The SINMAP Approach to Terrain Stability Mapping

R.T. Pack,
Terratech Consulting Ltd., Salmon Arm, British Columbia, Canada

D.G. Tarboton
Utah State University, Logan, Utah, U.S.A.

C. N. Goodwin
C.N. Goodwin Fluvial System Consulting, Logan, Utah, U.S.A.

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ABSTRACT: A promising approach to modeling the spatial distribution of shallow debris slides combines a mechanistic infinite slope stability model with a steady-state hydrology model. The spatial distribution of a “stability index” is governed primarily by specific catchment area (the upslope area per unit contour length) and slope. The model can be interactively calibrated to the unique characteristics of the topography, rainfall, and soils of a particular study area using simple parameters, graphs and maps. Once a landslide and terrain inventory is completed using aerial photographs, this approach is shown to have the capability of producing a stability classification map of a huge area in a very short time. An analysis of the Kilpala watershed of northern Vancouver Island, British Columbia is presented as an example.

RÉSUMÉ: Une approche prometteuse à modeler la distribution spatiale des glissments de débris peu profondes combine un modèle mécaniste de stabilité de pente infini avec un modèle d'hydrologie équilibré. La distribution spatiale d'un "classe de stabilité " est régie principalement par le bassin de captation spécifique (la surface vers le haut de la pente par longueur de découpe d'unité) et la pente. Le modèle peut être calibré en mode interactif aux seules caractéristiques de la topographie, des précipitations, et des sols d'une zone particulière d'étude en utilisant des paramètres, des graphiques et des cartes simples. Une fois qu'un inventaire de terrain et de glissments de terrain est terminé en utilisant les photographies aériennes, cette approche est montrée pour avoir la capacité de produire une carte de classification de stabilité d'une zone énorme dans en temps très peu. Une analyse de la ligne de partage de Kilpala de L'île Nordique de Vancouver, Colombie Britannique est présentée comme exemple.

1 INTRODUCTION

The SINMAP (Stability INdex MAPping) methodology presented in this paper 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 primary output of this modeling approach is a stability index, the numerical value of which is used to classify or categorize the terrain stability at each grid location in the study area. The topographic variables are automatically computed from digital elevation model (DEM) data. The other input parameters are recognized to be uncertain so are specified to SINMAP in terms of upper and lower bounds on the ranges they may take. The stability index (SI) is defined as the probability that a location is stable assuming uniform distributions of the parameters over these uncertainty ranges. This value ranges between 0 (most unstable) and 1 (least unstable). Where the most conservative (destabilizing) set of parameters 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 under the most conservative set of parameters. This yields a value greater than 1.

Terrain stability mapping practice in British Columbia (Province of British Columbia, 1995) requires that broad stability classes be identified and mapped, based upon relatively coarse information, to quickly identify regions where more detailed assessments are warranted. SINMAP is intended 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 with the most conservative parameters in the parameter ranges specified. 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 bounds with which uncertainty and variability can be quantified. We use the term 'defended slope' to characterize regions where, according to the model, the slope should be unstable for any parameters within the parameter ranges specified. Where such slopes exist, something other than the modeled parameters is holding the slope in place, or the model is inappropriate, as in the case of bedrock outcrops.

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

2 BACKGROUND

There are many approaches to assessing slope stability and landslide hazards (Sidle et al., 1985; Dietrich et al., 1986; Montgomery and Dietrich, 1988; Montgomery and Dietrich, 1989; Carrera et al., 1991; Dietrich et al., 1992; Sidle, 1992; Dietrich et al., 1993; Montgomery and Dietrich, 1994; Wu and Sidle, 1995, Pack, 1995). The most widely used include (Montgomery and Dietrich, 1994): (1) field inspection using a check list to identify sites susceptible to landslides; (2) projection of future patterns of instability from analysis of landslide inventories; (3) multivariate analysis of factors characterizing observed sites of slope instability; (4) stability ranking based on criteria such as slope, lithology, land form, or geologic structure; and (5) failure probability analysis based on slope stability models with stochastic hydrologic simulations. Each of these is valuable for certain applications. None, however, take full advantage of the fact that debris flow source areas are, in general, strongly controlled by surface topography through shallow subsurface flow convergence, increased soil saturation, increased pore pressures and shear strength reduction (Montgomery and Dietrich, 1994). Recently, the availability DEM data has prompted the development of methods that take advantage of geographic information system (GIS) technology to quantify topographic attributes related to slope instability and landsliding. GIS technology permits patterns of instability to be resolved and mapped at the scale of the DEM. This relatively fine scale mapping which can pinpoint hazard areas has particular value for land management. Notable recent contributions are Montgomery and Dietrich (1994) and Wu and Sidle (1995). Montgomery and Dietrich (1994) combine a contour based steady state hydrologic model with the infinite slope stability model (simplified for cohesionless soils) to define slope stability classes based upon slope and specific catchment area. Wu and Sidle (1995) present a more elaborate model that couples dynamic modeling of the hydrology with the infinite slope stability model, in a more complex form, accounting for cohesion and varying root strength.

The approach taken in this paper is similar to that of Montgomery and Dietrich (1994) in that it combines steady state hydrologic concepts with the infinite slope stability model. There are a few differences: (1) Grid-based rather than contour-based DEM methodology is used following the work of Tarboton (1997). This choice is primarily a matter of convenience. Grid-based DEMs are more common and their analysis is easier. (2) Cohesion is retained in the infinite slope stability model. This can be used to account for soil cohesion or root strength as modeled by Wu and Sidle (1995), or it may be set to 0 by a user who wants to consider cohesionless situations. (3) Parameter uncertainty is incorporated through the use of uniform probability distributions and lower and upper bounds on uncertain parameters. This is akin to the probabilistic approach of Hammond et al. (1992), and reflects the real uncertainty associated with estimating parameters in terrain stability mapping. We believe that this is an important capability. The results reduce to the deterministic case (equivalent to Montgomery and Dietrich, 1994) when upper and lower uncertainty bounds of the parameters are specified as equal and cohesion is set to zero. The range of uncertainty of the hydrologic wetness parameter may, in an approximate sense, substitute for the dynamic modeling over a range of storm events used by Wu and Sidle (1995), without requiring analysis and input of weather data. We believe that the complexity and additional computational burden of analyzing sequences of weather data is unwarranted.

3 INFINITE SLOPE STABILITY MODEL

The infinite slope stability model factor of safety (ratio of stabilizing to destabilizing forces) is given by (simplified for wet and dry density the same, from Hammond et al., 1992)

$$SI = \frac{C_r + C_s + \mathrm{Cos}^2\theta[\rho_s g(D - D_w) + (\rho_s g - \rho_w g)D_w]\tan\phi}{D\rho_s g \sin\theta\cos\theta} \quad (1)$$

where C_r is root cohesion [N/m^2], C_s is soil cohesion [N/m^2], θ is slope angle, ρ_s is wet soil density [kg/m^3], ρ_w is the density of water [kg/m^3], g is gravitational acceleration (9.81 m/s^2), D the vertical soil depth [m], D_w the vertical height of the water table within the soil layer [m], and ϕ the internal friction angle of the soil [-]. The slope angle θ is atan S, the slope as a decimal drop per unit horizontal distance. Figure 1 illustrates the geometry assumed in equation (1).

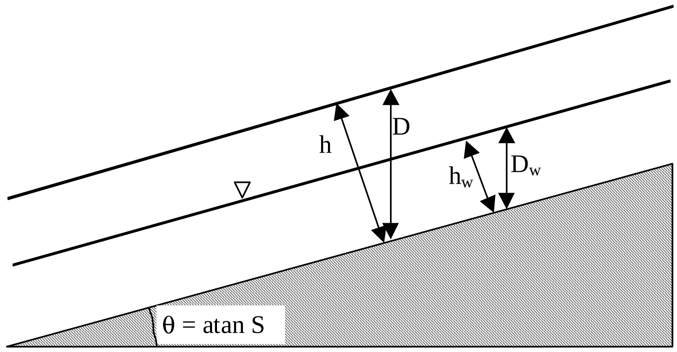

Figure 1. Infinite slope stability model schematic.

Our approach with the hydrologic model is to interpret the soil thickness as specified perpendicular to the slope, rather than soil depth measured vertically. Soil thickness, h [m], and depth are related as follows

$$h = D\cos\theta \quad (2)$$

With this change FS reduces to

$$FS = \frac{C + \cos\theta\,[1 - wr]\tan\phi}{\sin\theta} \quad (3)$$

where

$$w = D_w/D = h_w/h \quad (4)$$

is the relative wetness,

$$C = (C_r + C_s)/(h\,\rho_s\,g) \quad (5)$$

the combined cohesion made dimensionless relative to the perpendicular soil thickness and

$$r = \rho_w/\rho_s \quad (6)$$

the water to soil density ratio.

Equation (3) is the dimensionless form of the infinite slope stability model that we use. This is convenient because cohesion (due to soil and root properties) is combined with the soil density and thickness into a dimensionless cohesion factor, C (equation 5). This may be thought of as the ratio of the cohesive strength relative to the weight of the soil, or the relative contribution to slope stability of the cohesive forces. Figure 2 illusustrates this concept. The second term in the numerator of equation (3) quantifies the contribution to stability

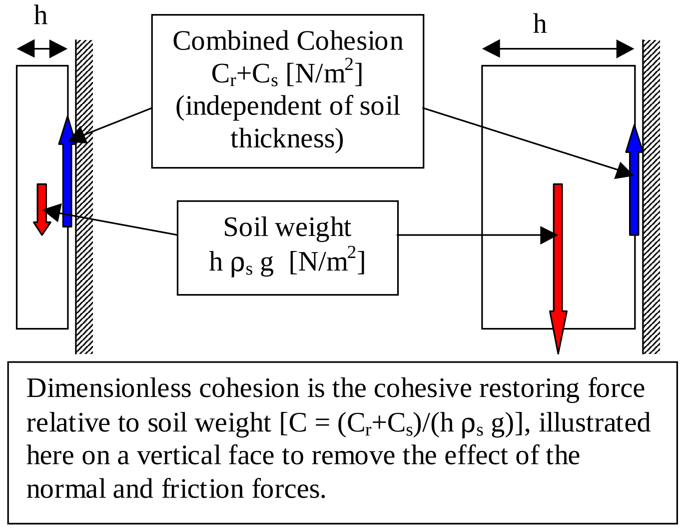

Figure 2. Illustration of dimensionless cohesion factor concept.

due to the internal friction of the soil (as quantified by friction angle, ϕ, or friction coefficient, $\tan\phi$). This is reduced as wetness increases due to increasing pore pressures and consequent reductions in the normal force carried by the soil matrix. The sensitivity to this effect is controlled by the density ratio r (equation 6).

Practically, the model works by computing slope and wetness at each grid point, but assuming other parameters are constant (or have constant probability distributions) over larger areas. With the form of equation (3) this amounts to implicitly assuming that the soil thickness (perpendicular to the slope) is constant. An alternative definition of C as

$$C' = (C_r + C_s)/(D\ \rho_s\ g) \qquad (5a)$$

would lead to instead of (3)

$$FS = \frac{C' + \cos^2\theta\,[1 - wr]\tan\phi}{\sin\theta\cos\theta} \qquad (3a)$$

which implicitly assumes the soil depth D (measured vertically) is constant, implying that soils on steeper slopes are thinner. In SINMAP we chose (3) and (5) over (3a) and (5a), in part for compatibility with the hydrology where constant soil thickness is consistent with constant transmissivity (hydraulic conductivity times thickness), and in part because it is probably more realistic.

4 TOPOGRAPHIC WETNESS INDEX

The emergence of the parameter specific catchment area, ‘a’, defined as upslope area per unit contour length [m^2/m](see Figure 3) has been one of the landmark developments in recent hydrology, due to

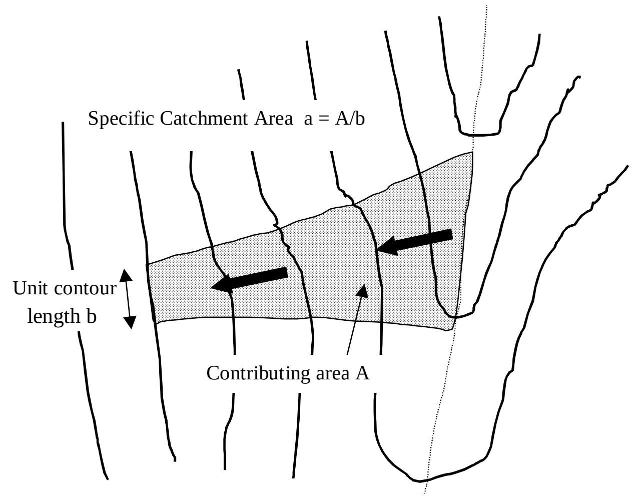

Figure 3. Definition of specific catchment area.

Beven and Kirkby (1979). It is tied closely to recent hydrologic models that represent runoff generation by the saturation from below mechanism (TOPMODEL Beven and Kirkby, 1979; O'Loughlin, 1986; TOPOG Moore et al., 1988; Moore and Grayson, 1991; and THALES Grayson et al., 1992a; and Grayson et al., 1992b). These developments follow the field observations that higher soil moisture or areas of surface saturation tend to occur in convergent hollow areas. It has also been reported that landslides most commonly originate in areas of topographic convergence (Montgomery and Dietrich, 1994).

Following TOPMODEL (and other similar topographically based wetness index models) we make the following assumptions:

(1) Shallow lateral subsurface flow follows topographic gradients. This implies that the contributing area to flow at any point is given by the specific catchment area defined from the surface topography (Figure 3).
(2) Lateral discharge at each point is in equilibrium with a steady state recharge R [m/hr].
(3) The capacity for lateral flux at each point is T $\sin\theta$, where T is the soil transmissivity [m^2/hr], i.e. hydraulic conductivity [m/hr] times soil thickness, h [m].

Assumptions (1) and (2) together imply that lateral discharge q, depth integrated per unit contour width [m^2/hr], is

$$q = R\ a \qquad (7)$$

Assumption (3) differs from a common TOPMODEL (Beven and Kirkby, 1979) assumption in that we have not assumed hydraulic conductivity decreasing with depth. Instead we assume uniform conductivity of a soil mantle overlying relatively impermeable bedrock. Also, we use $\sin\theta$ rather than $\tan\theta$. This is more correct because the flow distance is actually along the slope. The difference between tan and sin which is insignificant for small angles matters for the steep slopes that give rise to landslides. Now with assumption (3) the relative wetness is

$$w = \mathrm{Min}\left(\frac{R\,a}{T\sin\theta}, 1\right) \tag{8}$$

The relative wetness has an upper bound of 1 with any excess assumed to form overland flow. As illustrated in Figure 1, the relative wetness defines the relative depth of the perched water table within the soil layer. The ratio R/T in (8) which has units of $[m^{-1}]$ quantifies the relative wetness in terms of assumed steady state recharge relative to the soil's capacity within the soil for lateral drainage of water. It combines climate and hydrogeological factors. The quantity (T/R)sinθ [m] may be thought of as the length of hillslope (planar, not convergent) required to develop saturation, a concept that is useful for establishing field estimates of R/T which is treated as a single parameter.

5 STABILITY INDEX DEFINITION

To define the stability index, the wetness index from equation (8) is incorporated into the dimensionless factor of safety, equation (3), which becomes

$$FS = \frac{C + \cos\theta\,[1 - \min\left(\frac{R}{T}\frac{a}{\sin\theta}, 1\right) r]\tan\phi}{\sin\theta} \tag{9}$$

The variables a and θ are derived from the DEM topography whereas the values of C, tanϕ, r and R/T are user input. 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 the limits of uniform probability distributions over which these quantities are assumed to vary at random. We denote R/T = x, tan ϕ = t, and the uniform probability distributions with lower and upper bounds as

$$\begin{aligned} C &\sim U(C_1, C_2) \\ x &\sim U(x_1, x_2) \\ t &\sim U(t_1, t_2) \end{aligned} \tag{10}$$

The smallest C and t, (i.e. C_1 and t_1) together with the largest x (i.e. x_2) define 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 for which we define stability index as

$$SI = FS_{min} = \frac{C_1 + \cos\theta\,[1 - \min\left(x_2 \frac{a}{\sin\theta}, 1\right) r] t_1}{\sin\theta} \tag{11}$$

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, tanϕ 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

$$SI = \mathrm{Prob}(FS > 1) \tag{12}$$

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

$$FS_{max} = \frac{C_2 + \cos\theta\,[1 - \min\left(x_1 \frac{a}{\sin\theta}, 1\right) r] t_2}{\sin\theta} \tag{13}$$

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

$$SI = \mathrm{Prob}(FS > 1) = 0 \tag{14}$$

Regions with SI > 1 ($FS_{min} > 1$), 0 < SI < 1 and SI = 0 ($FS_{max} < 1$) are illustrated in Figure 4 in a space defined in terms of slope (tanθ) and specific catchment area. This provides a useful visualization medium for understanding this approach.

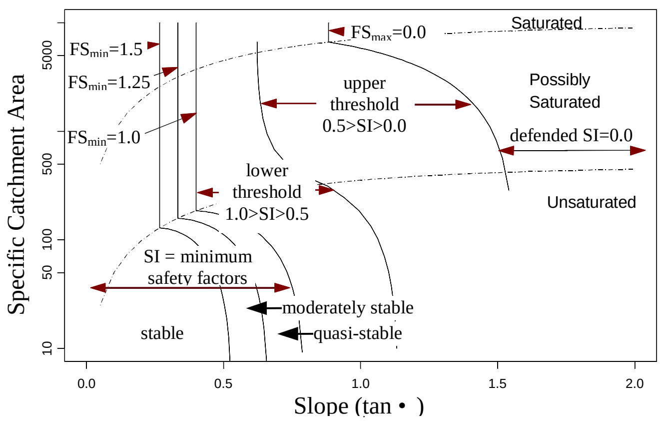

Figure 4. Stability index defined in slope-area space.

Full derivations of equations for evaluating the probability in equation (14) above, computing SI and drawing the lines on this figure are given in the documentation of the SINMAP software (Pack et al., 1998).

6 EXAMPLE FROM KILPALA DRAINAGE

6.1 Geologic Setting

This Kilpala 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 and both are derived from basaltic bedrock of the Karmutsen Formation. Few fine-grained fluvial or lacustrine sediments were observed and none were noted associated with landslides during our brief field reconnaissance of the area.

The majority of landslides observed during a two-day reconnaissance were noted to be shallow translational debris slides, some of which subsequently mobilized into debris flow. 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.

6.2 Input Data

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). These 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 effect on model results and is therefore deemed very important.

6.3 Analytical Results

Using the DEM and landslide inventory data, the SINMAP methodology was used to derive a stability index map. The analytic results as indicated by a slope-area plot are shown in Figure 5. A portion of the resulting map is shown in Figure 6.

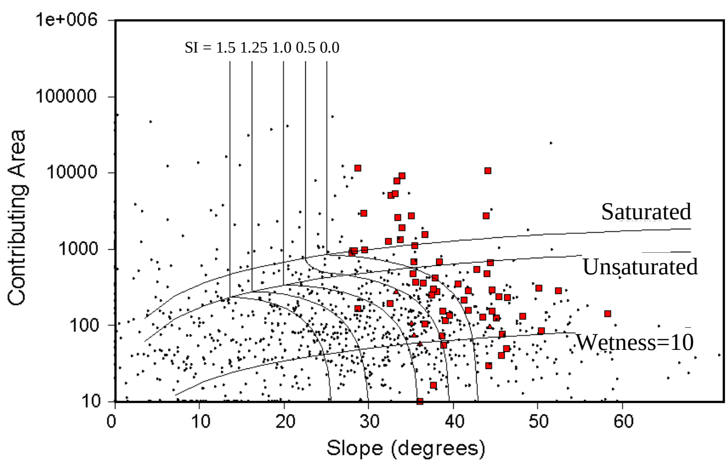

Figure 5. Analytic results of a SINMAP analysis for the Kilpala Watershed. Landslide sites are indicated by the dark boxes. Small points represent a random sample of natural terrain in the watershed.

The same parameters were used over the whole area because no detailed soils mapping was available at the time. Fortunately, it was also observed during the brief field visit that the geology is relatively homogeneous and similar textures occur in both glacial and colluvial soils within this area. 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 slope required for saturation would be between 500 and 1000 meters.

The statistical summary of the results of the analysis shown in Table 2 indicates that the 'defended' stability index includes 45 landslides or 69.2% of the total landslide inventory. At the same time, this class includes 17.6 km^2 or 16.8% of the study area. This class has an average landslide density of 2.6 landslides per square kilometer. The 'upper threshold' class has an average landslide

Table 2. Statistical results of the SINMAP analysis.

	Stable	Mod. Stable	Quasi-Stable	Lower Thresh	Upper Thresh	Defend	Total
Area (km^2)	41.8	9.8	14.4	11.6	9.6	17.6	104.8
% of Region	39.9	9.3	13.7	11.1	9.1	16.8	100.0
# of Slides	0	0	1	8	11	45	65
% of Slides	0.0	0.0	1.5	12.3	16.9	69.2	100.0
LS Density (#/km^2)	0.0	0.0	0.1	0.7	1.1	2.6	0.6

See Table 1 for a definition of stability classes.

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 only one landslide.

6.4 Discussion

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 of landslide material in this terrain.

The SINMAP analysis fairly well defines areas that intuitively appear to be susceptible to landsliding. In particular SINMAP does a good job of delineating the swales where many landslides originate (see Figure 6). However, it was noted in the field reconnaissance that several landslides occurred on the nose of a rocky slope that would not normally be considered susceptible to landsliding (see delta symbols on Figure 6). 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. It is therefore important to remember that the SINMAP tool should be used in combination with aerial photo analyses and field mapping techniques.

7 CONCLUSIONS

The SINMAP theory applies to shallow translational landsliding phenomena controlled by shallow groundwater flow convergence. It does not apply to deep-seated instability including deep earthflows and rotational slumps.

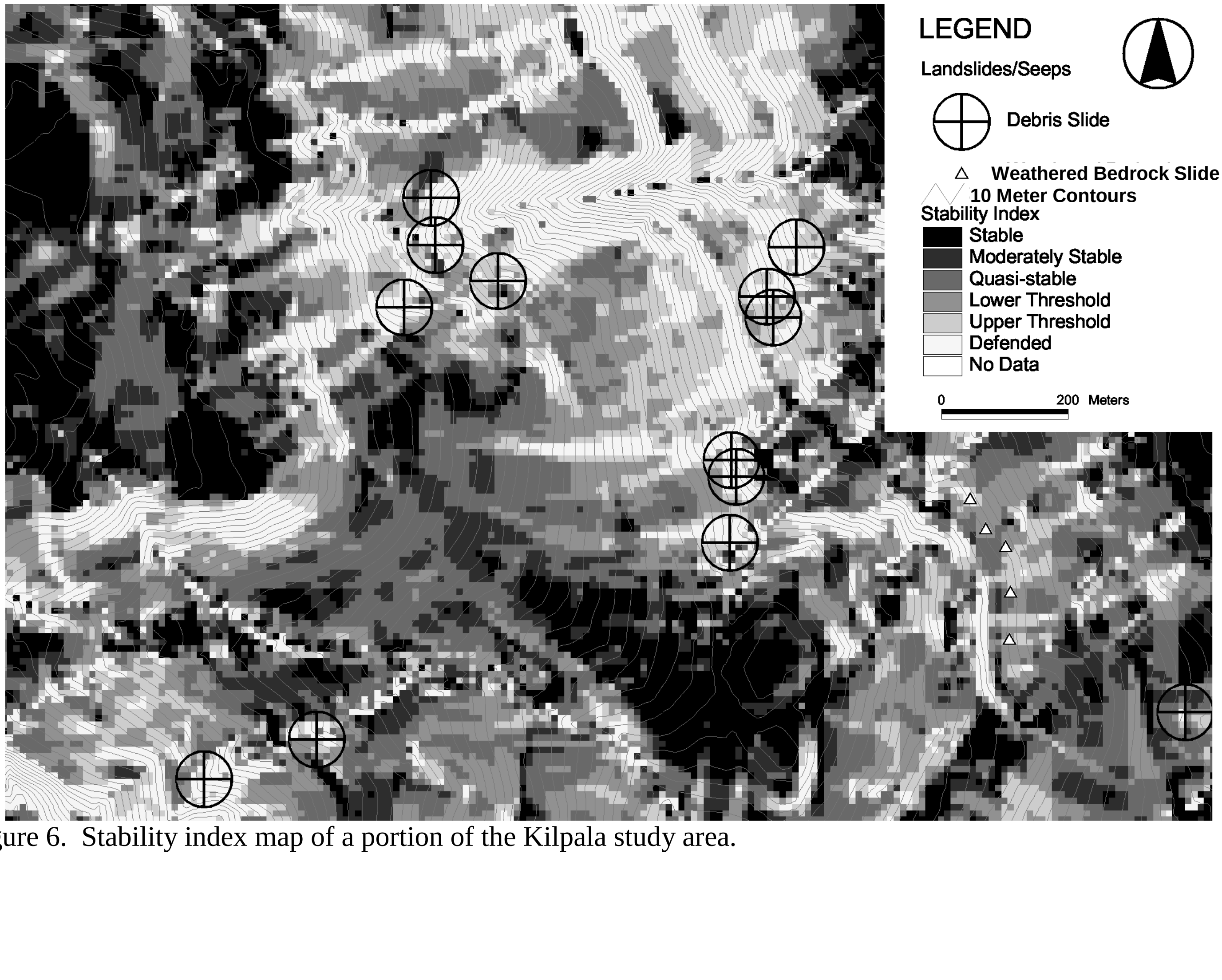

Figure 6. Stability index map of a portion of the Kilpala study area.

This theory is not intended for use in the absence of field information needed for calibration and is profitably used in conjunction with other terrain stability mapping methods.

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 representing this uncertainly. Stability indices output by the analysis should not be interpreted as numerically precise and are most appropriately interpreted in terms of relative hazard.

The methods implemented in the SINMAP software rely on grid-based data structures rather than vector-based polygons. The accuracy of output is heavily contingent on the accuracy of the digital elevation model (DEM) data input. It is also heavily reliant on the accurate positioning of known landslide initiation zones. Therefore, it is important that as much effort as possible be put into obtaining accurate DEM and landslide inventory data.

The methodology 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).

The SINMAP methodology has been specifically developed to compliment the subjective terrain stability mapping methods currently being practiced within the forest sector of British Columbia, Canada. However, the theory is equally applicable to many other parts of the world that have a similar physiographic setting.

REFERENCES

Beven, K. J. and M. J. Kirkby, (1979), "A Physically Based Variable Contributing Area Model of Basin Hydrology," *Hydrological Sciences Bulletin*, 24(1): 43-69.

Carrera, A. M., M. Cardinali, R. Detti, F. Guzzetti, V. Pasqui and P. Richenback, (1991), "GIS Techniques and statistical models in evaluating landslide hazard," Earth Surface *Processes and Landforms*, 16: 427-445.

Dietrich, W. E., C. J. Wilson, D. R. Montgomery and J. McKean, (1993), "Analysis of erosion thresholds, channel networks, and landscape morphology using a digital terrain model," *The Journal of Geology*, 101: 259-278.

Dietrich, W. E., C. J. Wilson, D. R. Montgomery, J. McKean and R. Bauer, (1992), "Erosion Thresholds and Land Surface Morphology," *Geology*, 20: 675-679.

Dietrich, W. E., C. J. Wilson and S. L. Reneau, (1986), "Hollows, colluvium, and landslides in soil-mantled landscapes," chapter 17 in *Hillslope Processes*, Edited by A. D. Abrahams, Allen & Unwin, Boston, p.361-388.

Grayson, R. B., I. D. Moore and T. A. McMahon, (1992a), "Physically Based Hydrologic Modeling 1. A Terrain-Based Model for Investigative Purposes," *Water Resources Research*, 28(10): 2639-2658.

Grayson, R. B., I. D. Moore and T. A. McMahon, (1992b), "Physically Based Hydrologic Modeling 2. Is the Concept Realistic," *Water Resources Research*, 28(10): 2659-2666.

Hammond, C., D. Hall, S. Miller and P. Swetik, (1992), "Level I Stability Analysis (LISA) Documentation for Version 2.0," General Technical Report INT-285, USDA Forest Service Intermountain Research Station.

Montgomery, D. R. and W. E. Dietrich, (1988), "Where do channels begin," *Nature*, 336: 232-234.

Montgomery, D. R. and W. E. Dietrich, (1989), "Source Areas, Drainage Density and Channel Initiation," *Water Resources Research*, 25(8): 1907-1918.

Montgomery, D. R. and W. E. Dietrich, (1994), "A Physically Based Model for the Topographic Control on Shallow Landsliding," *Water Resources Research*, 30(4): 1153-1171.

Moore, I., E. M. O'Loughlin and G. J. Burch, (1988), "A Contour Based Topographic Model for Hydrological and Ecological Applications," *Earth Surface Processes and Landforms*, l3: 305-320.

Moore, I. D. and R. B. Grayson, (1991), "Terrain-Based Catchment Partitioning and Runoff Prediction Using Vector Elevation Data," *Water Resources Research*, 27(6): 1177-1191.

O'Loughlin, E. M., (1986), "Prediction of surface saturation zones in natural catchments by topographic analysis," *Water Resources Research*, 22(5): 794-804.

Pack, R.T., (1995), "Statistically-based terrain stability mapping methodology for the Kamloops Forest Region, British Columbia", *Proceedings of the 48th Canadian Geotechnical Conference*, Canadian Geotechnical Society, Vancouver, B.C.

Pack, R. T., D. G. Tarboton and C. N. Goodwin, (1998), "Terrain Stability Mapping with SINMAP, technical description and users guide for version 1.00," Report Number 4114-0, Terratech Consulting Ltd., Salmon Arm, B.C., Canada (www.tclbc.com).

Province of British Columbia, (1995) "Mapping and Assessing Terrain Stability Guidebook", Forest Practices Code of British Columbia.

Sidle, R., (1992), "A Theoretical Model of the Effects of Timber harvesting on Slope Stability," *Water Resources Research*, 28(7): 1897-1910.

Sidle, R. C., A. J. Pearce and C. L. O'Loughlin, (1985), *Hillslope Stability and Land Use*, Water Resources Monograph 11 Edition, American Geophysical Union, 140p.

Sidle, R.C., A.J. Pearce and C.L. O'Loughlin, (1985), *Hillslope Stability and Land Use*, Water Resources Monograph 11 Edition, American Geophysical Union, 140p.

Tarboton, D. G., (1997), "A New Method for the Determination of Flow Directions and Contributing Areas in Grid Digital Elevation Models," *Water Resources Research*, 33(2): 309-319.

Wu, W. and R. C. Sidle, (1995), "A Distributed Slope Stability Model for Steep Forested Watersheds," *Water Resources Research*, 31(8): 2097-2110.