New Developments in Terrain Stability Mapping in B.C.

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Abstract
The introduction of the Forest Practices Code Act to British Columbia has dramatically increased the required volume of terrain stability mapping within the province. Three fundamental approaches to terrain stability mapping (sometimes referred to as landslide hazard mapping) are in common use in the world today. They include (1) subjective geomorphic analysis, (2) landslide attribute statistical analysis, and (3) deterministic stability analysis. The "subjective geomorphic analysis" approach is, by far, the most commonly employed method in B.C. Unfortunately, this approach lacks an objective framework and relies heavily on the experience of the mapper. This often results in a lack of consistency between mapped areas and mappers.

This paper introduces and demonstrates an objective mapping tool that could improve the speed and consistency of mapping in B.C. Deterministically-derived stability indices (calculated using GIS terrain modeling) are provided as attribute inputs to a landslide attribute study. The landslide attribute study then uses a simple statistical method to determine landslide frequencies associated with combinations of stability indices and observed landslide attributes. The attribute combinations that best discriminate between high and low landslide frequencies are then used as the basis for choosing terrain stability classifications. The results of the foregoing (which are largely assisted by a desktop GIS computer system) can be modified, as needed, using subjective aerial photo interpretation.

Recently completed reconnaissance-level terrain stability mapping in the Trout Lake Basin demonstrates the power of this approach.

The Trout Lake Basin has an area of 73,930 hectares and is located approximately 45 km northeast of Nakusp, B.C. in the Nelson Forest Region. Approximately 580 landslides were inventoried within this area using 1:15,000 nominal scale photography. Using this data with the above-noted approach, a terrain stability map was produced in which 75% of the inventoried landslides were found to fall within a high hazard zone covering 7% (5080 ha) of the study area. A second hazard zone was also identified that, if combined with the first zone, results in a hazard zone that covers 13% (9650 ha) of the map area and includes 91% of the observed landslides. Of this 9650 ha, approximately 3500 ha (5% of the Trout Lake Basin) is within productive forest. These results are very encouraging. Further application of this approach to terrain stability mapping in B.C. is therefore warranted.

Key words: Landslide hazards, terrain stability mapping, slope stability, hazard classification.

Introduction
The introduction of the Forest Practices Code in British Columbia has dramatically increased the required volume of terrain stability mapping. The purpose of this mapping is (1) to assist in an improved estimate of the volume of harvestable timber to be used in annual allowable cut calculations, and (2) to improve timber development planning so as to minimize the occurrence of landslides and resulting impacts. Over the last year, several million dollars were spent on the terrain stability mapping of millions of hectares across various portions of B.C. The results of this mapping are having multi-million dollar impacts on forest operations in terms of allowable forest practices.

In the document entitled "Landslide Hazard Mapping Guidelines for British Columbia" (Gerath et al, 1994), several types of terrain stability mapping methodologies are described including those based on (1) subjective geomorphic analyses, (2) landslide attribute statistical analyses, and (3) deterministic stability analyses. Subjective geomorphic analysis is the most commonly employed method in B.C. and is primarily based on the B.C. terrain classification system as described in

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"Mapping and Assessing Terrain Stability Guidebook" (MATSG) (Province of British Columbia, 1995). Derivation of stability classes from terrain classes must be done based on "...experience, field observations, and informed guessing. The quality of such mapping depends entirely on the experience of the mapper..."(Gerath et al., 1994). In order to provide improved consistency across a project and between several mappers, an algorithm (or weighting formula) has sometimes been developed. The weighting of terrain factors is entirely subjective (this is sometimes called "blind" weighting)(Gee, 1992). Because this is the primary method currently in use in B.C., it is a common problem to find a lack of consistency between products produced by different mappers.

Over the past few years, Terratech Consulting Ltd. (TCL) has been actively involved in research related to improving landslide hazard prediction (Pack, 1994). Included in this work has been the development of more objective criteria for terrain stability classifications (Pack, 1995). More recently, TCL has engaged in collaborative research with Utah State University that has lead to the testing of a more objective approach to terrain stability mapping in B.C. This approach uses a "deterministic" model that relies heavily on GIS methods. The approach also relies on landslide inventory data and therefore has a "statistical" component. Once a landslide inventory is completed using aerial photographs, this approach allows the production of a stability classification map over a huge area in a short period of time using digital methods. This tool has the potential to increase both the speed and objectivity of the stability mapping process while at the same time including the use of the judgment of experienced terrain mappers.

The Deterministic Approach

Past researchers (Sidle et al., 1985; Dietrich et al., 1986; Montgomery and Dietrich, 1988; 1989; Dietrich et al., 1992; Sidle, 1992; Dietrich et al., 1993; Wu, 1993; Montgomery and Dietrich, 1994, Carrera et al., 1991) have noted that landslide initiation is often strongly controlled by surface topography that results in surface and shallow subsurface flow convergence. This convergence is found to generally increase soil moisture and pore-water pressure and reduce effective soil shear strength. This is significant on slopes approaching the angle of repose where shallow sliding dominates. There are many deterministic slope stability models that address this problem. One promising approach (Dietrich et al. 1992, Montgomery and Dietrich 1994) combines a mechanistic infinite slope stability model with a steady-state hydrology model. This model is used to estimate the distribution of down-slope seepage that often influences the location of landslides.

Montgomery and Dietrich (1994) and Dietrich et al (1992) suggest that a relatively simple model, justifiable given the lack of detailed field information, could be used to delineate the relative potential for shallow landsliding. Two primary topographic variables explicitly used in this model include slope and specific catchment area (the upslope catchment area per unit contour width). The latter quantity expresses the convergence of shallow subsurface flow. Other factors that also influence the spatial and temporal distribution of landslides include soil thickness and transmissivity; soil strength properties; rainfall intensity, frequency and duration; snowmelt rate; and root strength. These factors can also be included in the analysis where such data is available.

The emergence of the parameter "specific catchment area" defined as upslope catchment area per unit contour width has been one of the landmark developments in recent hydrology, due to 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; Grayson et al., 1992b). Much work has been done in developing procedures for quantifying geomorphological variables from digital elevation models (DEMs) (Tarboton, 1989; Tarboton et al., 1989; Tarboton et al., 1991; Tarboton et al., 1992; Tarboton and Montgomery, 1994; Tarboton, 1996). The last of these papers presents a new procedure for the representation of flow directions and calculation of specific catchment area using rectangular grid DEMs. This procedure offers improvements over prior procedures that have restricted flow to eight possible directions (O'Callaghan and Mark, 1984) thereby introducing grid bias or proportioned flow according to slope (Freeman, 1991; Quinn et al., 1991) thereby introducing unrealistic dispersion. The work by Tarboton (1996) markedly improves the ability to model specific catchment across a landscape and provides valuable input to a slope stability model as demonstrated in this study.

This approach significantly improves upon most deterministic slope stability analysis methods currently in use. The widely-used LISA analysis developed by Hammond et al.(1992) of the US Forest Service, provides only suggestions as to how to subjectively estimate critical groundwater conditions. This is a major shortcoming that can be significantly improved by basing groundwater conditions on a specific catchment area model.

To our knowledge, the only work in BC that has attempted to use a deterministic model directly in terrain stability mapping of forest lands is reported by Niemann and Howes (1992). Their work uses a "Landslide Attribute Statistical Approach" that includes certain GIS-derived attributes. Our current method follows a similar general approach but provides a more advanced ability to extract data from the DEM. Hence it has a better spatial resolution. Also, because the current approach has a "deterministic" basis rooted in geomorphic theory, it provides a completely different product to end-users.

A deterministic slope stability mapping approach was used in the Slocan Lake area of B.C. by Pack (1982). In this work a probabilistic infinite slope stability equation (a precursor to Hammond et al, 1992) was used to estimate the probability of failure. In this case, terrain polygons (classified according to the BC Terrain Classification System) were overlain on a hand-drawn slope class map to produce a derivative map. Parameters were then estimated for the derivative polygons and a probability of failure calculated for each. Because of the early date of this work, GIS data and methods were not available at the time.

The SINDEX Model

This section provides the details of the deterministic model employed in this study. The primary output is a slope stability index number (referred to as a SINDEX in this paper). The model follows quite closely the suggestions of Montgomery and Dietrich (1994). The key assumption in relating specific catchment area a to soil moisture is that the lateral flux through any point on a watershed is proportional to a. The flux is written as $q\,a$ where q is the effective recharge from precipitation. This effective recharge q represents an average of precipitation intensity minus losses such as evaporation and deep percolation over a time scale sufficient for fluxes to reach equilibrium. The lateral water transmission capacity of a soil profile is given by $T \sin \theta$, where T is the soil transmissivity, the product of hydraulic conductivity and soil thickness, and θ is the topographic slope angle in degrees. Then, assuming hydrologic equilibrium, the *"relative wetness"* can be defined as

[1] $$W = q\,a / T \sin \theta$$

When the wetness W exceeds 1.0, the soil profile is saturated and overland flow is experienced. When the hydraulic conductivity is uniform with depth, W represents the ratio of thickness of saturated soil to total soil thickness. It can then be included in the cohesionless version of the infinite slope stability model that predicts instability when

[2] $$\tan \theta > [1 - W(\rho_w/\rho_s)] \tan \phi$$

where ϕ is the soil internal friction angle, ρ_w the density of water, and ρ_s the soil wet bulk density. Since W ranges from 0 to 1, this equation predicts instability dependent on moisture conditions for slopes ($\tan \theta$) between $[1-(\rho w/\rho s)] \tan \phi$ and $\tan \phi$. Slopes greater than $\tan \phi$ are theoretically unstable and likely represent areas of chronic instability where significant material does not accumulate. Slopes less than $[1-(\rho_w/\rho_s)] \tan \phi$ reach saturation and overland flow without failure due to increased pore pressures. Based on Equations (1) and (2), threshold relationships for overland flow and instability respectively can be written

[3] $$a > (T/q) \sin \theta$$

[4] $$a > (T/q) \sin \theta\, (\rho_s/\rho_w)[1-(\tan \theta / \tan \phi)]$$

These deterministically derived measures form the basis for the stability index (SINDEX). The SINDEX requires calibration for the specific physiographic region being modeled. In particular, the hydrologic characteristics of the soil expressed by T and q as well as the strength of the soil expressed by ϕ need to be estimated. This is done by calibrating the SINDEX map with areas of observed landsliding. In areas where weaker soils lead to landslides on lower slope angles, the threshold ϕ angle used in SINDEX derivation can be reduced to take this into account. At the same time, estimates of T and q can be varied until the resulting SINDEX map adequately discriminates between landslide prone areas and more stable areas.

Figure 1 is a graph where topographic slope is plotted against specific catchment area for the SINDEX Model. On this graph are lines that separate the points into regions according to the procedure outlined above (Equations (3) and (4)) based on Montgomery and Dietrich (1994). Areas with slopes greater than $\tan\phi$ (A) are considered "unconditionally unstable", meaning that they represent regions where there is perhaps outcropping bedrock or where the soil is held by cohesion. They may also represent regions where the specified ϕ is incorrect. Areas with slopes between $[1-(\rho_w/\rho_s)]\tan\phi$ and $\tan\phi$ (B&C) are susceptible to soil moisture induced landsliding. These areas can be represented by a stability index that represents the relative equilibrium at a particular location. This is analogous to the traditional "safety factor" used in soil mechanics where instability is expected if the index drops below 1.0. The higher the index is, the greater the stability is expected to be. Areas with slopes less than $[1-(\rho_w/\rho_s)]\tan\phi$ (D&E) are considered unconditionally stable, meaning that they would likely remain stable even when fully saturated. These areas may be subject to overland flow.

The occurrence of soil moisture induced landslides or overland flow depends on the ratio (T/q) of soil profile transmissivity and equilibrium recharge rate. The recharge rate varies with precipitation or snowmelt rate and T depends on soil thickness and conductivity. A family of curves for different T/q ratios can be constructed. For particular T/q and ϕ values, points can be categorized into the classes shown in Table 1. The areas of the graph in Figure 1 that meet each of the conditions of Table 1 are labeled A through E.

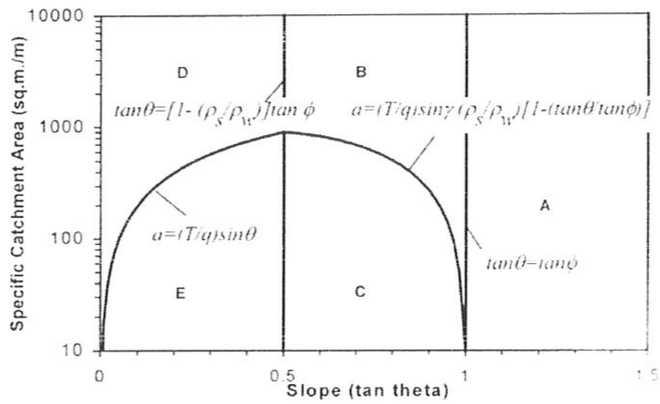


Figure 1. Area-slope plot showing regions A through E corresponding with states of stability. Parameters: $\rho_s/\rho_w=2$, $\tan\phi=1$, $T/q=2000$ m.

Trout Lake Case Study

SINDEX Mapping

The rationale and power behind the deterministic approach is illustrated with a case study in the Trout Lake Basin. Flow directions, topographic slopes, and specific catchment areas were computed using the procedures of Tarboton (1996) using a 20 m square grid DEM of the Trout Lake Basin. This model is derived from terrain resource inventory mapping (TRIM) data supplied by the B.C. provincial government. Figure 2 is a 1:200,000 scale map of this area where the specific catchment area has been grouped into grey-scale themes as shown on the legend.

***Table 1.** Conditions required for each stability class in the SINDEX model. See Figure 1 for the location of regions defining each condition.*

Condition Code	Stability Class	Condition
A	Unstable unconditionally	$\tan q > \tan\phi$
B	Unstable due to wetness	$a > (T/q)\sin\theta(\rho_s/\rho_w)[1-(\tan\theta/\tan\phi)$
C	Could become unstable due to wetness	$a < (T/q)\sin\theta(\rho_s/\rho_w)[1-(\tan\theta/\tan\phi)$
D	Stable, saturated.	$a > (T/q)\sin\theta$
E	Stable, Unsaturated	$a < (T/q)\sin\theta$

Using inventory data that provides the specific catchment area and slope of each landslide location in a study area, the graph shown in Figure 1 can be used to plot landslide locations. Given this plot, the values of T/q and $\tan\phi$ can be calibrated to fit the data. Similarly, areas of known moisture conditions can be plotted on the graph and the T/q ratio varied until it optimally matches the observed conditions.

A landslide inventory was completed using nominal 1:15,000 scale aerial photographs in order to calibrate the SINDEX model for the Trout Lake Basin. Point and line features indicative of slope instability were collected and all appropriate landslide data were entered into a GIS database. The spatial distribution of the 579 landslides inventoried is shown in Figure 3. The digital elevation model for the area was used to determine the slope and specific catchment area of each landslide site.

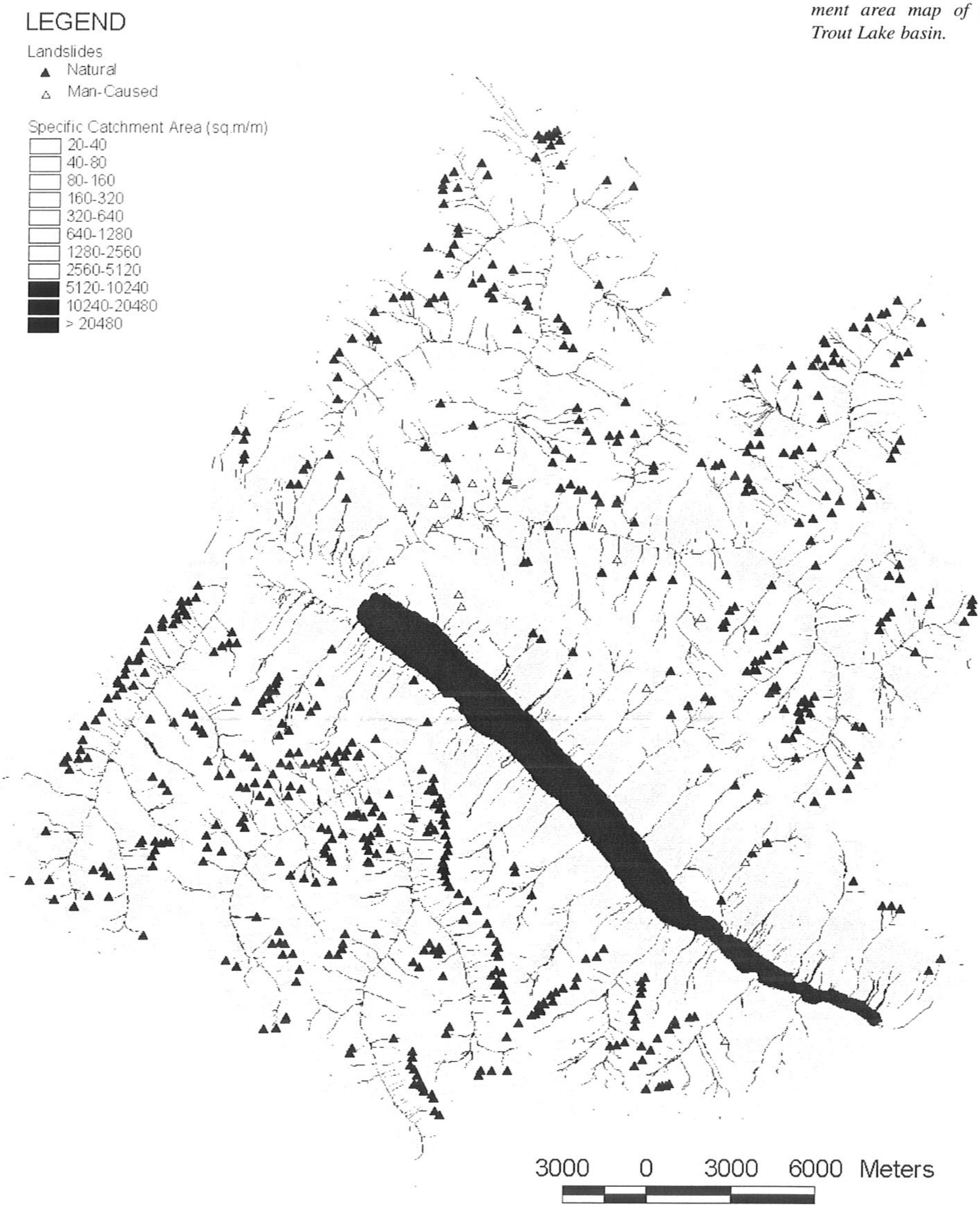
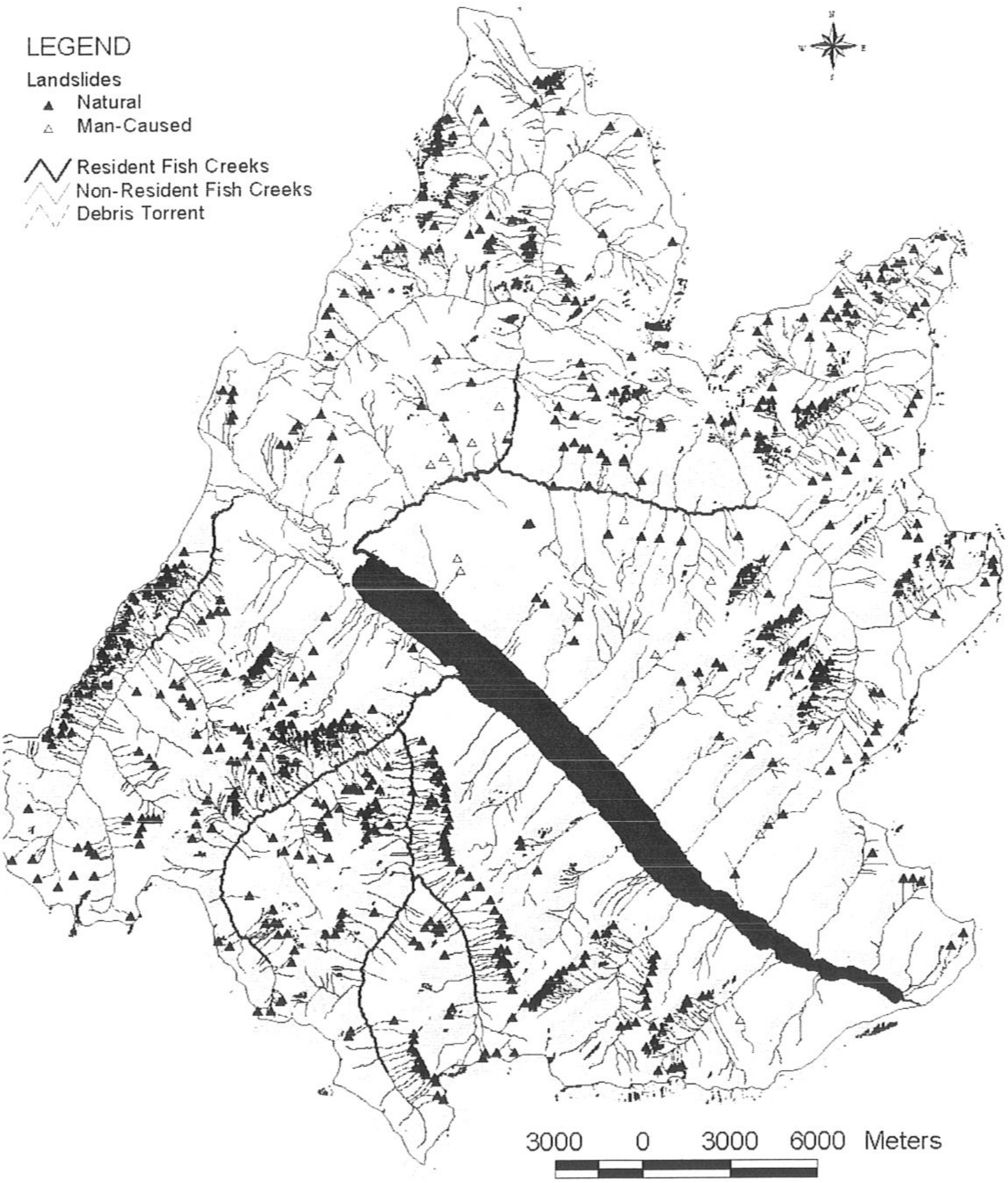


Figure 2. *Specific catchment area map of the Trout Lake basin.*

Figure 3. Landslide inventory map of the Trout Lake basin.



Each site was then plotted on the graph shown as Figure 4. This graph has the same layout as Figure 1 previously discussed. This graph allows the proper threshold parameters to be set for the Trout Lake Basin. As can be seen from the graph, a calibration of *T/q = 2000 m*, and a *tan* ϕ threshold of 1.0 (ϕ=45°) fits the data reasonably well. Given this calibration, the SINDEX map for the Trout Lake basin shown in Figure 5 was then automatically generated. This map shows those areas that are potentially "unstable due to wetness" (region B in Figure 4) and that are "unconditionally unstable" (region A in Figure 4) as red and light beige respectively. These two categories comprise approximately 13% of the total area of the Trout Lake Basin and include 91% of the landslides inventoried.

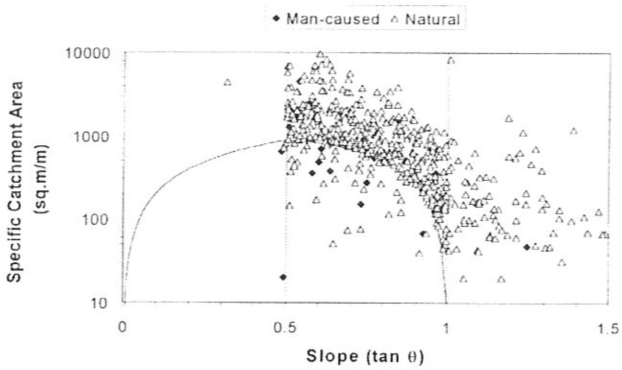


Figure 4. *Area-slope plot of landslides in the Trout Lake Basin.*

At each landslide location the micro-topography, as deciphered from aerial photographs, was compared with the topography indicated by the TRIM DEM. It was obvious from the outset that the TRIM data is locally inaccurate and in many cases either underestimates or overestimates the local steepness of slopes. This is particularly apparent where small gully-walls or benches are "averaged" by the TRIM DEM data. However, the accuracy appears to be acceptable at the reconnaissance level on the expectation that more detailed assessments will follow in potentially unstable areas.

Hazard Classification Results

The landslide inventory data was analyzed using simple statistics to determine the success of a classification scheme and then produce a terrain stability hazard rating appropriate for forest management. Table 2 summarizes the landslide statistics for this study and serves as the basis for discussion. The columns of the table represent SINDEX categories originating from the deterministic analysis. It can be seen in Table 2 that the condition code C category (representing slopes that could theoretically be destabilized by water as seen in Table 1) has been broken down into three subcategories (columns 5 through 7) according to index values as shown. Hence, a total of seven categories are represented. The rows represent various basin, landslide, and forest statistics. The purpose of the statistical analysis is to first define SINDEX categories (columns in the table) such that the landslide area or road density (in terms of number of landslides per square kilometer of area or kilometer of road) is maximized within some categories and minimized in others. Then, having done this, the next step is to properly assign ratings to each category so as to be consistent with land management strategies within the region or the province.

The process of minimizing and maximizing landslide densities within the classification was partially accomplished during the calibration phase of the SINDEX model. For this reason columns 1 through 4 already succeed relatively well in doing this. Columns 5 through 7 were broken down in order to test and represent the likely direct relationship between the number of landslides and the SINDEX values. The landslide statistics indicate this direct relationship by showing 29, 12, and 3 landslides occurring within progressively higher SINDEX categories. Column 4, which represents index values of less than 1.0 (which are theoretically unstable), captures 75% of all the landslides inventoried. When combined with column 3, which represents terrain steeper than 45° (also theoretically unstable), 91% of the observed landslide locations are included within the combined categories. These two categories represent 13% of the study area as can be seen from Table 2.

The "stable saturated" and "stable unsaturated" categories include less than 2% of the landslides and represent 44% of the basin area. When combined with columns 6 and 7, 5% of the landslides are represented within 75% of the basin area. These categories represent very low landslide densities.

These classification results are considered somewhat better than many of the results reported in the literature using other statistical methods. A possible reason for the improved results is that many of the previous studies used less predictive terrain variables such as slope curvature or concavity to model groundwater concentration. It is quite possible that a more realistic spatial representation of groundwater concentration using specific catchment areas has a better predictive capability as indicated by these model results. This supports

Column	1	2	3	4	5	6	7
Stability Category & Condition Code (see Figure 1)	**Stable Saturated D**	**Stable Unsaturated E**	**Steep Rock A**	**Index <1.0 B**	**Index 1 - 1.2 C**	**Index 1.2 - 1.5 C**	**Index > 1.5 C**
Basin Statistics							
Total Area (km^2)	102.4	219.2	45.6	50.81	90.0	143.7	87.5
% of total area	**14%**	**30%**	**6%**	**7%**	**12%**	**19%**	**12%**
Total Road Length (km)	180	265	1	24	21	51	44
Landslide Statistics			**Landslide Counts**				
Natural	2	2	91	424	25	5	3
Natural creek undercutting	1	0	0	3	0	3	0
In cut block	0	1	0	1	0	0	0
Road overloading slope	0	1	0	5	4	4	0
Road water diversion	0	0	0	4	0	0	0
Total Anthropogenic Slides	0	2	0	10	4	4	0
Total Slides of Any Kind	3	4	91	437	29	12	3
% of total number	**1%**	**1%**	**16%**	**75%**	**5%**	**2%**	**1%**
Landslide Density (#/ha)	0.000	0.000	0.020	0.086	0.003	0.001	0.000
Road Landslide Density	0.000	0.008	0.000	0.419	0.187	0.078	0.000
Preliminary Stability Class using Area Coastal Criteria (number/ha)	I	I	III	III+	II	II	I
Preliminary Stability Class using Road Coastal Criteria (km/km^2)	I	I	no data	III	III	II	II
Forest Statistics							
Non-Productive Forest (ha)	3416	7480	3484	2652	4697	6325	3570
Productive Forest (ha)	6813	14442	1072	2431	4302	8053	5189
Slides in Non-Productive	1	1	77	311	17	3	0
Slides in Productive Forest	2	3	14	126	12	9	3
Landslide Density (#/ha)							
Non-Productive	0.0003	0.0001	0.0221	0.1173	0.0036	0.0005	0.0000
Productive	0.0003	0.0002	0.0131	0.0518	0.0028	0.0011	0.0006
Recommended Rating	**I**	**I**	**III**	**IV**	**III**	**II**	**II**
Rating Within "-R" Units	**II**	**II**	**IV**	**V**	**IV**	**III**	**III**

Table 2. *Terrain stability hazard rating statistics.*

observations by other researchers (Montgomery and Dietrich, 1994).

Terrain Stability Ratings

Having now established the predictive capability of the hazard categories, the next step is to establish hazard ratings for the purpose of land management. The standard criteria for establishing these ratings suggested by "Mapping and Assessing Terrain Stability Guidebook" (MATSG)(Province of British Columbia, 1995) includes the number of landslides per hectare following harvesting (area density) and the number of landslides per kilometer of road following construction (road density). Using the coastal classification criteria based on area densities as reported in Appendix 1 of MATSG, a preliminary rating can be assigned for each category as shown in Table 2. In order for a category to be assigned to class IV, it's area density would need to be greater than 0.1 landslides per hectare. The category with the highest density in the Trout Lake Basin (which includes 424 landslides) is column 4 which has a density of 0.086 (Class III). However, the MATSG criteria involve area densities on harvested slopes, not necessarily unharvested ones. The densities reported in Table 2 are for mostly unharvested slopes (only 2 harvesting-related landslides were found in this study). Hence, the actual area densities following harvesting could eventually be higher than the natural density observed. Based on this, it was decided to raise the rating for this class to IV as shown on the second to last row of Table 2. The classes assigned to the remainder of the columns follow

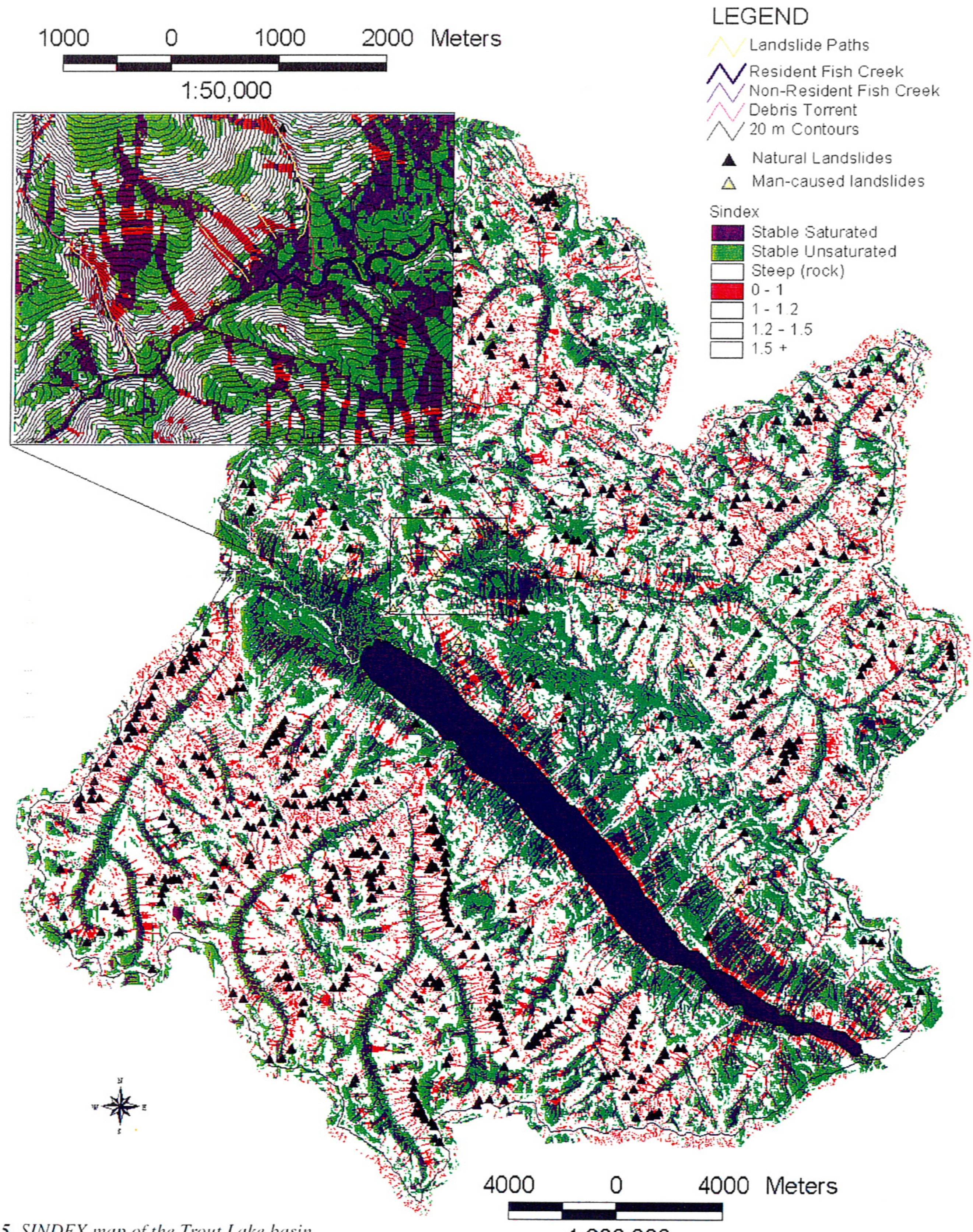


Figure 5. *SINDEX map of the Trout Lake basin using the parameters T/q =2000 and ϕ = 45°.*

the MATSG criteria for area densities.

Using the coastal classification criteria based on road densities, the maximum road density of 0.42 landslides per hectare in column 4 does not exceed the 1.0 landslides per hectare density required for class IV. Using the road density criteria alone, none of the slopes in the Trout Lake Basin would be classified above III.

The recommended hazard ratings shown in the second to last row of Table 2 are calculated as the highest rating resulting from either of the two preliminary ratings discussed above.

Class V terrain as defined by MATSG normally includes terrain polygons that contain active landslides. Using standard B.C. terrain mapping system definitions, terrain polygons that include active landslides are labeled with the "-F" or "-R" (failing) modifying process symbol and are then usually assigned to stability class V. The criteria used by terrain mappers to determine the number of landslides required within a polygon in order for it to be designated as "failing" is unclear. Large homogeneous polygons in which a single isolated landslide is found are not necessarily considered failing. The MATSG approach suggests that polygons enclosing areas that exceed a certain subjectively determined landslide density, e.g. 3 landslides per square kilometer, are designated as failing and are assigned to class V. The Class V definition (being the most severe) relies on the assumption that the greater the proximity to or inclusion of existing landslides, the more likely the terrain unit will experience instability following forest development.

In order to model this spatial correlation, polygons having local areas with landslide densities in excess of 1.0 landslides per square kilometer were designated as "failing". Figure 6 shows the distribution of these terrain polygons in relation to the distribution of known landslides. Within each of these polygons, the hazard rating associated with the SINDEX values previously calculated was raised one hazard class in order to reflect the proximity to higher landslide densities. This is a somewhat subjective but necessary judgement in order to comply with the requirements of MATSG. The last row of Table 2 reflects a modification of the hazard classification for terrain polygons designated as "failing". Figure 7 shows a final terrain stability map resulting from these classifications. This map can be compared with Figure 5 to see the changes brought about by the statistical and terrain analyses.

Forest Development Issues

Under the Forest Practices Code Act, terrain stability maps inevitably have impacts on forest development planning. The risk-cost benefit ratio associated with excluding tracts of land from forest development due to stability concerns should be an important part of forest development planning.

Table 2 lists the area of productive versus non-productive forest within Trout Lake Basin for each of the terrain stability classes. The forest productivity information originates from digital forest cover data obtained from the Ministry of Forests. It can be seen from the table that columns 3 and 4 (Classes III(IV) and IV(V)) include 1072 + 2431 = 3,503 hectares of productive forest. At the same time, it can be determined from the table that 130 natural landslides and 10 man-caused landslides have occurred within the same hazard zones in productive forest. A cost associated with the loss of timber can be calculated assuming that all land that falls within these two classes were excluded from the cut due to the risk of landslides. Calculations of this nature are normally completed by a development forester. Environmental and economic costs associated with likely rates of future landsliding could also be calculated through a complete risk analysis. Though a complete risk analysis is not a part of the current research, the likely number of landslides per hectare of harvesting or kilometer of road constructed within each of the stability units could be used as a starting point for such an analysis. By comparing the two above-noted costs, the environmental and economic viability of future forest development in certain areas could be assessed.

Discussion

This approach to reconnaissance-level mapping is less-expensive and faster than the approach suggested in MATSG as it does not require the direct delineation and digitizing of polygons by the terrain mapper. The professional terrain mapper's primary role is the determination of input parameters to the SINDEX model, the collection of landslide inventory data, and the modification of the model output to reflect peculiarities of the terrain.

The deterministic approach provides a well-described and objective tool for terrain stability mapping that can be used to compare regions within the province. The GIS and statistical data that

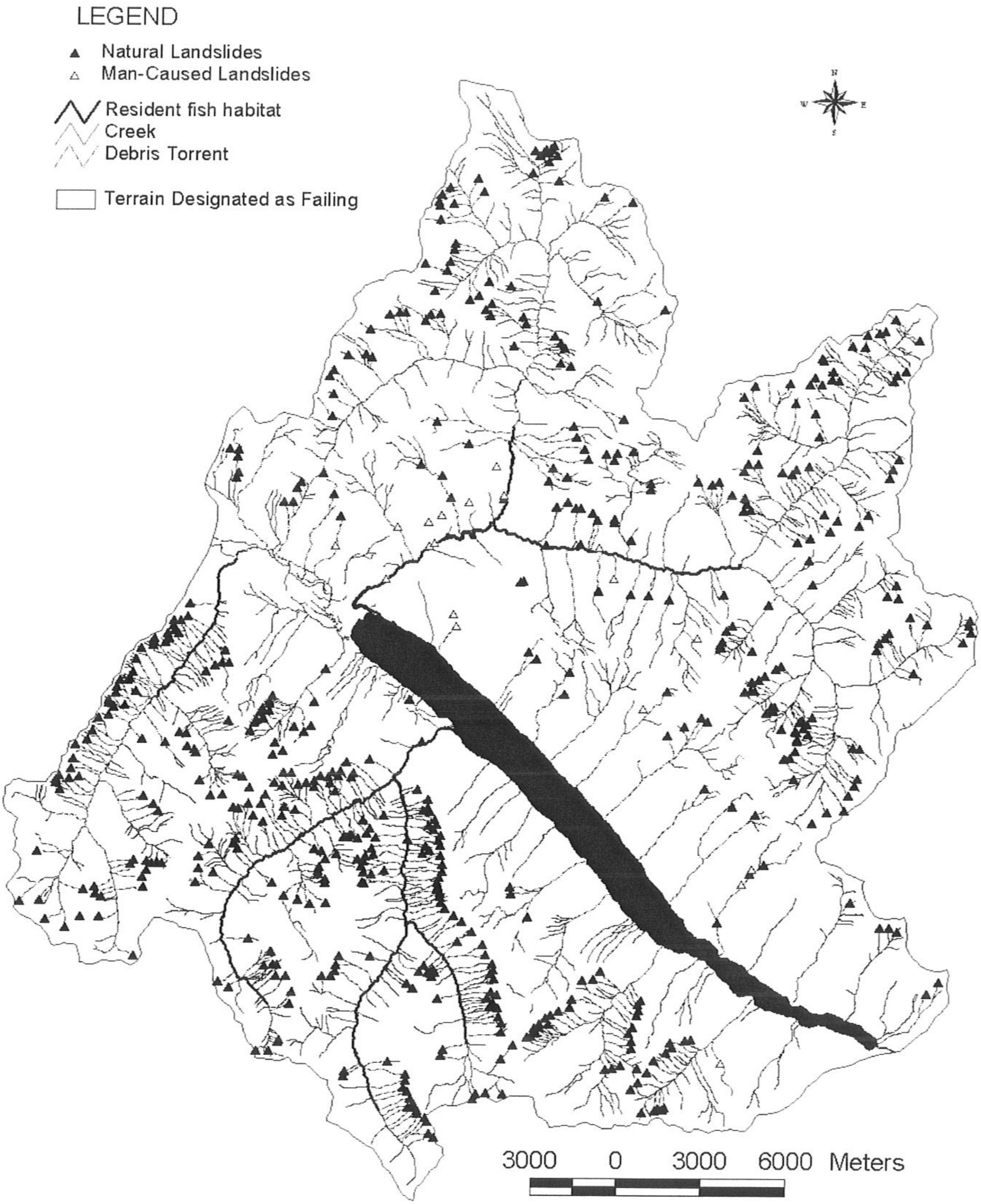


Figure 6. Map of terrain designated as failing in the Trout Lake basin.

Figure 7. Terrain stability map of the Trout Lake basin.

this methodology produces would help future mappers and auditors determine the relative conservatism of follow-up detailed terrain stability mapping.

All data and results from the reconnaissance level efforts are usable in, and beneficial to, follow-up Level-C/B mapping if it is required. Hence, there will be little wasted money when the eventual level of mapping detail required for an area is already known to be Level C/B.

There is a possibility that, given accurate 1:5000 scale topographic mapping derived from 1:15,000 scale photography, this approach could be appropriately used in level C/B terrain stability mapping. The TRIM-based delineations are subject to local errors in TRIM DEM data. The severity of these errors will vary from map sheet to map sheet. Manually interpreted polygons can explicitly delimit areas dominated by certain geomorphic processes. The proposed methodology might miss areas with critical microtopography such as small hummocky areas or areas with small gullies that don't show up on TRIM maps. A remedy to this drawback would be to include the delineation of areas with landforms relevant to slope stability in the landslide inventory. These areas could then be input into the GIS and given the appropriate rating that would then override the general hazard mapping model. Hence, the mapper could over-ride the computer-based delineations as necessary.

The application of this model is limited to shallow translational modes of failure and assumes that the dominant controls on stability are slope and shallow subsurface flow convergence. Other landslide types may not be as successfully predicted by this approach.

Conclusions

It is acknowledged that this proposed methodology has a mixture of potential benefits and drawbacks. Though the proposed approach is similar to approaches used by others outside of B.C., it has not yet been demonstrated in B.C. over a large area. Our experience with applying this method as a part of our on-going research at Trout Lake shows that it does hold promise. Further pilot studies should be conducted in various regions of the province to further test the effectiveness of this approach.

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