# Assessing Terrain Stability in a GIS using SINMAP

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Presented at the 15th annual GIS conference, GIS 2001, February 19-22, Vancouver, British Columbia

## Abstract

SINMAP (Stability Index MAPping) is an ArcView GIS extension that facilitates the assessment of landslide potential at the watershed scale. SINMAP has as its theoretical basis the infinite plane slope stability model. Digital elevation model (DEM) methods are used to estimate the slope of the terrain as well as the potential soil moisture conditions as influenced by topographic flow convergence. Other parameters considered include soil friction & transmissivity, root cohesion, and water recharge. Some parameters may be uncertain and can therefore be characterized by uniform distributions between specified limits. These may be adjusted and calibrated for geographic strata based upon soil, vegetation or geologic data. The software enables an interactive visual calibration that adjusts parameters while referring to observed landslide distributions. Parameters can be adjusted so that the resulting stability map “captures” a high proportion of observed landslides in regions with low stability index, while minimizing the extent of low stability regions and consequent alienation of terrain to regions where landslides have not been observed. SINMAP is implemented as a software extension to the ArcView GIS from Environmental Systems Research Institute, Inc.

## Introduction

SINMAP is an objective terrain stability mapping tool that compliments other types of terrain stability mapping methods. It is applied to shallow translational landsliding phenomena controlled by shallow groundwater flow convergence. The slope stability theory on which it is based does not apply to deep-seated instability including deep earthflows and rotational slumps. The data required to implement the theory include soil and climate properties that can be highly variable in both space and time. The theory does not require numerically precise input and accepts ranges of values that represent uncertainty. Stability indices are output by the analysis that represent the stability of terrain and hence the likelihood of landsliding. These indices are not intended to be interpreted as numerically precise and are most appropriately interpreted as indications of "relative" hazard.

The methods implemented in the SINMAP software rely on grid-based data structures. The accuracy of output is therefore heavily reliant on the accuracy of the digital elevation model (DEM) data input. It is also reliant on the accurate positioning of known landslide initiation zones. It is therefore important that as much effort a possible be put into obtaining accurate DEM and landslide inventory data before running this model.

## Slope Stability Theory

The underlying methodology is based upon the infinite slope stability model (e.g. Hammond et al., 1992; Montgomery and Dietrich, 1994) that balances the destabilizing components of gravity and the restoring components of friction and cohesion on a failure plane parallel to the ground surface with edge effects neglected. The pore pressure due to soil moisture reduces the effective normal stress, which through the friction angle is related to the shear strength. Pore water pressure is computed assuming a hydrologic steady state with depth of saturated soil computed sufficient to sustain a lateral discharge proportional to the specific catchment area (the upslope area per unit contour length). SINMAP derives its terrain stability classification from inputs of topographic slope and specific catchment area and from parameters quantifying material properties (such as strength) and climate (primarily a hydrologic wetness parameter). Each of these parameters is delineated on a numerical grid over the study area. The topographic parameters are automatically computed from digital elevation model (DEM) data. The other input parameters are recognized to be uncertain so are specified in terms of upper and lower bounds on the ranges they may take. Where the most destabilizing limit of the parameter ranges used in the model still results in stability, the stability index is defined as the factor of safety (ratio of stabilizing to destabilizing forces) at this location. This condition yields an index value greater than 1. If the index falls below 1, the index value takes on a different definition. In this case it is defined as the *probability* that a location is stable given probability distributions of the parameters over the uncertainty ranges. This index value ranges between 0 (most unstable) and 1 (most stable).

Terrain stability mapping practices sometimes require that broad stability classes be identified and mapped, based upon relatively coarse information to quickly identify regions where more detailed assessments are warranted. SINMAP can be used for this purpose. Table 1 gives an example of how broad stability classes may be defined in terms of the stability index (SI). The selection of breakpoints (1.5, 1.25, 1, 0.5, 0.0) is subjective, requiring judgement and interpretation in terms of the class definitions. In the example given we use the terms ‘stable’, ‘moderately stable’, and ‘quasi-stable’ to classify regions that, according to the model, should not fail given the most conservative limit of the parameter ranges. SI for these cases is the factor of safety that gives a measure of the magnitude of destabilizing factors (e.g. increased wetness due to road drainage, local loading, or local enhancement of pore pressures due to soil pipe effects) required for instability. We use the terms ‘lower threshold’ and ‘upper threshold’ to characterize regions where, according to the parameter uncertainty ranges quantified by the model, the probability of instability is less than or greater than 50% respectively. External factors are not required to induce instability in these regions. Instability may arise simply due to a combination of parameter values within the uncertainty limits specified. We use the term ‘defended slope’ to characterize regions where, according to the model, the slope should be unstable for any parameter combination within the given parameter ranges. Where such slopes occur in the field they are held in place by forces not represented in the model, or the model is inappropriate, as in the case of bedrock outcrops.

In the sections that follow, we give the theory that forms the basis for SINMAP in terms of the infinite slope stability model and topographic wetness index. These components are combined with an accounting for parameter uncertainty to define the stability index SI.

TABLE 1. Stability Class Definitions

| **Condition** | **Class** | **Predicted State** | **Parameter Range** | **Possible Influence of Factors Not Modeled** |
|---|---|---|---|---|
| SI > 1.5 | 1 | Stable slope zone | Range cannot model instability | Significant destabilizing factors are required for instability |
| 1.5 > SI > 1.25 | 2 | Moderately stable zone | Range cannot model instability | Moderate destabilizing factors are required for instability |
| 1.25 > SI > 1.0 | 3 | Quasi-stable slope zone | Range cannot model instability | Minor destabilizing factors could lead to instability |
| 1.0 > SI > 0.5 | 4 | Lower threshold slope zone | Pessimistic half of range required for instability | Destabilizing factors are not required for instability |
| 0.5 > SI > 0.0 | 5 | Upper threshold slope zone | Optimistic half of range required for stability | Stabilizing factors may be responsible for stability |
| 0.0 > SI | 6 | Defended slope zone | Range cannot model stability | Stabilizing factors are required for stability |

## Stability Index Definition

To define the stability index, the following equation is used:

$$FS = \frac{C + \cos\theta\,[1 - \min\left(\frac{R}{T}\frac{a}{\sin\theta}, 1\right) r]\tan\phi}{\sin\theta} \tag{1}$$

The variables a and θ are the specific catchment area and slope respectively and are derived from the topography. C is the dimensionless cohesion of the soil and tree roots combined, $\tan\phi$ is the soil friction angle, r is the water/soil density ratio, and R/T is the water recharge divided by the soil transmissivity. These last four parameters are manually input into the model. We treat the density ratio r as essentially constant (with a value of 0.5) but allow uncertainty in the other three quantities through the specification of lower and upper bounds. Formally these bounds define uniform probability distributions over which these quantities are assumed to vary at random. We denote R/T = x, $\tan\phi$ = t, and the uniform distributions with lower and upper bounds as

$$C \sim U(C_1, C_2); \qquad x \sim U(x_1, x_2); \qquad t \sim U(t_1, t_2) \tag{2}$$

The smallest C and t, (i.e. $C_1$ and $t_1$) together with the largest x (i.e. $x_2$) defines the worst case (most conservative) scenario under this assumed uncertainty (variability) in the parameters. Areas where under this worst case scenario FS is greater than 1 are in terms of this model, unconditionally stable and we define

$$SI = FS_{\min} = \frac{C_1 + \cos\theta\,[1 - \min\left(x_2\frac{a}{\sin\theta}, 1\right) r]t_1}{\sin\theta} \tag{3}$$

For areas where the minimum factor of safety is less than 1, there is a possibility (probability) of failure. This is a spatial probability due to the uncertainty (spatial variability) in C, $\tan\phi$ and T. This probability does have a temporal element in that R characterizes a wetness that may vary with time. Therefore the uncertainty in x combines both spatial and temporal probabilities. In these regions (with $FS_{min} < 1$) we define

$$SI = \text{Prob}(FS > 1) \tag{4}$$

over the distributions of C, x, and t (Equations, 10). The best case scenario is when $C=C_2$, $x=x_1$, and $t=t_2$, which leads to

$$FS_{\max} = \frac{C_2 + \cos\theta\,[1 - \min\left(x_1\frac{a}{\sin\theta}, 1\right) r]t_2}{\sin\theta} \tag{5}$$

In the case that $FS_{max} < 1$, then

$$SI = \text{Prob}(FS > 1) = 0 \tag{6}$$

Regions with SI > 1 ($FS_{min} > 1$), 0 < SI < 1 and SI = 0 ($FS_{max} < 1$) are illustrated in Figure 1 in a space defined in terms of slope ($\tan\theta$) and specific catchment area. This provides a useful visualization medium for understanding this approach.

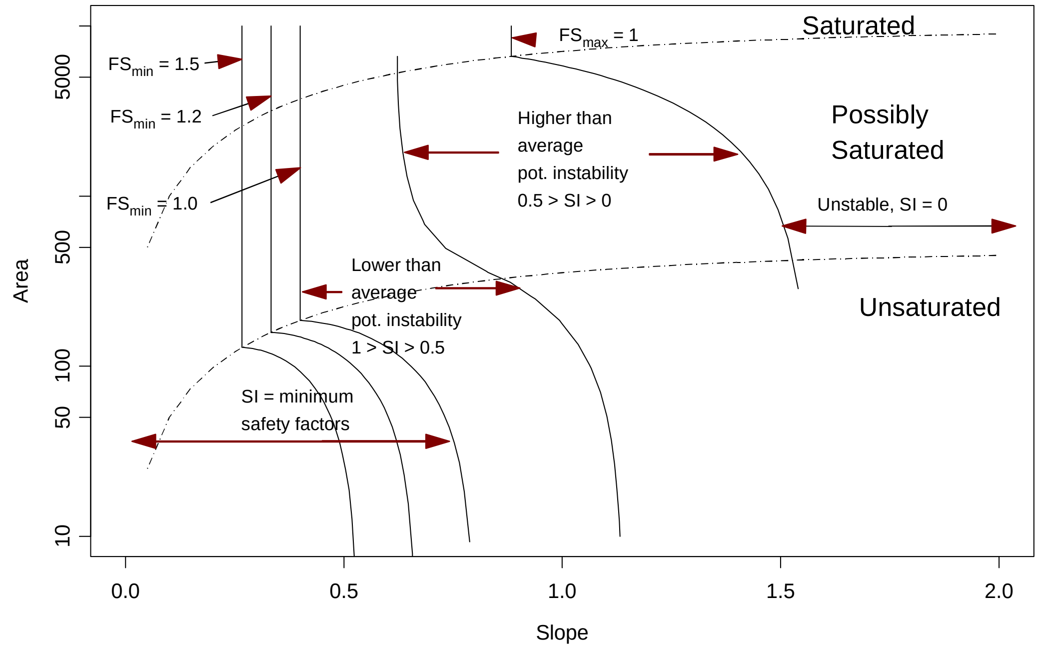


FIGURE 1. Stability Index defined in Area-Slope space.

## Processing of DEM Data

The grid DEM processing routines used are based upon methods described by O'Callaghan and Mark (1984), Marks et al. (1984), Band (1986), Jenson and Domingue (1988), Tarboton (1989), Tarboton (1997) and Garbrecht and Martz (1997). There are 4 steps involved: 1) Pit filling corrections, 2) Computation of slopes and flow directions; 3) Computation of specific catchment area; and 4) Computation of the SINMAP stability index.

Pits in digital elevation data are defined as grid elements or sets of grid elements surrounded by higher terrain that, in terms of the DEM, do not drain. These are rare in natural topography and are generally assumed to be artifacts arising due to the discrete nature and data errors in the preparation of the DEM. They are eliminated here using a ‘flooding’ approach. This raises the elevation of each pit grid cell within the DEM to the elevation of the lowest pour point on the perimeter of the pit (e.g. Jenson and Domingue, 1988).

The earliest and simplest method for specifying flow directions is to assign flow from each grid cell to one of its eight neighbors, either adjacent or diagonally, in the direction with steepest downward slope. This method, designated D8 (8 flow directions), was introduced by O'Callaghan and Mark (1984) and has been widely used. The D8 approach has disadvantages arising from the discretization of flow into only one of eight possible directions, separated by 45° (e.g. Fairfield and Leymarie, 1991; Quinn et al., 1991; Costa-Cabral and Burges, 1994; Tarboton, 1997). These have motivated the development of other methods comprising multiple flow direction methods (Quinn et al., 1991; Tarboton, 1997), random direction methods (Fairfield and Leymarie, 1991) and grid flow tube methods (Costa-Cabral and Burges, 1994). Tarboton (1997) discusses the relative merits of these. SINMAP uses the D∞ method, the multiple flow direction method developed by Tarboton (1997). In this method, the flow direction angle measured counter clockwise from east is represented as a continuous quantity between 0 and 2π. This angle is determined as the direction of the steepest downward slope on the eight triangular facets formed in a 3 x 3 grid cell window centered on the grid cell. The slope and flow direction associated with the grid cell is taken as the magnitude and direction of the steepest downslope vector from all eight facets. This is implemented using equations given in Tarboton (1997).

Upslope area (counted in terms of the number of grid cells) is calculated using a recursive procedure that is an extension of the very efficient recursive algorithm for single directions (Mark, 1988). The upslope area of each grid cell is taken as its own area (one) plus the area from upslope neighbors that have some fraction draining to it. Specific catchment area, a, is then upslope area per unit contour length, taken here as the number of cells times grid cell size (cell area divided by cell size).

## Software Implementation

The SINMAP theory has been incorporated into a library of C routines that can be called to perform computational tasks including calculating stability index and saturation (wetness index). Additionally, library routines are also available to perform many basic tasks of manipulating digital elevation model (DEM) grid data including topographic pit filling, calculating slopes, determining flow directions, and defining the area draining to a specific point. These various routines are contained within one dynamic link library (DLL) file.

Because of the spatial or geographic nature of SINMAP analyses, on-screen or printed maps are required for interpreting some computational output. Rather than create custom routines to provide standard geographic analysis abilities, SINMAP uses ArcView and Spatial Analyst from Environmental Systems Research Institute, Inc. (ESRI). The capabilities of ArcView are enhanced through the loading of a custom ArcView extension file called sinmap.avx and a dynamic link library called sinmap.dll. ArcView allows encapsulation of customizations (program code, user interface changes, etc.) in what it terms *extensions*, with extensions saved as *.avx files. The SINMAP extension provides a linkage between ArcView and the library of routines in the SINMAP dynamic link library, automates many of the SINMAP data preparation and manipulation tasks, and generates maps and charts of user data.

The final output of a SINMAP session are maps that define areas of potential terrain instability. Within ArcView, a map is displayed on-screen in a view window. Most tasks are conducted from SINMAP's DEM map view window. These tasks involve the creation, use, and display of geographic grid data. A DEM grid provides the topographic basis for a SINMAP study, and a grid of soils and hydrologic terrain parameters classified into 'calibration regions' provides non-topographic parameter information required for the study. Tasks using either one or both of these grids create another six grids that represent the geographic distribution of topography without pits, land slope, flow direction, contributing area, saturation, and stability index. In addition to grid data, point data for landslides are required if the user wants to compare locations of predicted instability with areas of actual instability. These geographic data sets are added to the DEM map view as themes – grid themes for the grid data and as a point theme for landslide data. A full SINMAP study therefore uses and/or creates a total of nine GIS themes.

In addition to the geographic display of study data in a DEM map view, SINMAP also generates a slope-area chart (graph) of study area data to aid in data interpretation and parameter calibration. The slope-area plot, illustrated and defined in Figure 1 is generated by SINMAP routines. An example of a SINMAP slope-area plot, termed 'SA Plot' herein, is illustrated in the next section. Plotted on the SA Plot are four types of information: 1) specific catchment area versus slope is plotted for a sampling of grid cell points across the study area that do not have landslides; 2) landslides are plotted based upon the slope and specific catchment area values of the cell in which each landslide point lies; 3) five stability index region lines provide boundaries for regions within slope-specific catchment area space that have similar potential for stability or instability; and 4) three wetness lines provide boundaries for regions within slope-specific catchment area space that have similar wetness potential.

## Kilpala Case Study

This study area lies immediately to the west of Nimpkish Lake and to the south of Port McNeill, British Columbia. The soils are predominantly coarse granular glacial tills and colluvium of variable thickness derived from basaltic bedrock of the Karmutsen Formation. Few fine-grained fluvial or lacustrine sediments were observed, and none were noted to be associated with landslides during a brief two-day field reconnaissance of the area.

The majority of landslides were noted to be shallow translational debris slides, some of which subsequently mobilized into debris flows. Many of the landslides originate in steep colluvial and bedrock-dominated slopes and are frequently found in swales. However, it was also observed that some landslides originate in local zones of weathered bedrock.

DEM data were obtained from the Englewood Division of Canadian Forest Products Ltd. (Canfor). These data were digitally complied from 1:45,000 scale photographs at an accuracy appropriate for a 10 meter contour interval map (i.e. spot elevation accuracies of plus or minus 2.5 meters). The data were then interpolated to a 10 m grid DEM using raw irregularly spaced elevation points and a triangulated network interpolation method. Orthophotos rectified using this DEM are also available for the area and have a one-meter pixel size. These orthophotos were found to be particularly useful for accurately locating landslides.

A previous landslide inventory had been completed for the subject area and was supplied in digital form by Canfor. These landslide point locations were overlain on the orthophotos and carefully compared with obvious headscarp locations. It was found that many of the inventory points were originally placed within the landslide scar but not within the zone of initiation. Because the SINMAP methodology applies to failure locations within a zone of initiation, the landslide inventory points were moved to this zone. This editing was found to have a marked improvement on model results and is therefore deemed very important.

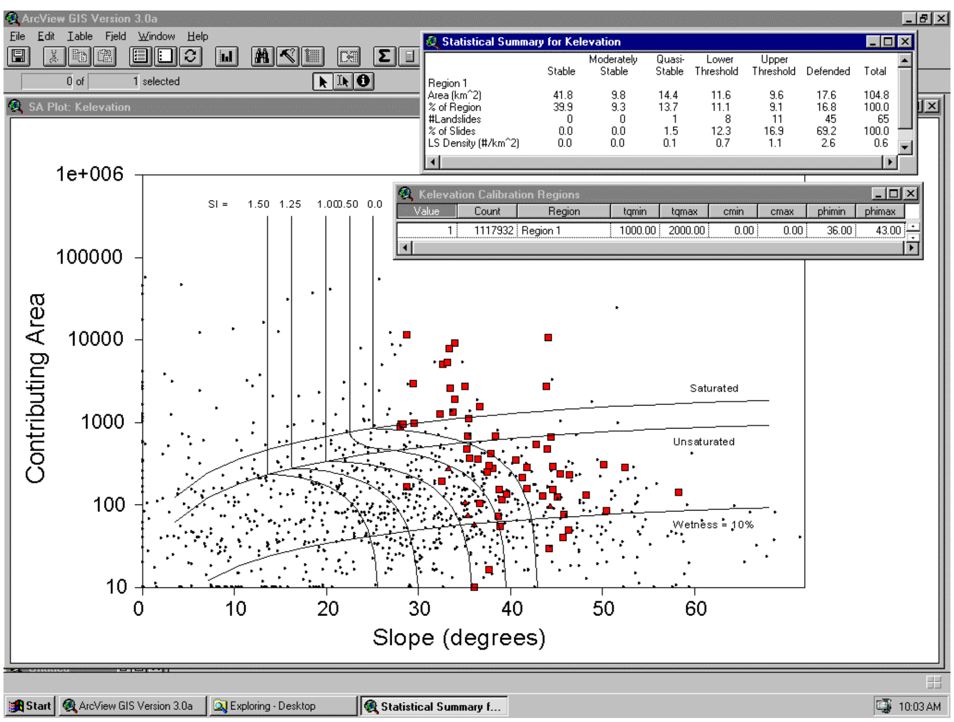


FIGURE 2. ArcView screen showing the analytic results of a SINMAP analysis for the Kilpala Watershed.

Using the DEM and landslide inventory data, the SINMAP software was used to derive a stability index map. The analytic results are shown in Figure 2. The figure shows a large slope-area plot, a small window showing the calibration parameters for the single calibration region used, and a larger window showing the statistical results of the analysis.

A single calibration region was used because no detailed soils mapping results were available. Fortunately, it was also observed during the brief field visit that the geology is relatively homogeneous and similar textures were observed in both glacial and colluvial soils across the area. Calibration parameters were derived by fitting calibration curves to the landslide data within the slope-area plot. Though no independent analysis of soil properties was completed, the 36 to 43 degree soil friction angles used in the calibration are considered realistic for the coarse subangular tills and colluvium found in the study area. The T/R parameter was set at between 1000 m and 2000 m in the calibration. This parameter range, when multiplied by the sine of the slope, may be interpreted to mean the length of hillslope (planar, not convergent) required to develop saturation. In other words, with a $30^{o}$ slope, the length of planar hillslope required for saturation would be between 500 and 1000 meters.

Figure 3 is an ArcView screen that shows a portion of the wetness map calculated in the analysis. It is interesting to note the spatial patterns of wetness on the map and how many of the landslides are located within the areas modeled as being wet.

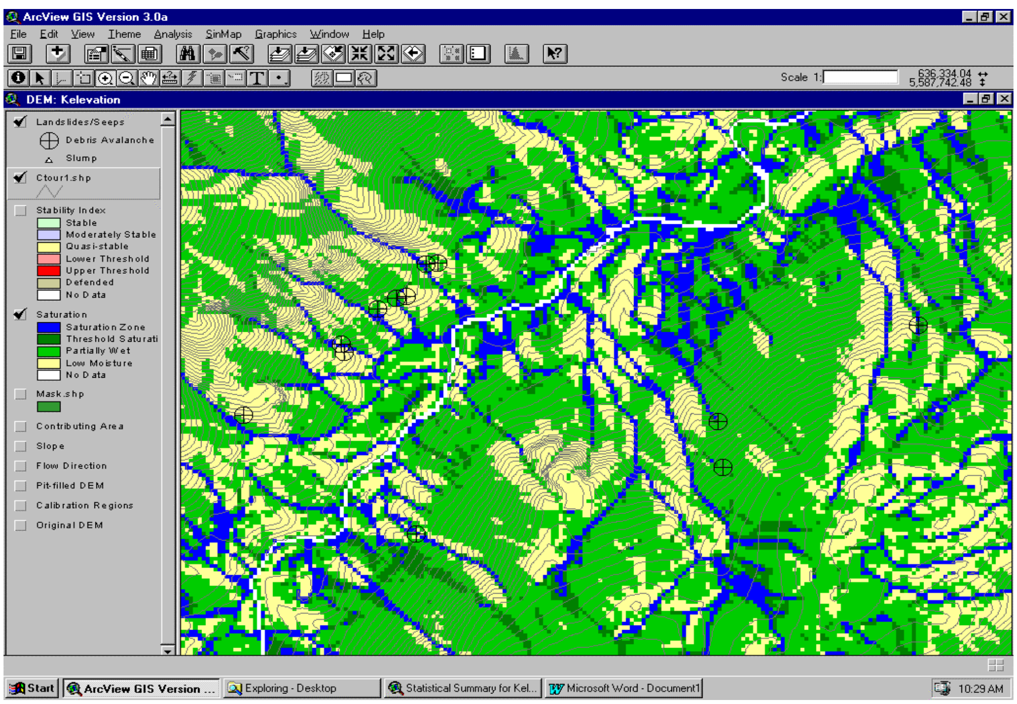


FIGURE 3. ArcView screen showing a portion of the wetness map derived by the SINMAP analysis for the Kilpala Watershed.

Figure 4 is an ArcView screen that shows a portion of the stability index map calculated in the analysis. The statistical summary shown in Figure 2 indicates that the “defended” stability index class (light brown in Figure 4) includes 45 landslides or 69.2% of the total inventory. At the same time, this class includes 17.6 $km^2$ or only 16.8% of the total study area. This class has an average landslide density of 2.6 landslides per square kilometer. The “upper threshold” class represented as red in Figure 4 has an average landslide density of 1.1 landslides per square kilometer and includes a total of 11 landslides. The “lower threshold” class includes 8 landslides, and the remaining stability index classes representing 62.9% of the total area include just one landslide. These statistics indicate excellent model performance.

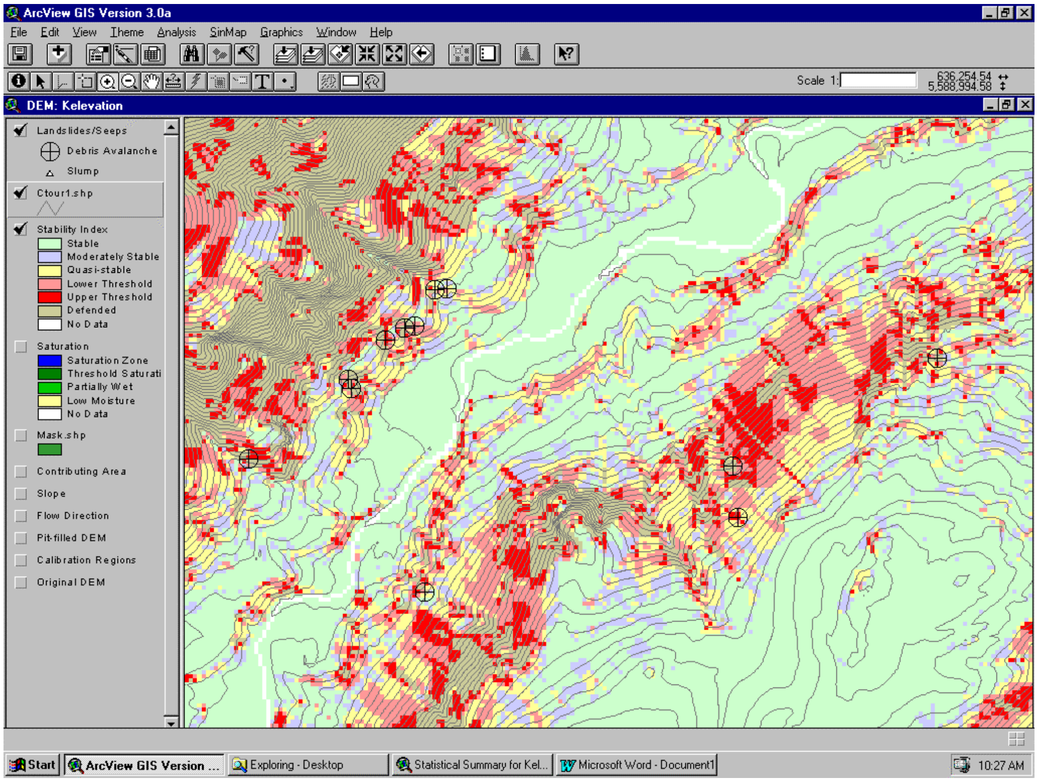


FIGURE 4. ArcView screen that shows a portion of the stability index map for the Kilpala Watershed.

When compared to other areas of the province, this area has a relatively high percentage of landslides occurring in steep bedrock-dominated terrain. During the field reconnaissance, it was noted that the bedrock tends to be irregular and the soils variable in depth. It is therefore possible that pockets of soil within areas of bedrock outcrop could be a source landslide material in this terrain.

## Conclusions

The case study suggests that the SINMAP analysis succeeds in delineating areas that intuitively appear to be susceptible to landsliding. In particular, it does a good job of delineating the swales where many landslides originate. However, it was noted in the field reconnaissance that some landslides occurred on the noses of a rocky slopes that would not normally be considered susceptible to landsliding. On closer examination, it was found that locally weathered bedrock may be responsible for these slides. The SINMAP methodology missed classifying several of these sites as being landslide-prone due to the site-specific geologic conditions not modeled. It is therefore important to remember that the SINMAP tool should be used in combination with aerial photo analyses and field mapping techniques.

The methodology described in this paper has been implemented in software and is available on the world wide web (http://www.engineering.usu.edu/dtarb/) as a free extension to ArcView Spatial Analyst GIS software distributed by the Environmental Systems Research Institute (ESRI).

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