on the basis of increased information content), the extraneous variables were eliminated from further consideration. Variables measuring distance or area, such as drainage area, channel distances, channel gradient, and fault distance, are distributed logarithmically. Logistic regression is not dependent on normally distributed data, but log transformation of these variables reduces the redundancy identified by principal-component analysis. We therefore chose to use the log-transformed values in modeling the probability of debris-flow occurrence. To properly evaluate zero values in log-transformed data, zero values were replaced with a value one order of magnitude smaller than the smallest non-zero variable. For source-lithology channel distances and gradients this value was 0.001, resulting in a log-transformed value of -3. For fault lengths, these values were 0.01 and -2.

We used a step-backward elimination process in our logistic regression (SAS, 1990). Variables of least statistical significance are removed from the model until only variables with significance (ρ_v) less than a given threshold (0.10 in this study) remain. We used the χ^2 measure of the Wald statistic (Hosmer and Lemeshow, 1989; SAS, 1990) to evaluate variable significance. We employed several statistics to evaluate the quality of the resulting models. These statistics include measures of the overall significance of the final model compared with the model containing all initial variables (ρ_m); a percentage of accurately predicted debris-flow occurrence as a rough measure of model accuracy (α); and the Hosmer/Lemeshow model goodness-of-fit statistic (C), which can be expressed as a χ^2 significance measure (ρ_C) (Hosmer and Lemeshow, 1989).

We also calculated the odds ratio (Ψ) for each variable in the model. This statistic measures the change in the odds of outcome occurrence per unit increase of the variable. We evaluated how robust the models were by attempting to reproduce model results using larger data sets drawn from the same population of drainages. For this purpose, we determined debris-flow probability for the "verification set," an additional 50 drainages — 25 each in eastern and western Grand Canyon — using a variety of non-photographic methods, including radiometric dating, stratigraphic evidence, and other field evidence (Melis and others, 1994). Unfortunately, a verification set of only 25 observations is too small for reliable logistic regression modeling alone. We therefore added each set of 25 drainages to the original calibration data and formed two larger verification data sets (fig. 7). This overlap of calibration and verification data limits the usefulness of the model comparison.

INITIATION OF DEBRIS FLOWS

Debris flows in Grand Canyon are initiated by a combination of intense precipitation and subsequent slope failure. The intensity of rainfall necessary to initiate debris flows in Grand Canyon is poorly known because few climatic stations are in debris-flow producing tributaries. Previous studies have reported rainfall that initiates debris flows to have intensities greater than 25 mm/hr with a total rainfall of at least 16 to 50 mm (Webb and others, 1989; Melis and others, 1994). The recurrence interval of precipitation on the days when debris flows have occurred in Grand Canyon ranges from less than one year to more than sixty years (table 2). Multiday storms that precede debris flows had larger recurrence intervals, typically greater than 100 years.

Intense precipitation may occur in summer or winter throughout Grand Canyon. Three types of storms can cause floods in the southwestern United States: localized or widespread convective thunderstorms in summer, regional frontal systems in winter, and dissipating tropical cyclones in late summer and early fall (Hansen and Shwarz, 1981; Hirschboeck, 1985; Webb and Betancourt, 1992; Thomas and others, 1994). Most historic debris flows in Grand Canyon are associated with the intense precipitation of convective summer thunderstorms that affect only one or two drainages at a time. These storms are fed by large quantities of moisture, evaporated from the northern Pacific and Gulf of California by monsoonal circulation patterns. Debris flows also occur during prolonged precipitation produced in winter by regional frontal systems (Cooley and others, 1977). These widespread storms sweep across the Colorado Plateau from the west along the Pacific storm track, which is shifted south during the winter by the Aleutian Low in the North Pacific Ocean (Webb and Betancourt, 1992). Rain that can be both

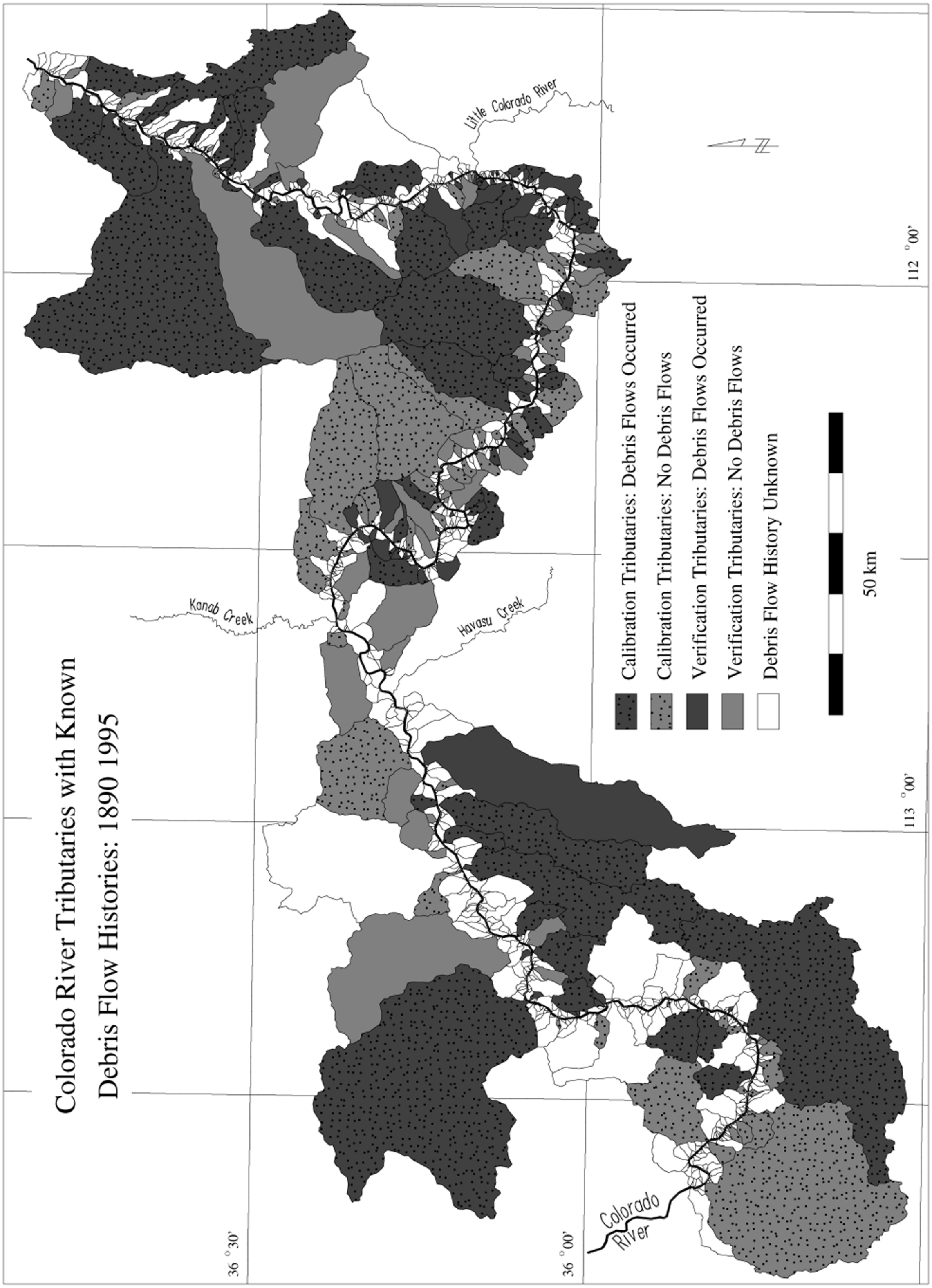

Figure 7. Map of Grand Canyon showing the locations of tributaries with histories of debris flows between 1890 and 1990.