# Initiation and Frequency of Debris Flows in Grand Canyon, Arizona

U.S. GEOLOGICAL SURVEY
Open-File Report 96—491

Prepared in cooperation with the
BUREAU OF RECLAMATION

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By PETER G. GRIFFITHS, ROBERT H. WEBB, and
THEODORE S. MELIS

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U.S. DEPARTMENT OF THE INTERIOR
BRUCE BABBITT, Secretary

U.S. GEOLOGICAL SURVEY
Gordon P. Eaton, Director

For additional information write to:

Regional Research Hydrologist
U.S. Geological Survey, MS-472
Water Resources Division
345 Middlefield Road
Menlo Park, CA 94025

Copies of this report can be purchased from:

U.S. Geological Survey
Branch of Information Services
Box 25286
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## CONVERSION FACTORS

For readers who prefer to use inch-pound units, conversion factors for the terms in this report are listed below:

| Multiply | By | To obtain |
|---|---|---|
| millimeter (mm) | 0.03937 | inch (in.) |
| meter (m) | 3.2818 | foot (ft) |
| square meter ($m^2$) | 10.76 | square foot ($ft^2$) |
| kilometer (km) | 0.6214 | mile (mi) |
| square kilometer ($km^2$) | 0.3861 | square mile ($mi^2$) |

Sea level: In this report, “sea level” refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)--a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called “Sea Level Datum of 1929.”

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## ABSTRACT

Debris flows occur in 600 tributaries of the Colorado River in Grand Canyon, Arizona when intense precipitation causes slope failures in bedrock or colluvium. These slurries transport poorly sorted sediment, including very large boulders that form rapids at the mouths of tributaries and control the longitudinal profile of the Colorado River. Although the amount of rainfall on the days of historic debris flows typically is not unusual, the storm rainfall on consecutive days before the debris flows typically had recurrence intervals greater than 10 yrs. Four types of failure mechanisms initiate debris flows: bedrock failure (12 percent), failure of colluvial wedges by rainfall (21 percent), failure of colluvial wedges by runoff (the “firehose effect;” 36 percent), and combinations of these failure mechanisms (30 percent). Failure points are directly or indirectly associated with terrestrial shales, particularly the Permian Hermit Shale, shale units within the Permian Esplanade Sandstone of the Supai Group, and the Cambrian Bright Angel Shale. Shales either directly fail, produce colluvial wedges downslope that contain clay, or form benches that store poorly sorted colluvium in wedge-shaped deposits. Terrestrial shales provide the fine particles and clay minerals — particularly kaolinite and illite — essential to long-distance debris-flow transport, whereas marine shales mostly contain smectites, which inhibit debris-flow initiation.

Using repeat photography, we determined whether or not a debris flow occurred in the last century in 164 of 600 tributaries in Grand Canyon. We used logistic regression to model the binomial frequency data using 21 morphometric and lithologic variables. The location of shale units, particularly the Hermit Shale, within the tributary is the most consistent variable related to debris-flow frequency in Grand Canyon. Other statistically significant variables vary with large scale changes in canyon morphology. Standard morphometric measures such as drainage-basin area, channel gradient, and aspect of the river corridor are the most significant variables in the narrow and deep eastern section of Grand Canyon. Measures of the location of source lithologies are more important in western Grand Canyon, which has broader and low-gradient drainages. Measures of geologic structure, and other standard hydrologic variates, were not significant.

Our results show that the probability of debris-flow occurrence is highest in eastern Grand Canyon. Throughout Grand Canyon, the probability of debris-flow occurrence is highest in reaches of the Colorado River that trend south-southwest. This direction is significant because most summer storms originate from a southerly direction, and the maximum slope of the regional structure is to the southwest. The binomial frequency of debris flows is not random in Grand Canyon, and tributaries of similar debris-flow frequency are clustered in distinct reaches.

## INTRODUCTION

Debris flows are the primary sediment transport process in 600 tributaries of the Colorado River between Lees Ferry and Diamond Creek, Arizona (fig. 1). This type of flash flood contains up to 80 percent sediment by weight and deposits poorly sorted sediment that ranges from fine clays to extremely large boulders (b-axis > 3 m) in the river (Melis and others, 1994). All but the largest boulders were entrained by typical, pre-dam Colorado River floods, and debris fans, which are composed of residual boulders, form rapids in the Colorado River (fig. 2). Because debris fans raise the bed elevation (Howard and Dolan, 1981), the Colorado River forms large pools upstream from rapids. Flow through rapids ends in pools (Dolan and others, 1978; Kieffer, 1985), the downstream end of which is controlled by bedrock outcrops or alternating debris bars that are outwash from the upstream debris fan (Howard and Dolan, 1981; Webb and others, 1989; Melis and Webb, 1993; Melis and others, 1994). Half of the vertical drop of the Colorado River occurs in rapids, which account for only 10 percent of the river's length through Grand Canyon (Leopold, 1969). By forming rapids, debris flows define the longitudinal profile and control the geomorphic framework of the Colorado River in Grand Canyon (Webb, 1996).

A better understanding of the factors and processes involved in the initiation of debris flows is critical to understanding the dynamic processes that shape and control the Colorado River in Grand Canyon National Park. Moreover, debris flows are a significant geomorphic hazard worldwide (Costa and Wieczorek, 1987). The debris-flow process is of interest not only to scientists but also to the more than 20,000 whitewater enthusiasts that run the rapids in Grand Canyon every summer (Stevens, 1990). An average-sized debris flow can alter the severity of a major rapid or riffle, or cover a popular camping beach with boulder-strewn debris in a matter of seconds. Because of operation of Glen Canyon Dam, rapids constricted by debris flows are only partially reworked by flow in the regulated Colorado River (Graf, 1980; Melis and Webb, 1993; Webb and others, 1996).

Most of Grand Canyon is unaffected by humans and provides an excellent setting for studying debris-flow processes that are little influenced by land-use practices. Also, the scenic beauty of Grand Canyon has generated an enormous body of photographs of the Colorado River beginning in 1872 (Melis and others, 1994). These photographs contain a wealth of information on the occurrence of debris flows over the last century (Webb, 1996), and provide us with binomial-frequency data: whether or not a debris flow has occurred in the last century.

This study examines the process of debris-flow initiation and transport in Grand Canyon and presents field observations on the roles of climate, canyon lithology, geologic structure, and drainage-basin morphometrics. Particular emphasis is given to the roles of intense precipitation and source areas. We evaluated the relative importance of different types of independent drainage-basin variables in generating debris flows using logistic regression (Hosmer and Lemeshow, 1989). Logistic-regression modeling permits the identification of statistically significant drainage-basin variables, isolating those geomorphic factors that most strongly control debris-flow initiation in the near-vertical cliffs of Grand Canyon and transport to the Colorado River.

The occurrence of debris flows in the last century was determined for 164 tributaries (the "calibration set") using repeat photography and analysis of hundreds of historical photographs taken of the river corridor from 1872 through 1995. Frequency information for 50 additional tributaries (the "verification set") was used to test the robustness of the logistic-regression model. Whether or not a debris flow occurred in that period was determined by analyzing the differences between historical photographs and the modern matches. We increased the available data (Melis and others, 1994) from 529 to 600 tributaries of the Colorado River by adding tributaries downstream from Diamond Creek for which frequency information is available. Using the model coefficients obtained from the calibration set, we estimated the probability of debris-flow occurrence for all 600 tributaries.

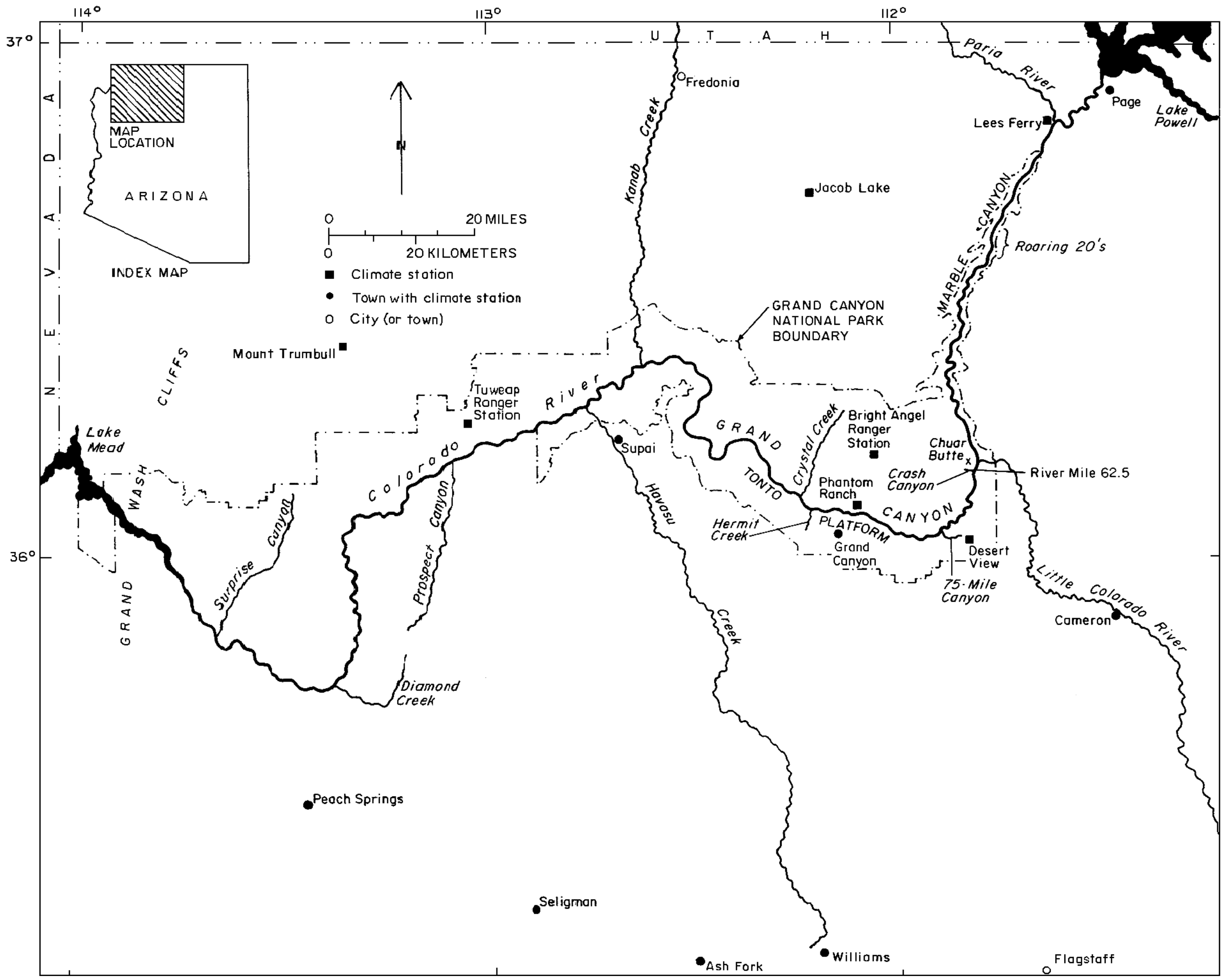


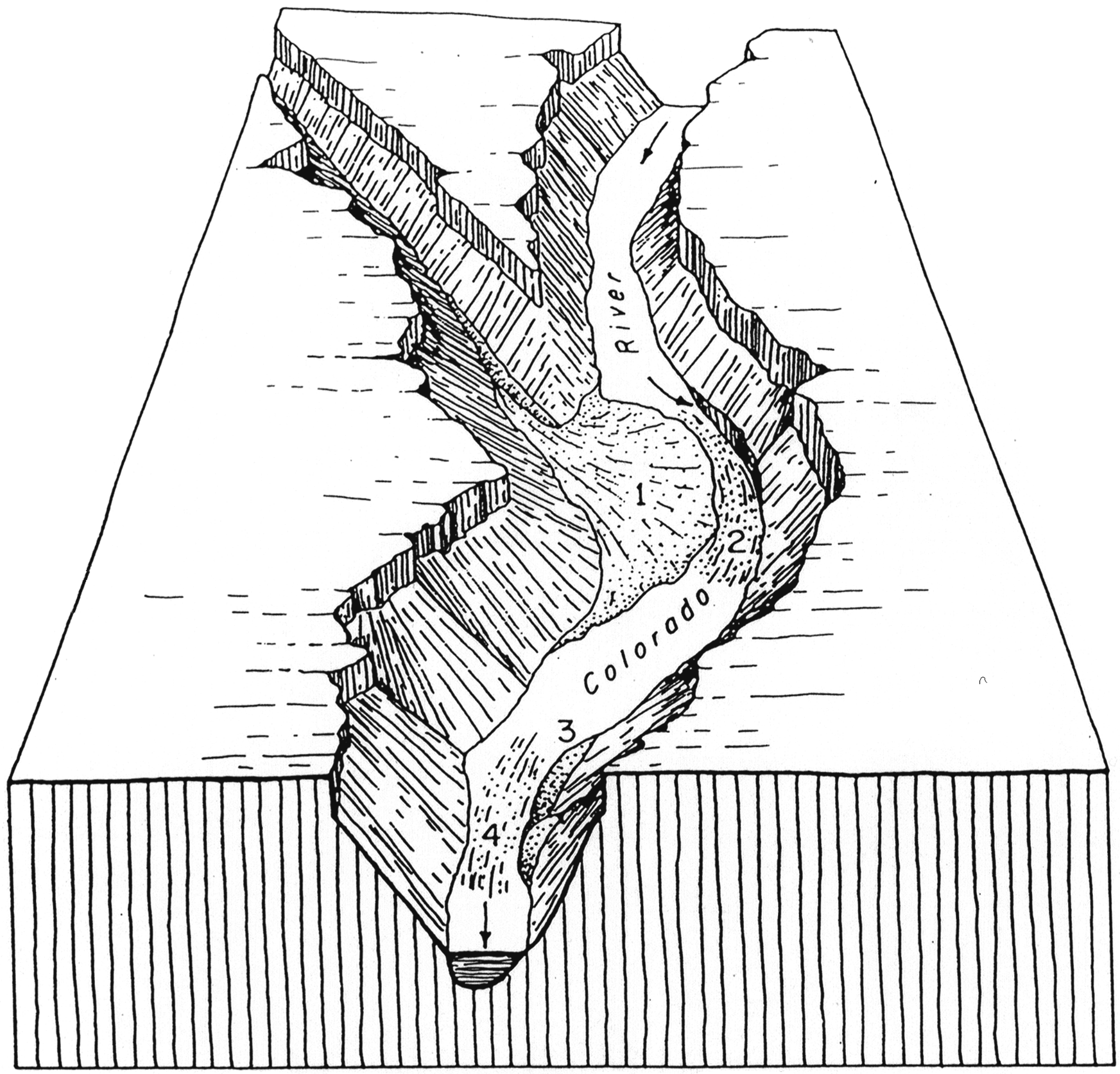

**Figure 1**. The Colorado River in Grand Canyon, Arizona.

## Purpose and Scope

This study provides an analysis of initiation mechanisms and frequency of historic debris flows in Grand Canyon National Park and vicinity, Arizona. The data presented here will be used as the basis for development of sediment-yield estimates from ungaged tributaries of the Colorado River, a critical element of long-term management of resources downstream from Glen Canyon Dam (U.S. Department of Interior, 1995). This report incorporates existing information on debris-flow frequency in Grand Canyon (Cooley and others, 1977; Webb and others, 1989; Melis and others, 1994), and includes 600 tributaries of the Colorado River between Lees Ferry and Surprise Canyon, Arizona (river miles 0 to 248), excluding the Paria and Little Colorado Rivers and Kanab and Havasu Creeks. Repeat photography from the 1889-1890 Stanton expedition (Webb, 1996) provides uniform data for estimation of the binomial frequency of debris flows in 164 tributaries in Grand Canyon. Logistic regression is used to develop a statistical model based on measured morphometric, lithologic, and climatic variables from these 164 tributaries for estimation of the probability of debris-flow occurrence in all 600 geomorphically significant tributaries. This work was funded in cooperation with the Glen Canyon Environmental Studies Program of the Bureau of Reclamation.

## Units and Place Names

In this report, we use the inch-pound unit of mile to describe location of tributaries along the




(Modified from Hamblin and Rigby, 1968)

Explanation

1. Tributary debris fan
2. Rapid controlled by large immobile boulders
3. Debris bar (synonymous with “island” or “rock garden”)
4. Riffle or rapid caused by debris bar

**Figure 2**. The morphology of a typical debris fan and rapid on the Colorado River in Grand Canyon.

Colorado River; metric units are used for all other measures. Use of river mile has considerable historical precedent (Stevens, 1990) and provides a reproducible method of describing the location of tributaries with respect to the Colorado River. The location of tributaries was described using river miles downstream from Lees Ferry and a descriptor of "L" for river-left and "R" for river-right. The left and right sides of the Colorado River are determined as one faces downstream.

We typically refer to "Grand Canyon" in broad reference to both Marble and Grand Canyons. "Marble Canyon" is the canyon reach of the Colorado River between Lees Ferry and the juncture with the Little Colorado River (river miles 0 to 61.5; fig. 1); we refer to Marble Canyon only for specific tributaries in that reach. Grand Canyon, which is formally designated between the juncture with the Little Colorado River and the Grand Wash Cliffs (river miles 61.5 to about 280), is considerably larger and better known than Marble Canyon. For geological and statistical reasons described in the text, we divide Grand Canyon into eastern Grand Canyon, between Lees Ferry and Crystal Rapid (river miles 0 to 98) and western Grand Canyon, between Crystal Rapid and Surprise Canyon (river miles 98 to 248; fig. 1).


### Acknowledgments

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## SETTING

Grand Canyon has formed where the Colorado River cuts deeply through the southwestern corner of the Colorado Plateau in northern Arizona (fig. 1), exposing nearly 2 km of Paleozoic and Proterozoic stratigraphy (fig. 3). The combination of the slow downcutting of the Colorado and the gradual rise of strata toward the Kaibab uplift in the west results in the rapid exposure of Paleozoic strata as one moves downstream (Huntoon and others, 1986). Numerous resistant strata — the Paleozoic Kaibab Formation, Coconino Sandstone, and especially the thick Redwall and Muav limestones — are exposed at river level, resulting in a narrow, steep-sided canyon. Owing to the steepness of the canyon walls, the divides for most drainages in Marble Canyon are at the rim, exposing the maximum extent of the stratigraphy. Marble Canyon encompasses much of eastern Grand Canyon.

The entire Paleozoic section and some Proterozoic units are exposed west of Phantom Ranch (river mile 87; fig. 1). The exposure of the Bright Angel Shale near river level results in a distinctly wider canyon. The drainage divides of many smaller tributaries are not at the rim; therefore, these tributaries do not contain some of the younger geologic units. The maximum dip in the regional structure is mostly to the southwest (Huntoon and others, 1986). From eastern to western Grand Canyon, increased faulting results in large changes in the elevation of stratigraphic units from one rim to the other (Huntoon and others, 1986). Western Grand Canyon lies entirely within Grand Canyon proper.

Elevations in Grand Canyon range from 975 to 2,804 m above sea level at the rim, and from 939 m to 402 m along the river. The river itself drops an