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A 4500-Year Record of Large Floods on the Colorado River in the Grand Canyon, Arizona[1]

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ABSTRACT

A sequence of flood deposits left by the Colorado River in the Grand Canyon, Arizona, provides evidence of at least 15 floods with peak discharges greater than 5500 m^3sec^{-1} over the last 4500 yr. Ten floods during the last 2000–2300 yr had discharges greater than 6800 m^3sec^{-1}. One flood, 1600–1200 yr ago, had a discharge exceeding 14,000 m^3sec^{-1}, a flow rate more than twice the largest gaged flood. This record of flooding is one of the longest for a major U.S. river, and, combined with the gaged record of twentieth century floods, allows determination of the frequency and history of large floods that have affected key aspects of Colorado River geomorphology.

"When the summer sun comes this snow melts and tumbles down the mountain sides in millions of cascades. A million cascade brooks unite to form half a hundred rivers beset with cataracts: half a hundred roaring rivers unite to form the Colorado which rolls, a mad, turbid stream, into the Gulf of California."

Powell (1875)

Introduction

Before construction of Glen Canyon Dam in the early 1960s, large Colorado River floods were an integral element of the geomorphology, hydrology, and ecology of the Grand Canyon. Consequently, many features of the present Colorado River environment reflect the passage of large floods. For example, most of the famous Grand Canyon rapids are the result of bouldery debris fans deposited by debris flows in steep tributary canyons (Cooley et al. 1977; Howard and Dolan 1981; Webb et al. 1988*a*, 1989). Only extremely large main-stem floods were competent to transport the large boulders contained in these debris fans (Graf 1979; Kieffer 1985). As a result, the present distribution and size of sand bars and river rapids, features of significant recreational value, are largely the cumulative result of the sequence of interactions between side canyon debris flows and past Colorado River floods (Howard and Dolan 1981; Kieffer 1985; Webb et al. 1991). Likewise, large floods played an important role in the development of clearly defined vegetation zones along the Colorado River (Stevens 1989). Flood-induced germination and mortality, deposition of suitable substrates, and moisture availability substantially influenced the distribution of long lived riparian plant species (Clover and Jotter 1944; Stevens 1989; Johnson 1991).

Determining the past sequence of large flows and quantifying the magnitude and frequency of floods large enough to have affected some of these aspects of the Colorado River has been difficult. The gaged record, while long (1921 to present) relative to gaged records on western U.S. rivers, is not long enough to address satisfactorily the issues described above. Researchers investigating long-time-scale processes such as channel-and-rapid evolution have had to rely on measurements of the largest historic floods (Graf 1979), or indirectly estimate the largest prehistoric floods on the basis of present channel morphology and a model of river hydraulics and particle erosion (Kieffer 1985), or

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have simply stated that the time scales of adjustment are too long to evaluate adequately with the present data (Howard and Dolan 1981). To provide a fuller picture of the incidence of large Colorado River floods, we report a 4500 yr stratigraphic record of large floods in the upper Grand Canyon near Lees Ferry, Arizona. This is one of the longest such records available for any major U.S. river, and it should be relevant to studies of Colorado River hydrology, geomorphology, and ecology, as well as Colorado River basin paleoclimatology. We have combined this stratigraphic record of prehistoric floods with the gaged record of 20th century floods to provide quantitative estimates of past recurrence of large floods.

The Gaged Record of Colorado River Floods in the Grand Canyon, Arizona

Where the Colorado River enters Grand Canyon National Park, near Lees Ferry, Arizona (figure 1), stages of annual Colorado River floods have been recorded by a staff gage established in May, 1921 and, since January 1923, at a U.S. Geological Survey (USGS) recording streamflow gage (Colorado River at Lees Ferry) (figure 2). A permanent streamflow gage was also established 150 km downstream (Colorado River near Grand Canyon) in October 1922. These two gages provide the best instrumented record of large Colorado River flows in the Grand Canyon. The largest flow considered part of the gaged record at Lees Ferry was on June 19, 1921, which had an estimated discharge of 6250 m^3sec^{-1} based on extrapolation of a stage-discharge rating curve to highwater marks at the Grand Canyon gage (Dickinson 1944, p. 174 and 190; USGS 1973, p. 611). For these two gages, the maximum discharge known outside the period of record was about 8500 m^3sec^{-1} on July 7, 1884. According to E. C. LaRue (1925), during this flood, a resident of Lees Ferry rescued his cat from the branches of an apple tree. Decades later, the resident, with "the height of the water on the trunk of the tree . . . well impressed on his mind," assisted a surveyor in referencing that elevation to the datum of the stream gage established at Lees Ferry in 1923. The 8500 m^3sec^{-1} discharge was estimated by extrapolating the Lees Ferry stage-rating relation above the stage associated with a measured discharge of 3400

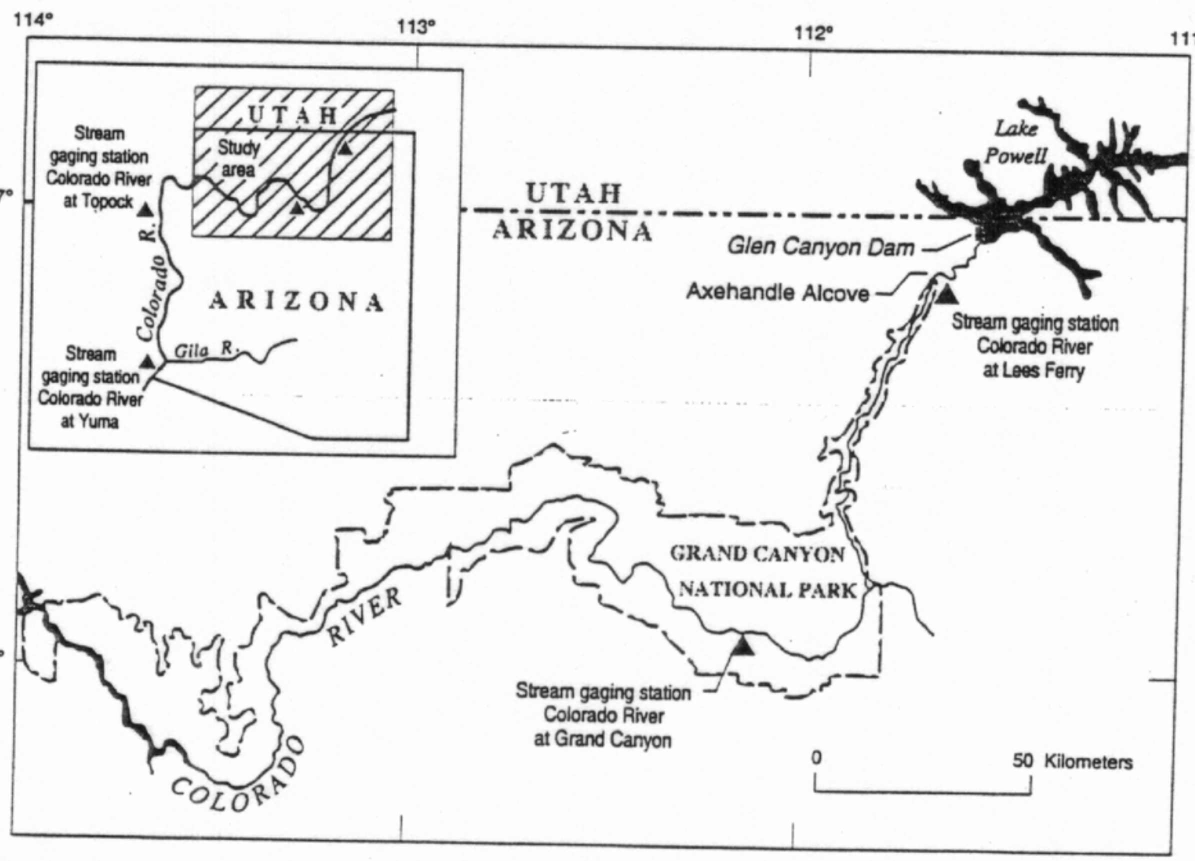


Figure 1. Location of study area and USGS Colorado River streamflow gaging stations referred to in text.

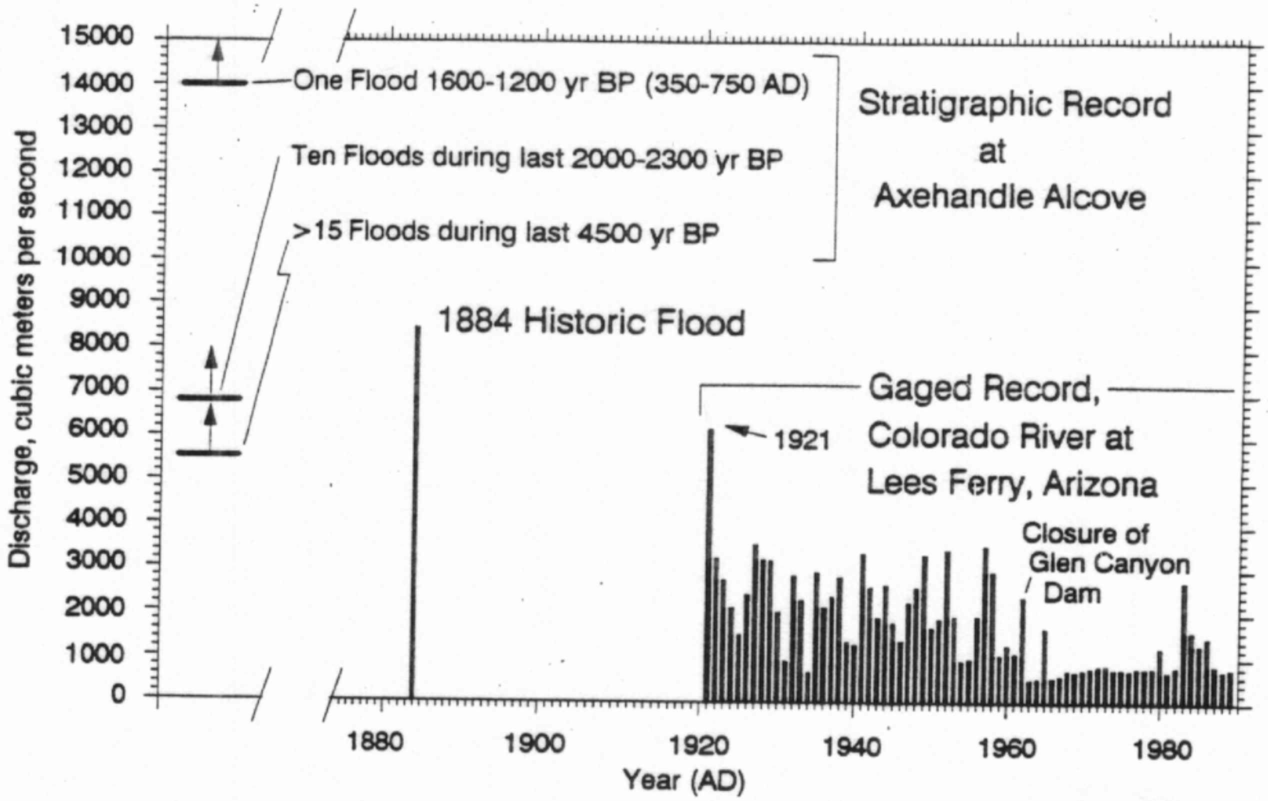


Figure 2. Measured and historic annual peak discharges of the Colorado River at Lees Ferry, and a summary of the stratigraphic record of floods, 3 km downstream, at Axehandle Alcove.

m^3sec^{-1} and the peak stage of the 1921 flood (as noted above, the discharge was calculated at the Grand Canyon gage; however, peak stage was measured at both gages) to the reconstructed stage of the 1884 flow (Dickinson 1944, p. 174). Therefore, the 1884 discharge estimate must be considered only an approximate one. The 1884 flow is thought to be the largest since at least 1868 (USGS 1973, p. 611). Flow has been regulated by the Glen Canyon Dam since the beginning of 1963. Flow records at the Lees Ferry gage are considered "excellent," meaning that 95% of the daily discharges are within 5% of true values (USGS 1973, p. 7). The accuracy of the annual peak discharges, which are the values used in the flood frequency analysis that follows, is uncertain, but probably is somewhat less. Dickinson (1944, p. 174) stated that records for flows greater than 4250 m^3sec^{-1} (only the 1921 flood) are "fair," indicating an accuracy of ±15%.

Flow records at other Colorado River gages provide little additional reliable information of large floods. Mean monthly flows at Lees Ferry for the period 1911–1921 have been estimated by LaRue (1925), and revised by Dickinson (1944, p. 175–177), from records at upstream gages. No mean monthly discharges in this period exceeded the mean monthly discharge of the 1921 flood, although a large June, 1917 discharge may have had a peak discharge close to the 6250 m^3sec^{-1} peak discharge of 1921. At Yuma, Arizona, Colorado River stage has been recorded since 1878, and discharges have been measured since January, 1903 (Dickinson 1944, p. 244–255). Gaged discharges of 5400 m^3sec^{-1} and 5300 m^3sec^{-1} were recorded in June, 1920 and June, 1921, respectively. Larger discharges at Yuma occurred some years during winter, due primarily to flood flows on the Gila River. In the period 1878–1902, the highest measured stage was during the Colorado River flood of 1884, except for January, 1891, when an exceptional flood on the Gila River resulted in a higher stage at Yuma. Near Topock, Arizona (figure 1), Colorado River discharges have been measured since 1917. Measurements before 1924, however, are considered unreliable (Dickinson 1944, p. 201). Observations of highwater marks near the site of the Topock gage indicate the a pre-1884 flood achieved a stage 2.6 m higher than the 1884 flood. Dickinson (1944, p. 201) estimated that this earlier discharge exceeded 11,300 m^3sec^{-1}, and "that it probably occurred within the period 1857–68 and most likely in 1862."

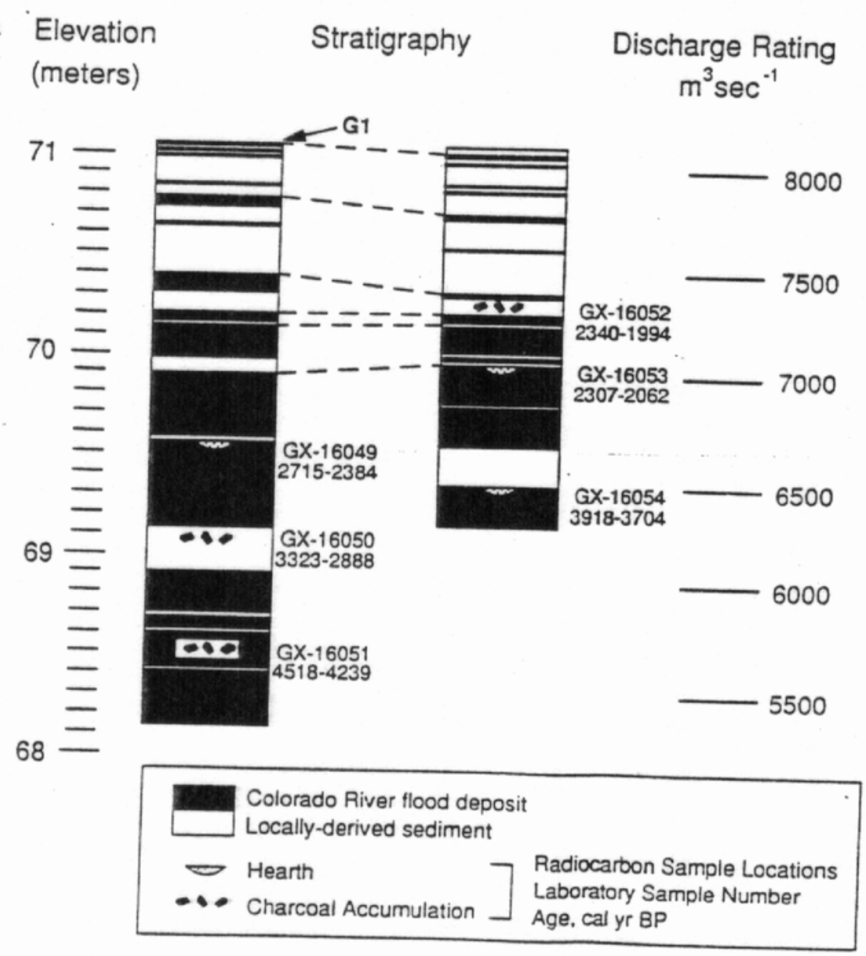
The Stratigraphic Record of Colorado River Floods in the Grand Canyon

Before construction of Glen Canyon Dam, Colorado River floods in the Grand Canyon had high suspended load concentrations, on the order of 2–3% by weight (e.g., Howard 1947). In regions of flow separation during floods, such as eddies and backwater areas, local velocities are 1–15% of those in the main thread of flow, and suspended sand and silt rapidly settles (McKee 1938; Schmidt 1990). Protected sites preserve sequences of these fine-grained flood deposits, forming a stratigraphic record of the largest floods (Patton and Dibble 1982; Kochel and Baker 1982, 1988; Webb et al. 1988*b*). We have found several such deposits between Glen Canyon Dam and the Grand Canyon streamflow gage. One remarkable site, which we have informally named Axehandle Alcove, is 3 km downstream from the gage at Lees Ferry. Axehandle Alcove is a small rock shelter within a 50 m high canyon wall of Kaibab Limestone (figure 1). Large floods inundated this alcove, leaving behind successive layers of grey silt and fine sand that, until recently, have remained relatively undisturbed.

Stratigraphy and Chronology of Deposits at Axehandle Alcove. Recent gullies have incised this sediment in Axehandle Alcove and exposed deposits of at least 15 floods that had discharges comparable to those of the large historic flows of 1921 and 1884 (figures 2 and 3). The stratigraphic sequence at Axehandle Alcove is capped by a thin, grey, silty sand layer (G1) that can be traced for several hundred meters along the canyon margin (figure 4). Based on the elevation, fresh appearance, and continuity of G1, we speculate that it was emplaced by the ≈8500 m^3sec^{-1} flood of 1884. In addition, at several places along both canyon walls, pockets of fine organic detritus in a matrix of grey, laminated silt and fine sand have been preserved in small crevices up to 4 m above the highest exposure of G1. These crevice deposits are the highest evidence of Holocene flooding found in this reach of the Colorado River.

At Axehandle Alcove, deposits from Colorado River floods are separated by layers of red coarse sand and gravel derived from local drainage of adja-

Figure 3. Schematic representation of two measured sections at Axehandle Alcove showing flood units, locations and results of dated samples of organic material, and a stage-discharge relation based on step-backwater flow modeling. The elevation datum is arbitrary. Colorado River flood deposits were discriminated from locally derived (non-flood) sediment on the basis of sedimentology and color. Dashed lines connect the tops of depositional units that could be traced from one section to the other. The highest G1 deposits were traced to a level about one meter higher than the top of the stratigraphic sections.



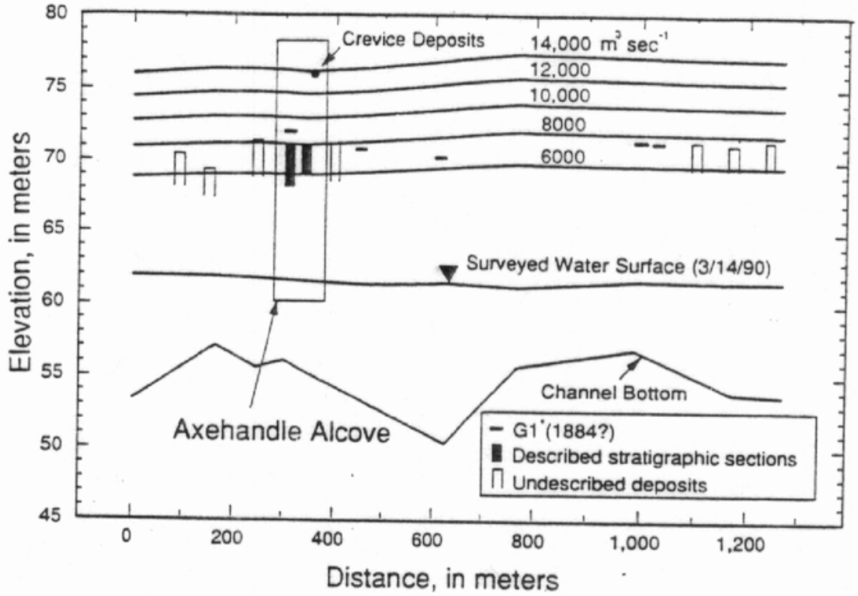


Figure 4. Distribution of flood sediment and calculated water surface profiles near Axehandle Alcove. All of the undescribed sections are capped by G1 deposits. The elevation datum is arbitrary. The surveyed water surface rises downstream because river stage was rising during the course of the survey. Flow is right to left.

cent cliffs, and charcoal accumulations from human occupation between floods. Limits on the chronology of floods were determined by several radiocarbon analyses of (1) charcoal from the sediment at Axehandle Alcove (figure 3) and (2) plant fragments and fecal pellets of Neotoma (pack rats) incorporated into the highest crevice deposits (table 1). The oldest dated material was a charcoal accumulation near the bottom of the exposure. The age of this sample requires that 14 of the 15 flood deposits exposed at Axehandle Alcove were emplaced by floods after 4518–4239 cal yr B.P. A date from a hearth in the middle of the section indicates that there were ten floods large enough to overtop the section after 2307–2062 cal yr B.P. In a correlative sequence of flood deposits across the river, radiocarbon analysis of plant fragments preserved immediately below G1 requires it to

Table 1. Radiocarbon Analyses

Laboratory Number	Material Analyzed	$\delta^{13}C$ (‰)	^{14}C Date[a] (^{14}C yr BP)	Calibrated Age[b] (cal yr BP)
GX-16055	Neotoma fecal pellets, plant fragments	−21.8	1425 ± 130	1517–1187
GX-16052	Charcoal	−25.8	2150 ± 140	2340–1994
GX-16053	Charcoal (hearth)	−25.9	2155 ± 75	2307–2062
GX-16049	Charcoal (hearth)	−22.2	2470 ± 85	2715–2384
GX-16050	Charcoal	−24.4	2930 ± 165	3323–2888
GX-16054	Charcoal (hearth)	−14.2	3530 ± 80	3919–3704
GX-16051	Charcoal	−21.6	3915 ± 85	4518–4239
Right Bank				
GX-16012	Plant Fragments	−25.7	330 ± 120	520–280
GX-16024	Neotoma fecal pellets	−23.3	1470 ± 190	1595–1179

[a] Radiocarbon ages (in ^{14}C yr B.P.) are based upon the Libby half life (5570 years) for ^{14}C. The error stated is $\pm 1\sigma$ as judged by the analytical data alone. The age is referenced to A.D. 1950.
[b] Calibrated ages are dendrologically calibrated (Stuiver and Reimer 1986), with results presented in calender years before present. "Present" is A.D. 1950. Reported ranges reflect $\pm 1\sigma$ uncertainty and no laboratory error multiplier.

have been deposited after 520–280 cal yr B.P. (Sample GX-16012; table 1), consistent with our interpretation that G1 was left by the flood of 1884. Neotoma fecal pellets and plant fragments from the crevice deposits above the stratigraphic section at Axehandle Alcove yielded an age of 1517–1187 cal yr B.P. for the largest flood in the 4500 yr record. An additional sample of Neotoma fecal pellets (GX-16024) from high crevice deposits across the river from Axehandle Alcove yielded a similar date of 1595–1179 cal yr B.P., strengthening the conclusion that there was one extremely large flood 1600 to 1200 years ago.

Discharge Estimation. The highest elevation of each flood deposit gives a minimum estimate for the peak stage of the flood that emplaced it. We developed a stage-discharge relation for Axehandle Alcove by calculating energy-balanced water surface profiles for a wide range of discharges (figures 3 and 4). The water surface profiles were calculated by the step-backwater method (Chow 1959; Hydrologic Engineering Center 1985; O'Connor and Webb 1988) for 11 surveyed and four interpolated cross sections for a 1.2 km reach encompassing the site. Because the top of each deposit provides only a minimum estimate of the peak flood stage, this stage-discharge relation (figure 3) likely provides minimum estimates for discharges of corresponding flood deposits.

Because these minimum discharge values are used in the following flood frequency analysis, some discussion of their accuracy is pertinent. Uncertainty in discharge estimates derived from the step-backwater method as applied here arises primarily from uncertainties in (1) downstream flow conditions and their effect on the local water-surface profile; (2) values of energy loss coefficients; (3) the channel geometry at times of peak flow stages; and (4) the depth of water above each deposit as it was emplaced. For Axehandle Alcove, sensitivity tests indicate that the maximum combined uncertainty resulting from 1 and 2 is about ±25% considering reasonable limits for the unknown parameters. Uncertainty in the channel geometry is probably the most important consideration, especially uncertainties in channel bottom elevation. We have used the present (1990) channel bottom for our step-backwater calculations. There is no evidence of long-term channel change at the site (based on inspection of matched photographs of the reach taken in 1890 and 1991–1992). Channel scour during floods is probably a larger source of error. Several meters of bed lowering coincident with flooding have been documented at both the Lees Ferry (Burkham 1986) and Grand Canyon (Leopold and Maddock 1953) gages. This effect can be large; 3 m of channel bottom lowering (similar to what has been observed at the Grand Canyon gage) at peak stage would increase the discharges associated with the elevations of the flood deposits at Axehandle Alcove by 20–30%. The likelihood of such scour during large flows, combined with the requirement that the peak flood stages were higher than the resultant deposits, leads us to believe discharge estimates assigned to the flood deposits should be considered minimum discharge estimates. The discharge values assigned to flood deposits (on the basis of the stage-discharge relation in figure 3) are overestimates only in the unlikely circumstance that energy-loss coefficients are significantly underestimated and channel scour is minimal at peak stage and there is little or no water above the sediment deposited by the flow. The maximum possible discharge overestimation, on the basis of the above discussion, is about 25%. It is far more likely, however, that the discharge value assigned to each individual flood deposit underestimates the magnitude of the flow that deposited it. The potential underestimation is large, depending primarily on the depth of water above the deposit left by the flow, and the amount of channel scour at the time of highest stage.

Assuming that the stage-discharge relation of figure 3 does not overestimate peak discharges associated with corresponding flood deposits, the 15 floods preserved in the stratigraphic record that post-date 4518–4239 cal yr B.P. all had discharges that exceeded 5700 m^3sec^{-1}. The ten floods since 2307–2062 cal yr B.P. (probably including the flood that emplaced the crevice deposits) had discharges larger than 6875 m^3sec^{-1}. On the basis of the stratigraphic continuity between flood deposits and the conformable contacts in the upper part of the two measured sections, we infer that the stratigraphy subsequent to 2307–2062 cal yr B.P. records all floods that overtopped the section. It is likely that all floods are not recorded in the lower part of the section where deposition occurred under more energetic, and locally erosive, conditions. The highest G1 deposits indicate that the most recent flood in the stratigraphic record had a discharge of at least 8800 m^3sec^{-1}. This estimate is similar to the USGS estimate of ≈8500 m^3sec^{-1} for the 1884 flood at Lees Ferry. The elevation of the highest crevice deposits requires a discharge of greater than 14,000 m^3sec^{-1}.

A discharge of 14,000 m^3sec^{-1} surpasses the 1921 flow by more than a factor of two, and is 1.65 times larger than the historic flow of 1884. Nevertheless, it is substantially less than the largest floods from equivalent size U.S. watersheds. The envelope curve of Costa (1987), which defines the limit of largest measured discharges compared to drainage area, indicates that for a drainage area the size of the Colorado River at Lees Ferry, the limiting discharge is about 43,000 m^3sec^{-1}; three times larger than the largest flood in the stratigraphic record at Axehandle Alcove.

Flood Frequency Using the Gaged and Stratigraphic Records

We combined the geologic record of flooding with the gaged record at Lees Ferry to evaluate flood frequency for the Colorado River by optimization of the parameters for a log-normal frequency distribution using maximum likelihood estimators (figure 5, table 2). This method efficiently combines stratigraphic evidence for ungaged floods with records of gaged floods to give estimates of the frequency of large floods (Stedinger and Cohn 1986; Stedinger and Baker 1987; Stedinger et al. 1988). A further advantage is that categorical information on flood discharges can be used, such as the case for the stratigraphic record at Axehandle Alcove (and many historical and prehistorical records) where we interpret flows to have exceeded

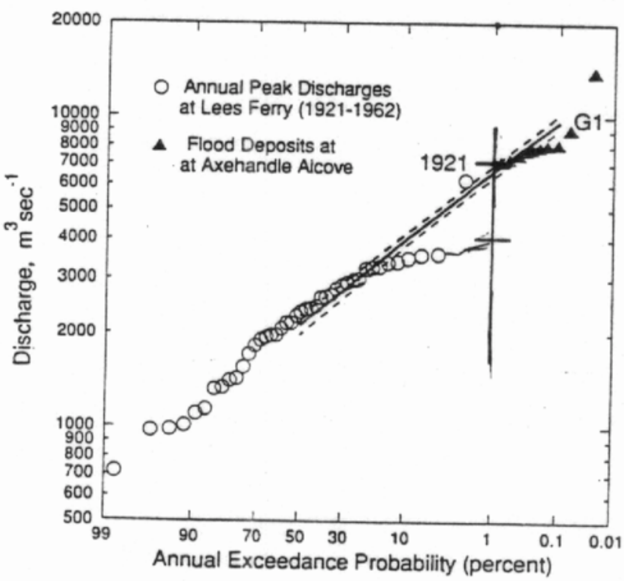


Figure 5. Log-normal frequency distribution and standard errors for floods on the Colorado River near Lees Ferry based on maximum likelihood analysis of the combined gaged and stratigraphic records. The plotted discharges for the floods recorded by deposits in Axehandle Alcove are minimum estimates. Plotting positions were assigned on the basis of Hirsch and Stedinger (1987, Appendix 3, $\alpha = 0.4$). There is considerable uncertainty in the plotting positions for the largest flows of both series.

known magnitudes, but are uncertain of their actual discharges.

A critical assumption in this analysis is that all floods above specified discharge thresholds are recorded in the stratigraphy; therefore, we have considered only the ten floods that postdate 2307–2062 cal yr B.P. because, as described above, we infer that the stratigraphic record is complete for this time period. The discharge of each flood in the stratigraphic record was described as an open-ended range bounded below by the minimum discharge value derived from the stage-discharge relation in figure 3. The largest flood, associated with the crevice deposits, was assigned a minimum value of 14,000 m^3sec^{-1} (figure 4).

Because the top of the stratigraphic section became higher with each deposit, the discharge threshold required for allowing deposition of the next deposit increased after each recorded flood. To factor this in, the "recording threshold" was described as rising in a stepwise fashion as the flood deposits accumulated, with its height corresponding to the top of the last deposited unit. The date of each flood is not known; consequently, each of the ten floods was assumed to be evenly spaced during the 2307 yr length of record. This assumption does not introduce significant error into the long-term frequency analysis because the discharge threshold increased only by a small amount (about 10%) over the 2307 yr record. Because of this assumption, however, we cannot use this analysis to address possible changes in flood frequency during the period of record. Because accurate discharge thresholds are required for this type of analysis (knowing the exact discharge of a flood that exceeded a discharge threshold is not as critical as knowing the threshold discharge accurately), frequency analyses were also performed assuming 25% uncertainty in the discharge thresholds (table 2).

The gaged record used in the flood frequency analysis consisted of the annual peak discharges at Lees Ferry between 1921 and 1962 (figure 2). Annual flood flows after 1962 have been artifically and substantially altered by closure of Glen Canyon Dam. Annual peak discharges in the gaged record were considered precise values in all analyses, although as discussed above, there is an unknown uncertainty in the accuracy of the gaged peaks. The USGS estimate for the 1884 flood was not included as part of the gaged record because we infer that the 1884 flood is recorded in the stratigraphy at Axehandle Alcove.

Used in this fashion, the stratigraphic record at Axehandle Alcove leads to improved estimates of

Table 2. Long-Term Flood Frequency on the Colorado River

Annual exceedance probability	50%	10%	5%	1%	0.5%	0.1%
Recurrence interval (yr)	2	10	20	100	200	1000
Analyzed flow records	Flood quantiles (discharge ± standard error) (m^3sec^{-1})					
Gaged record (Lees Ferry)	2133 ± 147	3778 ± 351	4443 ± 469	6022 ± 798	6732 ± 962	8468 ± 1401
Gaged + stratigraphic records	2131 ± 147	3997 ± 181	4777 ± 205	6674 ± 305	8749 ± 471	9708 ± 562
Case 3	2001 ± 116	3384 ± 127	3927 ± 138	5192 ± 193	5751 ± 228	7102 ± 335
Case 4	2220 ± 168	4509 ± 233	5512 ± 273	8033 ± 427	9221 ± 523	12254 ± 819

Note. All analyses were performed with the computer program developed by Stedinger et al. (1988) assuming that the flood observations came from a log-normal population distribution. Cases 3 and 4 result from assuming that all minimum discharges and observation thresholds associated with the stratigraphic record of floods are overestimated (case 3) or underestimated (case 4) by 25%. For case 3, we assumed that deposit G1 was left by the flood of 1921 (this would be consistent with the revised discharge estimates). These estimates for flow recurrence should only be considered as long-term averages, because the stratigraphic and gaged records possibly include time periods of distinctly different flood frequency resulting from changes in climate or watershed conditions. Therefore, the flood frequency estimates given in this table are not necessarily indicative of the present probability of flooding.

the recurrence of large floods compared to using the gaged record alone (figure 5, table 2). Adding the stratigraphic record to the gaged record results in slightly increased (<15%) discharge estimates for floods of 10 to 1000 yr recurrence intervals. More important, however, the standard errors for the estimates are much smaller: for flows with recurrence intervals ≥20 yr, the standard errors of the quantile estimates are less than half of those resulting from an equivalent analysis of the gaged record alone (table 2). This result indicates that incorporation of the stratigraphic record is equivalent to quadrupling the effective record length. Cases 3 and 4 of table 2 show the great sensitivity of the quantile estimates to the accuracy of the minimum discharge estimates, emphasizing the need for careful and accurate discharge calculation procedures when using historical or prehistorical records of flooding in this type of analysis.

Conclusions

A stratigraphic record of flooding, going back at least 4500 yr, provides evidence of at least 15 floods on the Colorado River in the Grand Canyon with discharges similar to the large historic flows of 1884 and 1921. Ten floods during the last 2000–2300 yr had discharges greater than 6800 m^3sec^{-1}. One flow, 1600–1200 cal yr B.P., had a discharge larger than 14,000 m^3sec^{-1}. The evidence of this large flood supports Kieffer's (1985) suggestion, on the basis of channel morphology, that many of the rapids in the Grand Canyon have been affected by a flow greater than 11,000 m^3sec^{-1}.

The stratigraphic record of the largest Colorado River floods, combined with a long record of annual peak discharges from a nearby streamflow gage, provides quantile estimates of 10–1000 yr floods that are somewhat larger, but similar, to those obtained by evaluating the gaged record alone. For example, the 100-yr flood determined from a maximum likelihood analysis incorporating the stratigraphic record is 4000 ± 180 m^3sec^{-1}, compared to 3780 ± 350 m^3sec^{-1} obtained from a similar analysis of the gaged record alone. Furthermore, the stratigraphic record provides information regarding the past sequence of extremely large floods. This geologic information, unobtainable by extrapolation of modern streamflow records, is important for understanding the sequence of events that have acted cumulatively to shape the present Colorado River geomorphology, where timescales of adjustment for some processes are longer than modern records of observation.

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