs from Glen Canyon Dam, resulting in the deposition of abundant sand at a substantial elevation above present river grade, within the Silver Arrowweed terrace. In this position, sand would have considerable durability, probably enough to last until the next restocking event.

The proposal discussed here pertains to a geological process—the restocking of beaches. However, it is well known that proper managing of the Grand Canyon involves a complex and often contradictory interplay of geological, biological, and other considerations (Schmidt et al., 1998). All of these must be considered when making management decisions. Nevertheless, the proposal attempts to recreate—to the extent possible now that the dam is built—the sediment transport and river stage characteristics of the pre-dam river. These are the conditions to which the Grand Canyon ecosystem was originally adjusted.

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[3]Defined here as the time interval, starting in 1884, for which observational information is available.

[4]This discharge is based on the observed level reached by the flood at Lees Ferry—within the orchard of Lee’s Lonely Dell Ranch. In the 1920s, a profile was surveyed from this level to the river, allowing determination of the channel cross section during the flood. This, in turn, led to an evaluation of the flood discharge.

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