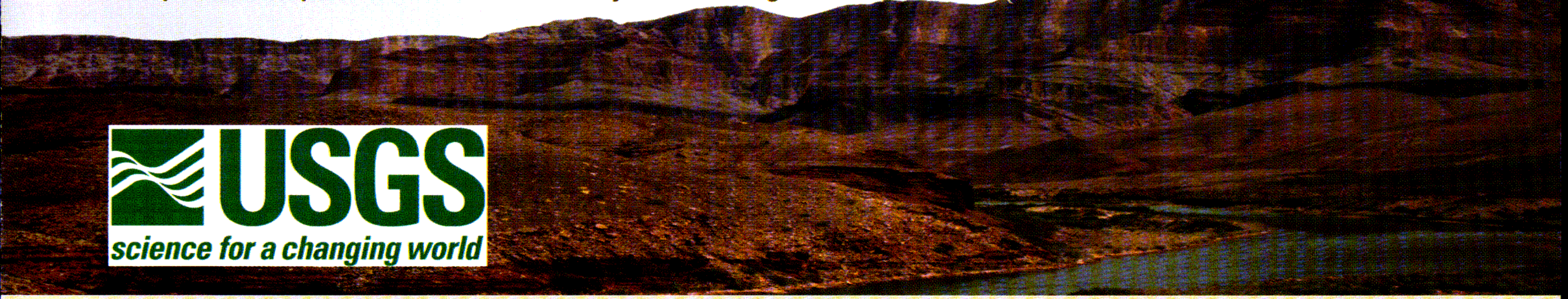
Prepared in cooperation with the Grand Canyon Monitoring and Research Center



Frequency of Debris Flows in Grand Canyon

Debris flows from 740 tributaries within Grand Canyon, Arizona, contribute coarse-grained sediment to the Colorado River (Webb and others, 2000). Distributed along 444 km (kilometers) of river between the Paria River and the Grand Wash Cliffs, these tributaries drain 12,000 km^2 of steep terrain, most of which lies between the North and South Rims of the canyon, and are little affected by land-use practices. Grand Canyon debris flows are more than 80% sediment by weight and deposit poorly sorted sediment in the river that ranges in size from clay to large boulders (Melis and others, 1994). Debris flows constrict the Colorado River at tributary junctures, raising the river bed until floods rework debris deposits and remove or reposition boulders (Webb and others, 1989). The large boulders deposited in the river by debris flows form the core of rapids that modify the longitudinal profile and locally control the geomorphic framework of the Colorado River in Grand Canyon (Webb, 1996).

Rapids account for most of the vertical drop of the river through Grand Canyon, 66% of which occurs in only 9% of the river's length. Debris flows can be hazardous to the recreational community, affecting navigation of white water and potentially trapping hikers in narrow canyons. Debris flows have repeatedly damaged the water-supply pipeline along Bright Angel Creek, destroyed hiking trails, destroyed vehicles, and threatened lives. This Fact Sheet presents debris-flow frequencies for the periods of observed debris flows (1984-2002) and the historic photographic record (1871-1984). A total of 1,365 historical photographs of the river corridor taken between 1871 and 1984 were matched between 1989 and 1995 and were analyzed for the occurrence of debris flows that reached the Colorado River. A frequency distribution also is given for the four debris-flow initiation mechanisms observed between 1984 and 2003 in Grand Canyon.

DEBRIS-FLOW FREQUENCY

Direct Observations (1984 – 2002)

We directly observed and compiled notes from river runners on when debris flows, rockfalls, or significant streamflow floods occurred in Grand Canyon from 1984 through 2002, updating the work of Melis and others (1994) and Webb and others (2000). In several cases (*e.g.*, the 1993 Tanner Canyon debris flow), eyewitnesses described the floods (Melis and others, 1994). From 1984 through 2002, an average of 4.9 debris flows occurred per year for a total of 93 events in 81 tributaries (fig. 1, table 1). A total of 14 debris flows occurred in 2001 and 13 in 2002, the most prolific 2-year period in the record. The number of debris flows in a given year is not directly related to the total amount of summer precipitation (fig. 1) but instead is a function of the number of intense precipitation events and where they occur in Grand Canyon (Webb and others, 1999a).

Several tributaries had more than one debris flow between 1984 and 2002. For example, 75 Mile and Monument Creeks each had three debris flows, suggesting that storms are not randomly distributed in Grand Canyon, at least during this time period. Multiple debris flows from a single drainage also suggest that slope and

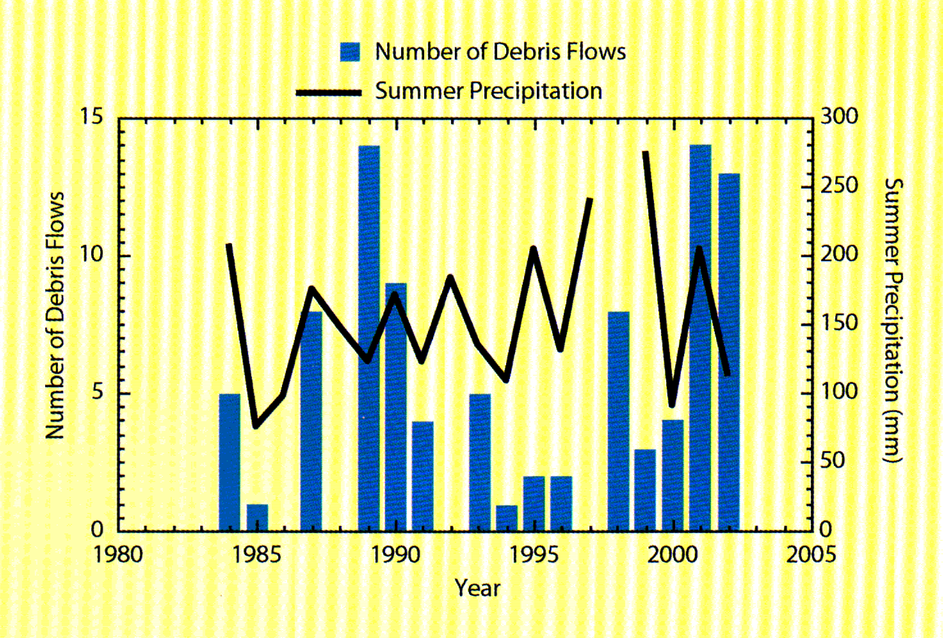


Figure 1. Number of debris flows in Grand Canyon and summer precipitation at Grand Canyon National Park Airport. Rainfall records are missing for the summer of 1998 and 1999.

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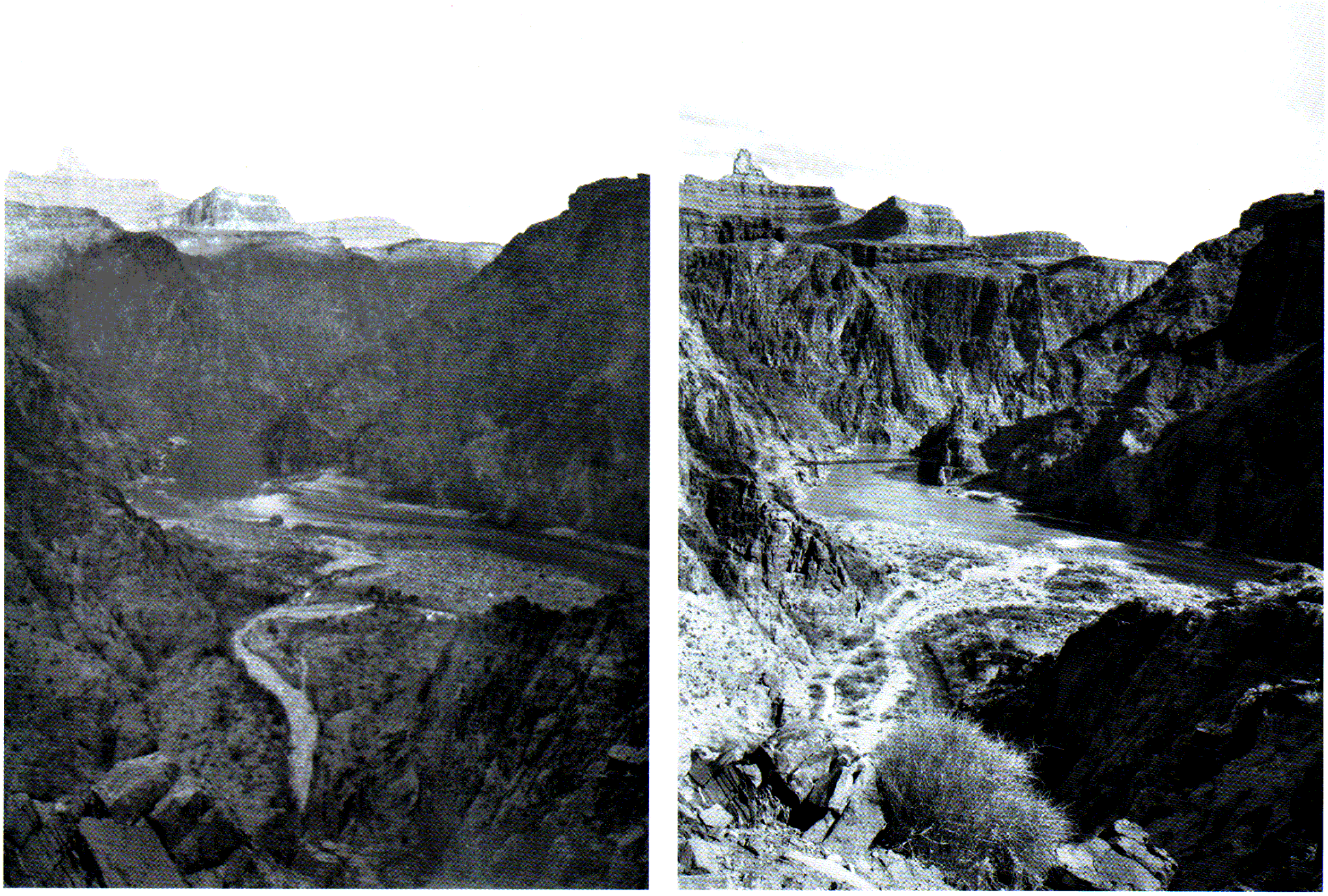

Figure 2. Replicate photographs of the debris fan at Bright Angel Creek (river mile 87.8-R). (A) (February 5, 1890) Bright Angel Creek, a perennial stream, has its headwaters on the North Rim. In 1890, the channel is distinct, relatively narrow, and hooks right to join the Colorado River beyond the cliff at lower right (photograph by Robert Brewster Stanton). (B) (February 13, 1991) Beginning in December 1966, several debris flows have significantly changed the debris fan, moving the edge of the debris fan closer to the Colorado River (photograph by Ted Melis).

channel destabilization caused by the initial event may lead to repeated events until either the destabilized sediment is removed or sufficient respite from severe storms allows stabilization. Several debris flows can result from a single local thunderstorm, which may be of sufficient size to cover adjacent tributary canyons simultaneously. As a result, debris-flow frequency in Grand Canyon does not appear to be uniformly distributed in space. Of the 19 debris flows in 2000 and 2001, many of the deposits extended into the river and 5 created major changes in the river.

Repeat Photography (1890 – 1983)

Repeat photography has been used successfully in Grand Canyon in numerous studies to document long-term changes in both terrestrial ecology and geomorphology (Turner and Karpiscak, 1980; Stephens and Shoemaker, 1987; Webb, 1996; Webb and others, 1989, 1999b). This type of scientific photography is particularly useful for evaluating the types of landscape changes associated with debris flows (fig. 2). For Grand Canyon, the year with the most abundant widespread coverage is 1890, when the well-documented Stanton expedition occurred (Webb, 1996). Debris flows that occurred between 1984 and the year a photograph was matched were not included in this analysis, yielding a debris-flow record from 1890 to 1983.

By developing a time series of historical photographs for specific debris fans, we were able to bracket when debris flows occurred at the mouths of tributaries. For example, at Prospect Canyon, 121 of 232 historical photographs were matched to provide detailed reconstruction of debris-flow occurrence (6 events between 1939 and 1995) and changes to Lava Falls Rapid (Webb and others, 1999a). For some tributaries, the dates of debris flows could be determined to within 1 year; for others, we know only that one or more debris flows occurred during the period of record (1890-1983). Detailed descriptions of the repeat photography collection and the criteria used to identify debris flows are given in Melis and others (1994), Webb (1996), and Webb and others (1999b).

We also analyzed several sets of low-altitude aerial photographs taken between 1935 and 1984 for evidence of debris flows. In 1935, aerial photographs of river miles 0 to 61 and 225 to 280 were taken at

Table 1. Frequency of debris flows in Grand Canyon, Arizona

Period	Interval (yrs)	Debris flows	Tributaries in sample			Percent of population	Tributaries per year		Debris flows per year	
			Debris flows	No debris flows	Total		Sample	Population	Sample	Population
1890-1983	94	93	84	63	147	19.9	0.89	4.5	1.0	5.0
1984-2002	19	93	81	659	740	100.0	4.3	4.3	4.9	4.9

a scale of 1:31,800; a second set of unrelated photographs, taken in November 1935, recorded river miles 87 to 129; and a third set was taken in 1938 at a scale of about 1:20,000 and recorded river miles 211 to 280. Spatially continuous aerial photography of the river corridor was taken in 1965, 1973, and annually between 1980 and 2002.

The combination of repeat and aerial photography resulted in the detection of 108 debris flows in Grand Canyon tributaries that occurred between 1890 and 1983. Combining these results with observations between 1984 and 2002, 201 debris flows are known to have occurred in Grand Canyon tributaries since 1890. In order to determine the frequency of debris flows before 1984, we evaluated the 445 Stanton photographs taken in 1890 and matched between 1990 and 1995 (Webb, 1996). These photographs provide upstream and downstream views of the river corridor at approximately 1 km intervals, including images of many major rapids. This remarkable set of photographs is an essentially unbiased sample of tributary debris fans, 147 of which are depicted with sufficient coverage for proper evaluation of significant geomorphic change. One important attribute of this data set is that the photographic record captures only the mouths of tributaries, therefore the resulting frequency estimates refer only to debris flows large enough to reach the Colorado River.

The photographic evidence reveals that 93 debris flows occurred at 84 of 147 tributaries between 1890 and 1984 (table 1), indicating that 57% of the tributaries with photographic data had at least one historical debris flow. In the remaining 43% of tributaries, debris flows are assumed to have occurred at a frequency of less than one per century. Only 6% of tributaries had 2 or more debris flows in the last century, up to a maximum of 6 at Lava Falls Rapid (including the 1995 event; Webb and others, 1999a). Taking this data set as an unbiased sample of the entire population of 740 tributaries, we calculate a rate of occurrence of 5.0/yr in the entire canyon for the period of 1890 to 1983, which is statistically identical to the 4.9/yr frequency observed between 1984 through 2002. The rate of debris flows before 1984 may actually have been higher because smaller events may not have been recorded owing to reworking during the pre-dam (before 1963) part of the record, when annual floods could easily remove the evidence of smaller events.

Radiogenic and Cosmogenic Dating

Radiogenic and cosmogenic dating methods have been used to date prehistoric Grand Canyon debris flows (Melis and others, 1984; Hereford and others, 1998). The oldest radiocarbon date on a Grand Canyon debris flow is 5,410±175 yrs BP (before present) from a small canyon at river mile 63.3 (Melis and others, 1994), and dates of 2 ka (kiloannum, thousands of years ago) or younger are common (Hereford and others, 1998). Cosmogenic ^{3}He dating (age-dating using Helium-3 that has been produced by cosmic rays) has been applied to Holocene debris-flow deposits that contain olivine-rich basalts (Webb and others, 1999a).

The oldest debris flow known in Grand Canyon occurred in Whitmore Canyon (river mile 189) and was dated at 8.5±0.2 ka using cosmogenic ^{3}He (Fenton and others, 2001); this debris flow did not reach the Colorado River. The largest Holocene debris flow to reach the Colorado River, from Prospect Canyon at river mile 179.4, was dated at 3.0±0.5 ka using this method; several smaller flows at this site were dated at 1-2 ka (Webb and others, 1999a). Hereford and others (1998) used radiogenic and cosmogenic dates to calibrate a dissolution-pit dating method for Grand Canyon debris-flow surfaces, thereby estimating frequency data for 26 tributaries. These studies suggest that historic debris-flow activity in Grand Canyon is a continuation of prehistoric activity that dates back to the early Holocene. Further research on prehistoric debris flows may address the question of whether debris-flow frequency in the historic period represents a change from conditions in the rest of the Holocene.

INITIATION MECHANISMS FOR DEBRIS FLOWS

Debris flows in Grand Canyon are initiated by a combination of intense precipitation and subsequent slope failure in source sediment. Detailed discussions of the hydroclimatology that contributes to debris-flow initiation are presented in Melis and others (1994), Griffiths and others (1997), and Webb and others (1999a). Intense summer or prolonged winter precipitation causes slope failures in either bedrock or colluvium, and these failures mobilize into debris flows that can flow as far as 22 km (Webb and others, 1989).

In Grand Canyon, Melis and others (1994) identified four debris-flow initiation mechanisms: (1) direct failure of weathered bedrock, (2) streamflow runoff falling directly onto colluvium at the base of cliffs (the “firehose effect,” Johnson and Rodine 1984), (3) direct failure of colluvium by saturation or undercutting along channels, and (4) combinations of these mechanisms.

Observed initiation mechanisms for selected debris flows in Grand Canyon from 1939 to 2002 appear in Figure 3. Owing to the steep, commonly inaccessible topography, initiation points for many recent debris flows could not be determined. These data include 51 debris flows occurring between 1984 and 2001 and 17 debris flows occurring between 1890 and 1983 with known initiation mechanisms (Cooley and others, 1977). The firehose effect is the most common initiation mechanism (62%) for debris flows in Grand Canyon. This mechanism requires

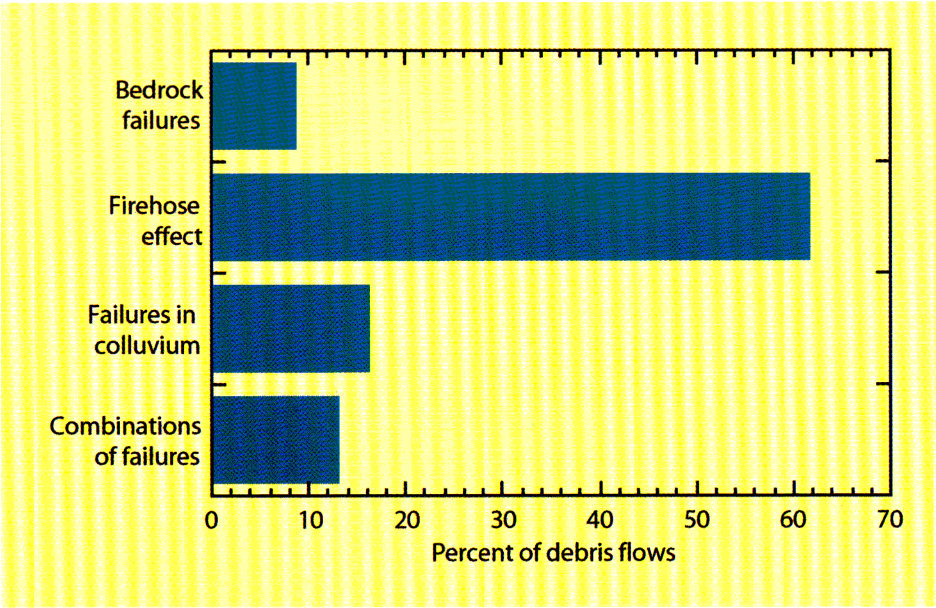

Figure 3. Initiation mechanisms for selected debris flows between 1939 through 2002 in Grand Canyon (n = 68; modified from Griffiths and others, 1997).

preexisting colluvial wedges at the base of cliffs, and presumably repeated debris-flow occurrence is at least partially dependent on regeneration of these wedges following their partial or total removal during an event. Direct failure of colluvium owing to saturation or undercutting adjacent to channels accounts for 16% of debris flows in this period. Direct failure of weathered Paleozoic shales and sandstones, most often in either the Hermit Formation or Supai Group, is triggered by intense, localized rainfall from convective summer thunderstorms or prolonged winter precipitation (Cooley and others, 1977); debris flows initiated by bedrock failures tend to be the least numerous but among the largest in Grand Canyon (Webb and others, 1988).

MANAGEMENT IMPLICATIONS

Debris flows occur, on average, five times per year in Grand Canyon. Most debris flows occur during the summer, when the river is most heavily used. Therefore, debris-flow activity may be a significant threat to the safety of recreationists along the river corridor. Education about the causes and frequency of debris flows in Grand Canyon may help reduce the potential for life-threatening situations along the river corridor.

Debris flows are a natural process, unaffected by land-use practices in the tributary drainages within Grand Canyon. No watershed management methods are known that would alter the probability of debris flows in Grand Canyon, although wildland fire might temporarily increase the probability of an event if a storm with sufficient intensity followed closely after a burn. Debris flows, combined with streamflow floods, are the source for gravel that lines the bed of much of the river corridor, providing optimal spawning habitat for nonnative salmonids, which prey on endangered native fish. Reduction of this gravel can only be achieved by periodic flushing flows released from Glen Canyon Dam.

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