Predicting Debris-Slide Locations in Northwestern California[1]

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Abstract

We tested four topographic models for predicting locations of debris-slide sources: 1) slope; 2) proximity to stream; 3) SHALSTAB with "standard" parameters; and 4) debris-slide-prone landforms, which delineates areas similar to "inner gorge" and "headwall swale" using experience-based rules. These approaches were compared in three diverse study areas of northwestern California having multiple inventories of historical non-road-related debris slides in a variety of topographic settings. We implemented the models in a GIS using USGS 10-m digital elevation models (DEMs).

The topographic models show moderate predictive success. Slope performs comparatively well in all study areas. SHALSTAB is rarely superior. The proximity-to-stream model is competitive in one area but falls short in the others. The landforms model performs somewhat better than the others for nearly all the debris-slide data sets in all three areas, and appears especially effective for large debris slides that deliver sediment to streams.

Large landslide deposits also influence the propensity for debris sliding in some areas. The areal density of historical debris-slide sources in steep ground within large, geomorphically fresh landslide deposits can be more than twice that in steep ground outside landslide deposits. Thus, prediction of debris-slide sources can be improved using maps of geomorphically fresh large landslide deposits.

Key words: debris slide, landslide, model, northwestern California, slope, topography

Introduction

Debris slides, shallow, fast-moving landslides from steep slopes, are widely recognized as a significant source of sediment to streams. As part of a study of mass wasting in forested terrain of northwestern California, we tested four topographic models aimed at predicting locations of debris-slide sources. Topographic models can be effective in predicting locations of debris slides because this kind of landslide tends to develop within characteristic parts of the landscape. We examined model

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performance in three diverse study areas, each of which had several maps of historical debris slides prepared by different investigators. We also investigated the relation of debris sliding to deposits of large, slower moving kinds of landslides, which are abundant in the region.

Methods of Model Comparison

The Models

We compared four topographic models: 1) slope (as measured at each 10-m cell), 2) proximity to stream, 3) SHALSTAB with "standard" parameters (Dietrich and others 2001), and 4) debris-slide-prone landforms. Each model was implemented in a geographic information system (GIS) using USGS 10-m digital elevation models (DEMs). The models are generated solely from topography and stream channels, and so can be tested against all available debris-slide data sets.

Each model consists of several categories that form a descending hierarchy of hazard. Categories in the slope model are 1) slopes steeper than 80 percent, 2) slopes 65 to 80 percent, 3) slopes 50 to 65 percent, and 4) slopes 35 to 50 percent. Categories in the proximity-to-stream model are zones (buffers) based on horizontal distance from any class I, II, or III stream plus valley bottom (low flat area adjacent to a stream, similar to a channel migration zone). Here, categories are 0 to 30 m, 30 to 60 m and 60 to 90 m from the stream plus valley bottom. SHALSTAB categories are the values of log (q/T) commonly used by Dietrich and others (2001), where q is defined as effective precipitation and T is soil hydraulic transmissivity.

The landforms model uses rules, based on accumulated geologists' experience with debris sliding in northwestern California, to identify two landforms widely considered prone to debris slides: steep slopes contiguous to streams (comparable, but not identical, to "inner gorge"), and steep convergent areas that lead directly to streams (comparable to "headwall swale"). We created a GIS approach to implement these rules. The "steep to stream" categories of the model consist of steep slopes that extend up from streams until interrupted by a DEM cell with a specified gentler slope. This category may include ground traditionally identified as inner gorge, but can also include contiguous steep ground extending to a ridgeline. "Steep swales" consist of steep, transversely concave areas that are connected to a stream by a continuous transverse concavity. Thus, both these landforms explicitly incorporate direct pathways to the stream system. The model categories form the hierarchy: 1) steep (>65 percent) to stream, 2) steep (>65 percent) swales, 3) steep (>50 percent) to stream, 4) steep (>50 percent) swales, 5) other steep (>65 percent) ground not in the previous categories, and 6) other steep (>50 percent) ground not in the previous categories.

Study Areas

To test the models, we selected three diverse study areas that are representative of the geologic materials, topography, and landslide processes in the area *(fig. 1)*. The areas and their selection are described further by Ellen and others (2006). All three areas have been subjected to rapid tectonic deformation, large rainstorms, strong earthquake shaking, and a hundred-year history of timber-harvest activities. Each study area contains historical debris sliding documented in at least three inventories of debris slides mapped by different investigators, as well as an inventory of larger landslide deposits. Some debris-slide sources are mapped as point locations, others as polygons delineating the source area. Tracks or deposits from debris flows or debris slides were not included in our analyses. In all, we used 16 different data sets of past debris slides spanning multiple triggering events. From these data sets, we used only locations of debris-slide sources that the mapper considered unrelated to roads or other significant grading.

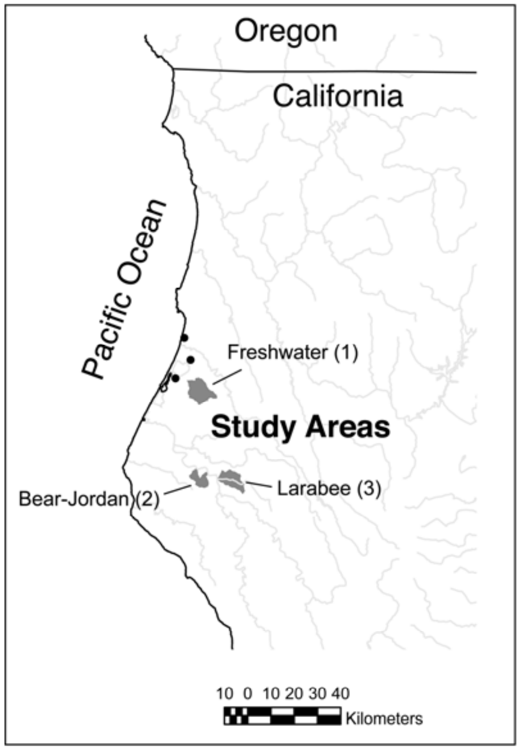

Figure 1—Map showing locations of the three study areas in northwestern California. Dots mark the communities of Eureka, Arcata, and McKinleyville, from south to north.

Debris slides in different study areas tend to originate in different parts of the landscape. In the Freshwater study area, most debris slides initiate from steep upper hillslopes within scalloped or swale topography. In the Bear-Jordan study area, most initiate from steep foot-slopes along the larger streams. Within the Larabee study area, debris slides originate in both of these settings.

Measure of Success

Predictive success was measured using the interplay of two criteria, 1) the percentage of debris-slide cells captured in a hazard class, and 2) the percentage of the study area occupied by that hazard class. This interplay shows the ability of a model to target debris slides, that is, to selectively capture areas of abundant debris sliding without encompassing areas of sparse debris sliding. *Figure 2* explains the resulting plots, which are derived from map data similar to that illustrated in *figure 3*.

This measure allows rational comparison among topographic models regardless of whether debris slides have been mapped as points or polygons. Where debris slides have been mapped as polygons, this measure provides a more conservative appraisal of success than that used in SHALSTAB, wherein an entire slide area is attributed to the highest hazard class of any cell within the slide (Dietrich and others

2001, p. 205). The measure used here makes no assumptions about the location of initial failure within mapped debris-slide polygons.

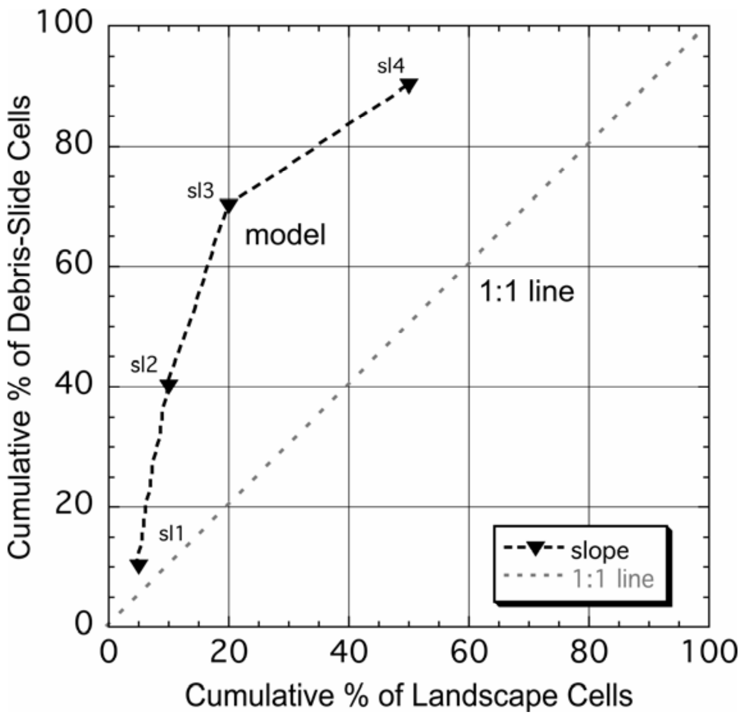

Figure 2—Schematic plot showing the measure of predictive success used in this study, for one topographic model applied to one data set of mapped debris slides. The slope model illustrated here, like all models evaluated in the study, includes several categories (see *fig. 3*). Point SL1 marks the predictive success of the most severe category, slopes greater than 80 percent. This category captures 10 percent of the debris-slide cells while occupying 5 percent of cells in the study area (landscape cells). Point SL2 marks the cumulative success of the two most severe categories, the >80 percent slope class and the 65-80 percent slope class. Thus, point SL2 represents all slopes greater than 65 percent, and these capture 40 percent of the debris-slide cells while occupying 10 percent of the study area. Points SL3 and SL4 include progressively gentler slope categories. The 1:1 line represents random success; at any point on this line, a model captures the same percentage of debris-slide cells as the ground it occupies in the study area. Model performance is best when points lie far from the 1:1 line toward the upper left-hand corner. In this part of the plot, a model captures a large percentage of the debris-slide cells while encompassing only a small percentage of the study area.

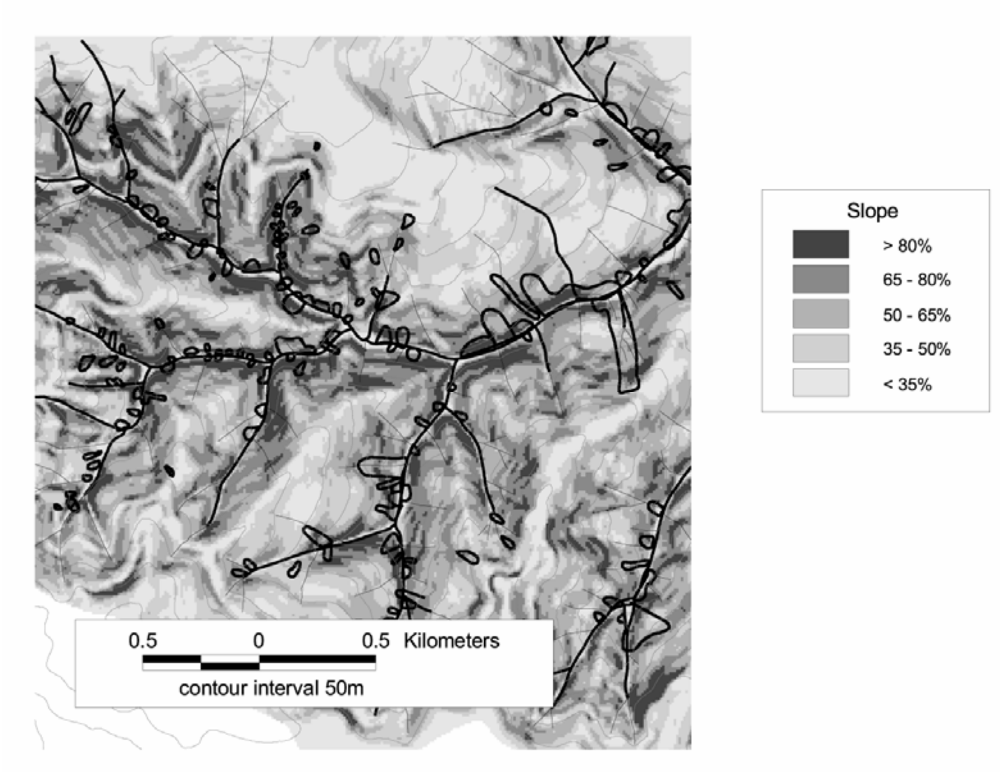

Figure 3—Map showing the slope model in part of the Bear-Jordan study area. Gray tones (or colors) show 10-m DEM cells that fall within the designated slope classes. Black outlines show debris slides mapped as polygons. Note that most debris-slide sources include cells of different slope classes.

Results

Model Comparisons

In most tests, the topographic models display a consistent pattern *(fig. 4)*. The presumed strongest predictors for each model (for example, the steepest hillside slopes) are plotted first and so are represented by the points near the lower left-hand corner of each plot. These points tend to capture the greatest proportion of mapped debris-slide sources in the smallest proportion of land, and so they plot steeply above the origin. As weaker-predictor categories are added (for example, gentler slope intervals), the lines tend to curve over toward the 1:1 line as fewer debris slides are captured per unit area.

The lines generally arch well above the 1:1 line, indicating better than random prediction. In most cases, the models manage to capture about 45 to 75 percent of debris-slide cells before encompassing 20 percent of the ground. Thus, at the resolution of topography and mapping tested here, the models can be considered moderately successful.

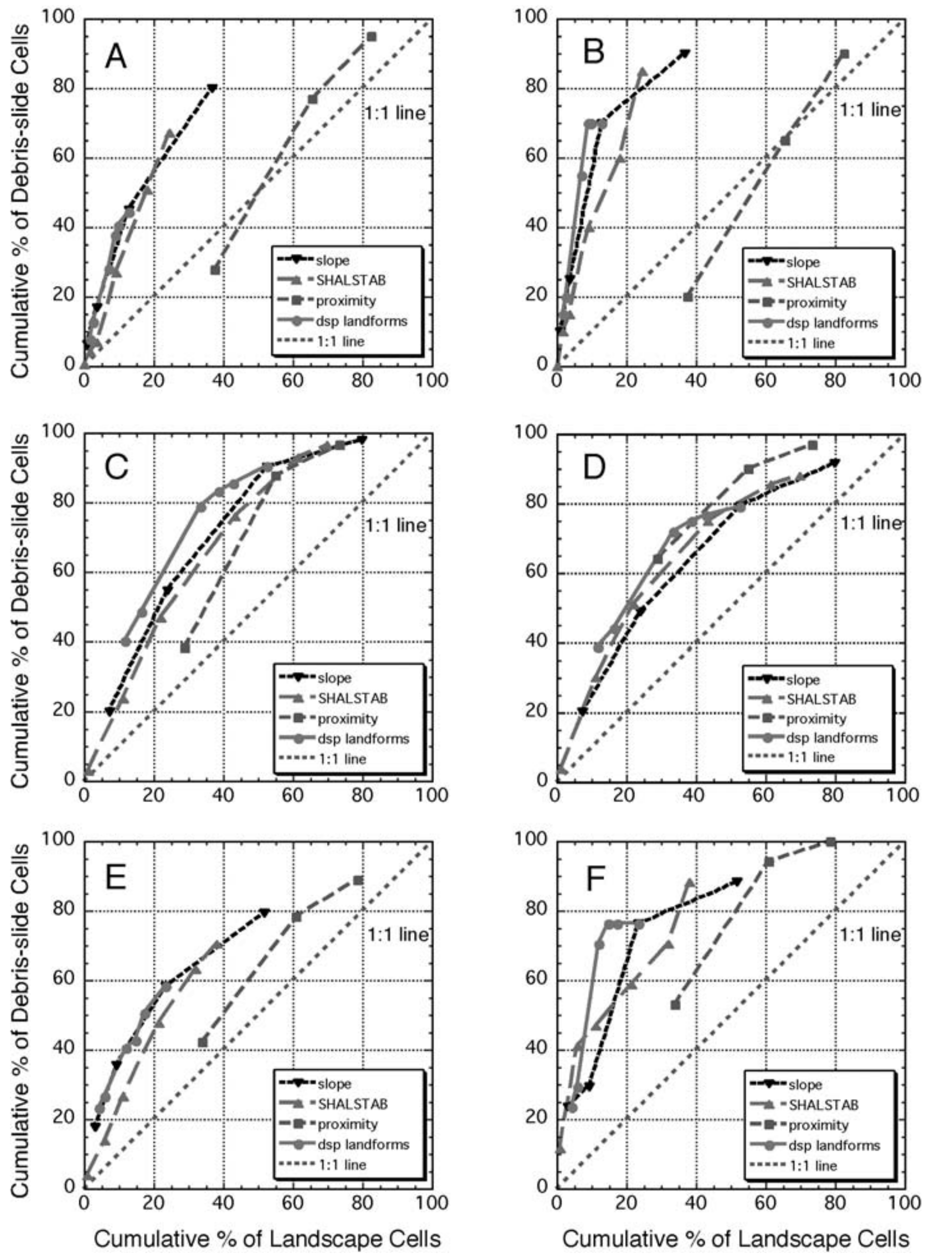

Figure 4—Some of the plots that compare success of models in predicting locations of non-road-related debris slides. Each graph shows results for a different debris-slide data set. A. Using debris slides delivering sediment to streams in Freshwater study area, mapped as points (PWA, 1999b). B. Using large (>2300 m^3) debris slides delivering sediment to streams in Freshwater study area, mapped as points (PWA, 1999b). C. Using debris slides delivering sediment to streams in Bear-Jordan study area, mapped as points (PWA, 1998, 1999a). D. Using debris slides in Bear-Jordan study area, mapped as polygons.[9] Using debris slides in Larabee study area, mapped as polygons.[10] F. Using large (>1500 m^3) debris slides delivering sediment to streams in Larabee study area, mapped as points.[11]

[9] Unpublished mapping from de la Fuente and Hicks, 2001.
[10] Unpublished mapping from Ellen, 2001.
[11] Unpublished mapping from Golder Associates Ltd., 2001.

For many of the data sets, tightly grouped plots indicate that some models are about equally successful *(figs. 4A, 4D, 4E)*. The full spectrum of tests across the different terrains, however, reveals differences in model performance. Slope, the simplest model, performs consistently and comparatively well in all study areas. SHALSTAB is fairly consistent but rarely superior, even in Freshwater where many debris slides initiate from topographic swales *(figs. 4A, 4B)*. The proximity-to-stream model is competitive only in the Bear-Jordan study area, where many debris slides initiate adjacent to streams *(fig. 4D)*. In Freshwater, some categories of this model perform more poorly than random.

The debris-slide-prone landforms model exhibits slightly to somewhat better predictive success than the other models for nearly all the debris-slide data sets in all three study areas. This model has an added advantage, in that the areas it delineates as most hazardous include explicit pathways to the stream system. Some of the comparisons suggest that this model may be especially effective in data sets where points represent large debris slides that deliver sediment directly to streams (compare *figs. 4A* to *4B*, and *4E* to *4F*). This advantage is significant, because a large proportion of the debris-slide sediment delivered to streams in this region commonly originates from a small number of especially large debris slides (Kelsey and others 1995; PWA 1999b, p. 31-33).

Effect of Large Landslide Deposits

In two of the three study areas, large deposits from slower moving kinds of landslides influence the propensity for debris sliding *(fig. 5)*. In Bear-Jordan and Larabee, the areal density of mapped debris-slide sources in steep ground (>65 percent) within geomorphically fresh, large landslide deposits is more than twice that in ground outside landslide deposits *(fig. 6)*. Geomorphic freshness of landslide deposits was rated systematically using qualitative measures of apparent freshness of landslide scarps, toes, and internal topography. The Freshwater study area did not show this relation.

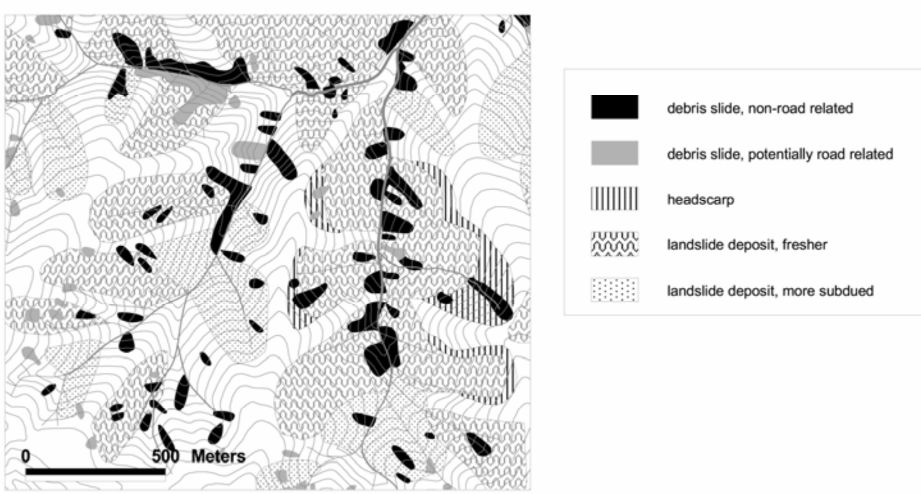

Figure 5—Map of part of the Bear-Jordan study area, showing relation between debris slides and large landslide deposits.[12]

[12] Unpublished mapping from de la Fuente and Hicks, 2001.

To determine whether the differences shown in *figure 6* are significant statistically, we examined the differences using a one-sided chi-square statistical test (Conover 1980). A one-sided test for discrete (not continuous) data is useful here because rejection of the null hypothesis indicates that the areal density in one category is greater than in the other category. For each area, the statistical tests indicate that debris-slide areal density is higher in fresher landslide deposits than in more subdued landslide deposits or in ground outside landslide deposits; in both study areas the tests reject the null hypothesis at a 95 percent confidence level.

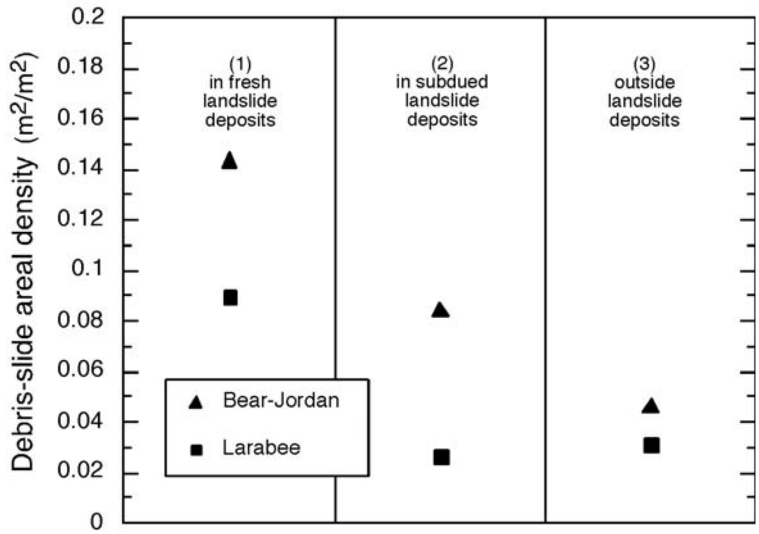

Figure 6—Plot showing relation of debris slides, from one data set in each study area, to mapped large landslide deposits in steep (>65 percent) ground of the Bear-Jordan and Larabee study areas. Areal density, the proportion of ground mapped as debris-slide sources, is distinguished for debris slides located in fresher landslide deposits, in more subdued landslide deposits, and outside of landslide deposits.

Discussion

The topographic models compared here meld aspects of local slope, topographic convergence, and pathways to streams in different combinations to predict future debris-slide locations; all these topographic factors can be obtained from a DEM. Model success varies in different terrain, however local slope is a strong predictor in all the study areas. Slope alone often performs better than slope plus topographic convergence (as represented by SHALSTAB); thus convergence appears to be a detriment to SHALSTAB's performance in some cases. The general success of the debris-slide-prone landforms model, for both point and polygon data in all three study areas, indicates that it targets debris-slide sources slightly better than just slope or slope plus convergence (SHALSTAB). The model identifies landforms that appear to be prime locations for debris slides, probably because of factors related to landform evolution beyond just slope and convergence. The apparent success of this model in identifying areas prone to large delivering debris slides likely results from the pathways to streams incorporated in the model. This aspect of the model's success could be significant in assessing sediment delivery and merits further testing.

The debris-slide-prone landforms model requires two factors in addition to slope to distinguish the intended landforms: 1) the stream system, including flat or gently sloping ground that forms part of the valley bottom; and 2) the degree of concavity that defines steep swales and their path to the stream system. Both these items can be identified from a DEM. In some terrains, these factors may need to be adjusted to properly distinguish the intended landforms within the regional topography.

One might anticipate that topographic model performance could be enhanced by "calibrating" factors to specific terrain. For example, slope or proximity-to-stream intervals could be adjusted to improve predictive success. However, the overall performance of specific topographic models cannot be improved significantly by choosing different model categories than those used in this study. Different or additional points might change the result of an individual category somewhat, but overall performance still must pass through the points on the current plots.

The use of DEMs with higher resolution than those used in this study may change the relative performance of these topographic models, and the performance of specific models may improve markedly. To test the effect of higher DEM resolution, however, will require new debris-slide mapping, in which slides observed in photographs or in the field are plotted directly on base maps made from the new DEM. Otherwise, tests will be jeopardized by mislocation. The models and mapping reported here used the same topographic base, in that the 10-m DEM used for the models is derived directly from the USGS 7-1/2' contours used in the mapping.

Conclusions

The topographic models we tested, when run on 10-m DEMs, generally show a similar pattern of prediction, and in many cases perform comparably, in a variety of terrain representative of northwestern California. They generally target past debris-slide sources at moderate levels of success, typically capturing 45 to 75 percent of debris-slide cells in about 20 percent of the ground. When all test results are compared, some differences emerge. Slope, the simplest model, performs consistently and comparatively well in all the study areas. SHALSTAB is fairly consistent but rarely superior, even in terrain dominated by topographic swales. The proximity-to-stream model is competitive in one study area but falls short in the others. The debris-slide-prone landforms model consistently performs as well or better than the others and may excel in capturing large debris slides that deliver directly to streams. In two of the three study areas, debris slides are markedly concentrated within geomorphically fresh, large landslide deposits. Delineation of areas susceptible to debris sliding in northwestern California can be improved by making use of a good topographic model and mapping of large, geomorphically fresh landslide deposits.

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