Table 1. Characteristics of climate stations in the vicinity of Grand Canyon National Park

Station Name[1]	Elevation (m)	Record Length	Mean Annual Precipitation (mm)	Summer Precipitation (%)	Winter Precipitation (%)
Bright Angel RS	2,726	7/48-3/95	646	29	60
Desert View	2,271	9/60-7/95[2]	347	40	48
Grand Canyon	2,204	10/04-3/95	403	42	46
Lees Ferry	978	4/16-3/95	148	50	38
Mount Trumbull	1,818	10/20-12/78[3]	297	49	37
Peach Springs	1,613	7/48-3/95	280	45	43
Phantom Ranch	834	8/66-3/95	234	39	49
Tuweep RS	1,551	7/48-12/86[4]	306	42	43

Notes:
1 All stations are in Arizona (Fig. 1).
2 Daily data from September 1, 1960, to July 1, 1975, have been lost at this station, which is not part of the NOAA network of climate stations. Monthly data is available after September 1960 from the National Park Service.
3 Station discontinued.
4 In 1986, Tuweep Ranger Station was discontinued as a cooperative observer station, which records rainfall in 0.01 in. accuracy and reports in increments of daily rainfall. A tipping-bucket recording rain gage, which records rainfall in 0.10 in. increments and reports hourly as well as daily rainfall (e.g., U.S. Department of Commerce, 1966), remains in operation.

average of 1.5 m in every linear kilometer. The climate is semiarid to arid, producing a wide range of annual and seasonal precipitation (table 1). Melis and others (1994) and Webb and others (1996) discuss the regional hydroclimatology in relation to debris-flow initiation. Precipitation generally increases with elevation, and the amount of summer precipitation generally decreases towards the west.

METHODS

Initiation Mechanisms and Precipitation Recurrence Intervals

During the course of this study (1986-1995), 25 debris flows occurred in Grand Canyon (Melis and Webb, 1993; Melis and others, 1994; Webb and Melis, 1995; Webb and others, unpublished data). For as many of these events as feasible, we traced the debris flow to its initiation point to evaluate the failure mechanism and source material. Using other reports (for example, Cooley and others, 1977), we augmented our data with data on other notable, historic debris flows.

We obtained climatic data from the National Climatic Data Center in Asheville, North Carolina, and from their reports (for example, NOAA, 1996). We used daily rainfall data, and we calculated storm precipitation by summing over consecutive days with rainfall preceding historical debris flows. We estimated the probability of daily and storm precipitation using the modified Gringorten plotting position (U.S. Water Resources Council, 1981),

$$p = ((m - 0.44)/(n + 0.12)) \bullet d, \qquad (1)$$

where p = probability of the event, m = the ranking of the event, n = the number of days in the record, and d = the number of days in the season per year. The recurrence interval, R (yrs), is

$$R = 1/p. \qquad (2)$$

Selection of Geomorphically Significant Tributaries

Melis and others (1994) identified 529 geomorphically significant tributaries to the Colorado River in Grand Canyon from Lees Ferry to Diamond Creek, excluding the four largest tributaries (the Paria and Little Colorado Rivers, and Kanab and Havasu Creeks). They selected tributaries that have the potential to produce debris flows that affect the geomorphology of the river channel. Their criteria include: 1) drainage areas larger than 0.01 km^2; 2) mapped perennial or ephemeral streams; 3) previously designated

Figure 4. Replicate photographs of the debris fan at South Canyon (river mile 32.5-R). A. Photograph taken in July 17, 1889 by Franklin A. Nims. The debris fan is relatively small, and boats were parked relatively close to the mouth of the canyon.

official name; 4) clear termination at the Colorado River in a single channel; 5) formation of obvious debris fans and (or) rapids. We extend these definitions to 71 additional tributaries between Diamond Creek and Surprise Canyon in western Grand Canyon (river miles 225 to 248).

Repeat Photography and Binomial Frequency of Debris Flows

Although there are a variety of possible methods for dating recent debris flows, including the ^{3}He, ^{14}C, and ^{137}Cs techniques (Hereford and others, 1996; Melis and Webb, 1993; Melis and others, 1994; Webb and others, 1996), the most useful method in Grand Canyon is repeat photography for historic events (Webb, 1996). Repeat photography has been used to identify changes in plant distributions, effects of operations of Glen Canyon Dam on sand bars, and the appearance of debris-flow and flood deposits in previous studies in Grand Canyon (Turner and Karpiscak, 1980; Stephens and Shoemaker, 1987; Webb and others, 1988, 1989; Melis and others, 1994; Schmidt and others, 1996; Webb, 1996). This success is in large part due to the numerous photographs that have been taken of Grand Canyon since 1872.

More than 1,039 historical photographs of the river corridor taken since 1872 have been replicated and interpreted (Melis and others, 1994). Of these, 478 photographs capture views of tributary junctures, debris fans, and rapids. By comparing photographs of a given debris fan taken at different times, we have identified geomorphic changes that indicate the occurrence of one or more debris flows during the time interval separating the photographs.

B. Replicate view taken on January 2, 1992 by Jim Hasbargen. Several debris flows have aggraded the debris fan, including a large one that deposited the prominent levee at right between 1940 and 1965.

Figure 4. Continued.

Geomorphic change in Grand Canyon is largely catastrophic in nature, especially on a decadal time scale, and changes to debris fans resulting from debris flows are usually obvious. Such changes include the appearance of new boulders and disappearance of old ones, extensions of debris fans, new debris levees, and/or large channels cut through old deposits (fig. 4). Where no debris flows have occurred, fans show few changes, even after a hundred years (fig. 5). For some tributaries, we can determine the dates of debris flows to within one year, but it is impossible to determine whether fan alteration is the result of single or multiple events. Therefore, we chose to measure binomial rather than absolute frequency for each debris fan. Instead of tallying the total number of recent debris flows at each site, we indicate simply whether or not any debris flows have occurred since 1890.

The century over which we measure the binomial frequency of debris flows is determined by a remarkable baseline of photographs taken in 1889 and 1890 by Franklin A. Nims and Robert B. Stanton (Melis and others, 1994; Webb, 1996). A total of 445 photographs record the general topography of the river corridor at roughly 2-km intervals along the entire length of Grand Canyon. We replicated the Nims and Stanton photographs between 1990 and 1994 (Webb, 1996); in addition, we used 38 photographs of the Canyon taken by John K. Hillers in 1872 (Fowler, 1989). A total of 178 of these 483 photographs capture debris fans at the confluences of 164 of the 600 tributaries and the