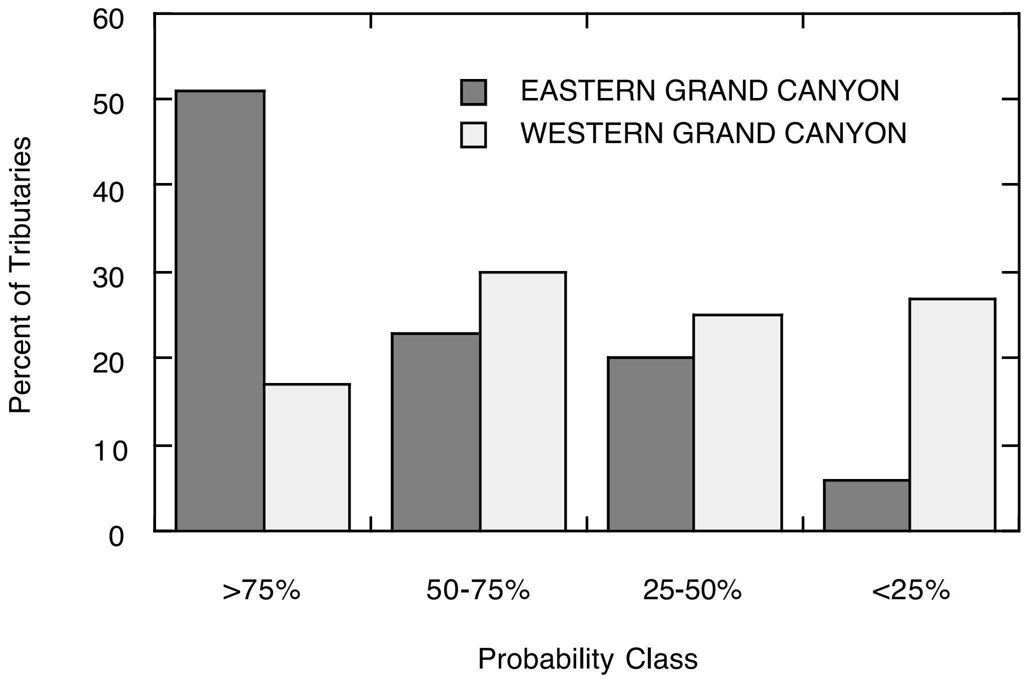

Figure 19. Histograms of the probability of debris-flow occurrence in eastern and western Grand Canyon.

Canyon, but it is not a primary contributor in the overall pattern of debris-flow probability. Although faults control the locations of tributaries (Dolan and others, 1978; Potochnik and Reynolds, 1990), the area and volume of fractured material produced by faulting does not appear to be important in initiating debris flows, except locally.

DISCUSSION AND CONCLUSIONS

Debris flows in Grand Canyon are one of the main controls on the geomorphic framework of the Colorado River, depositing large boulders that define the river's longitudinal profile. These mass movements are initiated when weathered bedrock or colluvial wedges fail during intense rainfall. These failures can be classified according to four failure mechanisms: 1) direct failure of weathered bedrock (12 percent); 2) failure of colluvium from the impact of runoff cascading from cliff pourovers, known as the "firehose effect" (36 percent); 3) failure of saturated colluvium (21 percent); and 4) combinations of these three mechanisms (30 percent).

A variety of geomorphic factors relating to climate, exposed lithologic strata, geologic structure, and drainage-basin morphology play various roles in the process of debris-flow initiation. Among these factors, the exposure of shale source areas at heights greater than 100 m above the mainstem is particularly critical in each of the four initiation mechanisms. Shales fail readily as weathered bedrock, produce abundant colluvial source material, and form slopes where colluvium collects. Shales also provide the fine particles and clay minerals (for example, kaolinite and illite) that appear to be essential to the stability of slurries, enabling debris flows to transport poorly-sorted sediments up to several kilometers from tributary sources to the Colorado River.

Earlier work has investigated the statistical significance of various morphometric variables in relation to flood magnitude, usually emphasizing drainage-basin area, mean-basin elevation, and amount or intensity of precipitation (Roeske, 1978; Thomas and others, 1994). Patton and Baker (1976) suggest that stream magnitude may also be a good predictor of flash-flood potential for small drainage basins. They argue that transient controls, such as climatic variability, also play a significant role. Shown (1970) includes all of these variables in modeling sediment transport in the southwest, as well as factors relating to surface geology and soils such as rock type, hardness, weathering, and texture.

Those drainage-basin variables that are most significant in influencing the binomial frequency of debris flows are well illustrated by a plot of the modeled probability of debris flows in all 600 geomorphically significant tributaries of Grand Canyon between Lees Ferry and Surprise Canyon (river miles 0-248; fig. 18). The results of the logistic regression model clearly demonstrate that debris flows in Grand Canyon do not occur randomly in space. The binomial frequency of debris flows is substantially higher in eastern Grand Canyon, where 51 percent of the tributaries have had a probability of debris flows greater than 75 percent during the last 100 years (fig. 19). In contrast, 17 percent of tributaries in western Grand Canyon have had a probability of debris flows greater than 75 percent. For all of Grand Canyon, 60 percent of the tributaries have had a debris-flow probability greater than 50 percent, although that probability was 74 percent in eastern Grand Canyon and 47 percent in western Grand Canyon.

Distinct patterns are evident in the debris-flow probability map, such as an overall higher probability of debris flows in eastern Grand Canyon (fig. 18). This is due to a combination of an increase in precipitation and a general trend in river aspect to the southwest that takes maximum advantage of increased precipitation. Also significant in eastern Grand Canyon is the presence of the Hermit Shale at an optimum height above the river. All three elements combine to make the stretch from Lees Ferry to 75-Mile Canyon the most prolific zone of debris-flow production in the Grand Canyon, as evidenced by the high probability of debris-flow occurrence (fig. 18).

These same trends also occur in western Grand Canyon. Debris flows fall off notably where the canyon turns to the north-west, perpendicular to the movement of severe storms. Although climatic variables were not selected as statistically significant in the models, they still seem to have an underlying influence. Debris-flow probability is lowest downstream from Diamond Creek, where precipitation is lowest and the river trends northwest. The results of the logistic regression model clearly demonstrate that variation in lithologic, morphometric, and climatic variables have a strong effect on the probability of debris flows in Grand Canyon.

REFERENCES CITED

Beverage, J.P., and Culbertson, J.K., 1964, Hyperconcentrations of suspended sediment: American Society of Civil Engineers, Journal of the Hydraulics Division, v. 90, p. 117-126.

Billingsley, G.H., and Elston, D.P., 1989, Geologic log of the Colorado River from Lees Ferry to Temple Bar, Lake Mead, Arizona, *in* Elston, D.P., Billingsley, G.H., and Young, R.A. (editors), Geology of Grand Canyon, northern Arizona: Washington, D.C., American Geophysical Union, p. 1-47.

Billingsley, G. H., Jr., and Huntoon, P.W., 1983, Geologic map of Vulcan's Throne and vicinity, western Grand Canyon: Grand Canyon Natural History Association, scale 1:48 000, 1 sheet.

Cooley, M.E., Aldridge, B.N., and Euler, R.C., 1977, Effects of the catastrophic flood of December, 1966, North Rim area, eastern Grand Canyon, Arizona: U.S. Geological Survey Professional Paper 980, 43 p.

Costa, J.E., and Wieczorek, G.F., 1987, Debris flows/avalanches: Process, recognition, and mitigation: Geological Society of America, Reviews in Engineering Geology, v. 7, 239 p.

Dolan, R., Howard, A., and Trimble, D., 1978, Structural control of the rapids and pools of the Colorado River in the Grand Canyon: Science, v. 202, p. 629-631.

Ford, T.D., Huntoon. P.W., Billingsley, G.H., Breed, W.J., 1974, Rock movement and mass wastage in the Grand Canyon, in Geology of the Grand

Canyon: Flagstaff, Museum of Northern Arizona, Grand Canyon Natural History Association Publication, p. 116-128.

Graf, W.L., 1979, Rapids in canyon rivers: Journal of Geology, v. 87, p. 533-551.

Graf, W.L., 1980, The effect of dam closure on downstream rapids: Water Resources Research, v. 16, p. 129-136.

Hamblin, W.K., and Rigby, J.K., 1968, Guidebook to the Colorado River, Part 1 — Lees Ferry to Phantom Ranch in Grand Canyon National Park: Provo, Utah, Brigham Young University Geology Studies, v. 15, part 5, 84 p.

Hampton, M.A., 1975, Competence of fine-grained debris flows: Journal of Sedimentary Petrology, v. 45, p. 834-844.

Hansen, E.M., and Shwarz, F.K., 1981, Meteorology of important rainstorms in the Colorado River and Great Basin drainages: National Weather Service Hydrometeorological Report No. 50, 167 p.

Haynes, D.D., and Hackman, R.J., 1978, Geology, structure, and uranium deposits of the Marble Canyon 1° x 2° quadrangle, Arizona: U.S. Geological Survey Miscellaneous Investigations Series Map I-1003, scale 1:250,000, 2 sheets.

Hereford, R., and Huntoon, P.W., 1990, Rock movement and mass wastage in the Grand Canyon, in Beus, S.S., and Morales, M. (editors), Grand Canyon geology: New York, Oxford University Press, p. 443-459.

Hereford, R., Thompson, K.S., Burke, K.J., and Fairley, H.C., 1996, Tributary debris fans and the late Holocene alluvial chronology of the Colorado River, eastern Grand Canyon, Arizona: Geological Society of America Bulletin, v. 108, p. 3-19.

Hirschboeck, K.K., 1985, Hydroclimatology of flow events in the Gila River Basin, central and southern Arizona [Ph.D. dissertation.]: Tucson, Arizona, University of Arizona, 335 p.

Hosmer, D.W., and Lemeshow, S., 1989, Applied logistic regression: New York, John Wiley and Sons, 307 p.

Howard, A., and Dolan, R., 1981, Geomorphology of the Colorado River in Grand Canyon: Journal of Geology, v. 89, p. 269-297.

Huntoon, P.W., and Billingsley, G.H., 1983, Geologic map of Vulcan's Throne and vicinity, western Grand Canyon, Arizona: Grand Canyon Natural History Association, scale 1:48 000, 1 sheet.

Huntoon, P.W., Billingsley, G.H., and Clark, M.D., 1981, Geologic map of the Hurricane Fault Zone and vicinity, western Grand Canyon, Arizona: Grand Canyon Natural History Association, scale 1:48 000, 1 sheet.

Huntoon, P.W., Billingsley, G.H., Breed, W.J., Sears, W.J., Ford, T.D., Clark, M.D., Babcock, S., and Brown, E.H., 1986, Geologic map of the eastern part of the Grand Canyon National Park, Arizona: Grand Canyon Natural History Association Map, scale 1:62,500, 1 sheet.

Johnson, A.M., and Rodine, J.R., 1984, Debris flow, *in* Brunsden, D., and Prior, D.B. (editors), Slope instability: New York, John Wiley and Sons, p. 257-361.

Kieffer, S.W., 1985, The 1983 hydraulic jump in Crystal Rapid — Implications for river running and geomorphic evolution in the Grand Canyon: Journal of Geology, v. 93, p. 385-406.

Leopold, L.B., 1969, The rapids and pools — Grand Canyon, *in* The Colorado River Region and John Wesley Powell: U.S. Geological Survey Professional Paper 669, p. 131-145.

Major, J.J., and Pierson, T.C., 1992, Debris flow rheology: Experimental analysis of fine grained slurries: Water Resources Research, v. 28, no. 3, p. 841-858.

Melis, T.S., and Webb, R.H., 1993, Debris flows in Grand Canyon National Park, Arizona — Magnitude, frequency and effects on the Colorado River, *in* Shen, H.W., Su, S.T., and Wen, F. (editors), Hydraulic Engineering '93: New York, American Society of Civil Engineers, Proceedings of the ASCE Conference, San Francisco, California, p. 1290-1295.

Melis, T.S., Webb, R.H., Griffiths, P.G., and Wise, T.J., 1994, Magnitude and frequency data for historic debris flows in Grand Canyon National Park and vicinity, Arizona: U.S. Geological Survey Water-Resources Investigations Report 94-4214, 285 p.

National Oceanic and Atmospheric Administration (NOAA), 1996, Climatological data, Arizona, February 1996: Asheville, North Carolina, Climatic Data Center, v. 100, no. 2, 36 p.

Patton, P.C., and Baker, V.R., 1976, Morphometry and floods in small drainage basins subject to diverse hydrogeomorphic controls: Water Resources Research, v. 12, p. 941-952.

Pierson, T.C., and Costa, J.E., 1987, A rheologic classification of subaerial sediment-water flows, *in* Costa, J.E., and Wieczorek, G.F. (editors), Debris flows / avalanches — Process, recognition, and mitigation: Reviews in Engineering Geology, v. 7, p. 1-12.

Potochnik, A.R., and Reynolds, S.J., 1990, Side canyons of the Colorado River, Grand Canyon, *in* Beus, S.S., and Morales, M. (editors), Grand Canyon geology: New York, Oxford University Press, p. 461-481.

Powell, J.W., 1875, Exploration of the Colorado River and its canyons: New York, Dover Publications, 400 p.

Rodine, J.D., and Johnson, A.R., 1976, The ability of debris, heavily freighted with coarse clastic materials, to flow on gentle slopes: Sedimentology, v. 23, p. 213-234.

Roeske, R.H., 1978, Methods for estimating the magnitude and frequency of floods in Arizona: Arizona Department of Transportation Final Report ADOT-RS-15(121), 82 p.

SAS, 1990, SAS/STAT User's Guide, Version 6, Fourth Edition, Volume 2: Cary, North Carolina, SAS Institute, Incorporated, 846 p.

Savage, S.B., and Hutter, K., 1987, The motion of a finite mass of granular material down a rough incline: Journal of Fluid Mechanics, v. 199, p. 177-215.

Schmidt, J.C., Grams, P.E., and Webb, R.H., 1995, Comparison of the magnitude of erosion along two large regulated rivers: Water Resources Bulletin, v. 31, p. 617-631.

Sellers, W.D., Hill, R.H., and Sanderson-Rae, M. (editors), 1985, Arizona climate: Tucson, University of Arizona Press, 143 p.

Shown, L.M., 1970, Evaluation of a method for estimating sediment yield: U.S. Geological Survey Professional Paper 700-B, p. B245-B299.

Smith, W., 1986, The effects of eastern North Pacific tropical cyclones on the southwestern United States: Salt Lake City, Utah, National Oceanic and Atmospheric Administration, Technical Memorandum NWS-WR-197, 229 p.

Starkey, H.C., Blackmoun, P.D., Hauff, P.L., 1984, The routine mineralogical analysis of clay-bearing samples: U.S. Geological Survey Bulletin 1563, 32 p.

Stephens, H.G., and Shoemaker, E.M., 1987, In the footsteps of John Wesley Powell: Boulder, Colorado, Johnson Books, 286 p.

Stevens, L., 1990, The Colorado River in Grand Canyon, A guide: Flagstaff, Arizona, Red Lake Books, 107 p.

Thomas, B.E., Hjalmarson, H.W., and Waltemeyer, S.D., 1994, Methods for estimating the magnitude and frequency of floods in southwestern United States: U.S. Geological Survey Open-File Report 93-419, 219 p.

Turner, R.M., and Karpiscak, M.M., 1980, Recent vegetation changes along the Colorado River between Glen Canyon Dam and Lake Mead, Arizona: U.S. Geological Survey Professional Paper 1132, 125 p.

U.S. Department of Commerce, 1966, Arizona, Hourly precipitation data, December 1966: U.S. Department of Commerce, Environmental Science Services Administration, v. 16, no. 12, 5 p.

U.S. Department of Interior, 1995, Operation of Glen Canyon Dam, Final environmental impact statement: Salt Lake City, Utah, Bureau of Reclamation, 337 p. + appendices.

U.S. Water Resources Council, 1981, Guidelines for determining flood flow frequency: Hydrology Subcommittee Bulletin 17B, 183 p.

Webb, R.H., 1996, Grand Canyon, a century of environmental change: Tucson, University of Arizona Press, 290 p.

Webb, R.H., and Betancourt, J.L., 1992, Climatic variability and flood frequency of the Santa Cruz River, Pima County, Arizona: U.S. Geological Survey Water-Supply Paper 2379, 40 p.

Webb, R.H., and Melis, T.S., 1995, The 1995 debris flow at Lava Falls Rapid: Nature Notes, v. 11, p. 1-4.

Webb, R.H., Pringle, P.T., Reneau, S.L., and Rink, G.R., 1988, Monument Creek debris flow, 1984 — Implications for formation of rapids on the Colorado River in Grand Canyon National Park: Geology, v. 16, p. 50-54.

Webb, R.H., Pringle, P.T., and Rink, G.R., 1989, Debris flows in tributaries of the Colorado River in Grand Canyon National Park, Arizona: U.S. Geological Survey Professional Paper 1492, 39 p.

Webb, R.H., Melis, T.S., Wise, T.W., and Elliott, J.G., 1996, "The Great Cataract," The effects of late Holocene debris flows on Lava Falls Rapid, Grand Canyon National Park, Arizona: U.S. Geological Survey Open-file Report 96-460, 96 p.