LANDSLIDE SUSCEPTIBILITY FROM WATERSHED AND FAN CHARACTERISTICS, SALMON ARM AND VERNON FOREST DISTRICTS

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Abstract

Landslide occurrence in the Salmon Arm and Vernon forest districts in the last five years has stimulated research to determine how small drainage basins might be classified into debris flow prone, debris flood prone, or flood prone. Alluvial fans situated at the base of several entrenched stream systems may have people dwelling on them. In addition to safety concerns, water quality and habitat are also of importance. A procedure is presented here that uses both map-based (GIS) and field-based (fan and channel mapping) analysis to show relative risk of impact on fans. Bedrock and surficial geology are used to type the basins that are dominated by metamorphic rocks. Basin area, aspect, slope, inner gorge, and gentle-over-steep conditions were determined. GIS-generated channel longitudinal profiles were compared between the data sets. Fan morphology and stratigraphy aided in identifying previous debris flow events and their magnitude. Historical information provided by time-series air photo interpretation, historic maps, and archival research provides clues to recurrence intervals. Some fans will have relict paraglacial deposits that include debris flows and may still support future debris flows. Last, the methods proposed here can be used to signal special concerns for forest development. The use of this template may find application in risk assessment outside the selected forest districts.

Introduction

The purpose of this paper is to develop a landslide susceptibility model. This project, which is in progress, will help determine susceptibility based on watershed and fan characteristics for Hunters Range. It is organized by impetus behind the project, overview of the geographic area, data sources available, and information technology that can be employed. The methods and procedures used will be briefly described, followed by a summary of the results where the technique was applied in the Salmon Arm and Vernon forest districts.

The concerns in forest development in mountainous terrain in the southern Interior of British Columbia include the occurrence of landslides and debris flows. People living on alluvial fans below harvested watersheds are particularly at risk. Alluvial fans are often the depositional zones of rapid mass movements down steep watercourses. This is a concern due to their sudden and unpredictable occurrence. Forest development has sometimes been implicated in the initiation of some of the debris flows in the B.C. Interior.

The study was stimulated by our interest in landslides and process geomorphology. We had researched other publications on this topic and wished to try existing methods and new methods

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on a particular part of the landscape. We decided on the Salmon Arm Forest District and the Vernon Forest District, in particular, the Hunters Range (Figure 1). A total of 56 watersheds were analyzed. The area covered by the Hunters Range is about 1300 km^2 with main drainages of Kingfisher and Yard creeks. It is bounded on the south by Shuswap River, on the north by Eagle River, on the west by Mara Lake, and on the east by Wap Creek and Mabel Lake. One of the largest reported non-volcanic debris flows in British Columbia occurs in this area on Hummingbird Creek (Jakob et al. 2000).

Debris flows result from the interaction of several factors. To create a hazard classification system, an understanding of how each factor contributes to debris flow occurrence is needed. However, key factors including basin morphology, slope, soil moisture, road location, and soil porosity/permeability can be analyzed. Research is needed in (1) identification of fans that are susceptible to debris flow, (2) methods for estimating physical properties and character of debris flows, and (3) characteristics of debris flow source areas (Hungr et al. 1987; Reneau and Dietrich 1987; Ritter et al. 1995). Here, we wish to address the question of what factors trigger debris flows at Hunters Range and what is their relative significance.

Debris flows are gravity-induced rapid mass movements of sediment of varying size ranges, from clay to boulders (Ritter et al. 1995). The transported mass includes varying amounts of water and moves by differential shearing with waves that overtake one another (Johnson and Rahn 1970; Jackson et al. 1987).

It is generally felt that small basins with steep slopes are prone to landslides. This is borne out by the work of Jackson (1987) in the Canadian Rocky Mountains and the Mackenzie Mountains. The ultimate factors that cause debris flows are gravity and water.

Soil porosity and its influence on landslides were investigated by Iverson et al. (2000). In a scale model experiment, they determined that loose soil started sliding about 300 times faster than dense soil. Initial soil porosity of 0.5 led to abrupt failure while that around 0.41 led to slow episodic motion. Critical porosity was 0.44 for landslides. The critical pore water pressure in less dense soils does not have to be as high to trigger a failure.

Data Sources

For at least part of Hunters Range, there exist topographic maps, historical maps, bedrock geology maps, soil maps, and surficial geology that are available to the public. In addition, the provincial government has Terrain Resource Inventory Mapping (TRIM) at 1:20 000 scale with 20 m contour intervals. Their geographic information system (GIS) includes an extension to ArcView 3.1 called Geographic Object Analysis Tool (GOAT). The GIS files include several coverages that assist our tasks, including 1997 black and white orthophoto imagery, slope, road networks, regional bedrock geology, and landslide inventory coverages.

Historic mapping exists for the Railway Belt Surveys, which were carried out along the Canadian Pacific Railway corridor between 1877 and 1907. These show the location of channels traversing fans in the valley of the Shuswap River, for example (Figure 2). Geological Survey of

Canada surficial geology maps show fans, alluvium, moraine, and lacustrine deposits for part of the area (Fulton 1975). Terrain mapping has been done over part of the Hunters Range (EBA Engineering 1998). The soil coverage was based on Kowall (1980).

Archival material was searched out and collected from various newspapers (Kamloops Sentinel, Enderby Commoner) and the Enderby Museum.

Because water is a key component for debris flow systems, its spatial concentration should be included in this model. This would include the sources of water (snowmelt, rainfall, rain-on-snow) as well as the routes that surface runoff takes once on the ground. Drainage networks are mapped to varying degrees but road systems can also redirect water, intercept shallow groundwater and vadose zone water, and expand the volume flowing across the surface.

Precipitation data are only available from a few sites (Salmon Arm stations and Ministry of Forests Sicamous Research Site stations). Gauged streams in Hunters Range are rare but there exist some spotty records. The PRISM model (**P**arameter-elevation **R**egressions on **I**ndependent **S**lopes **M**odel) developed at Oregon State University was used by Ministry of Forests to develop a 4 km by 4 km grid of mean annual precipitation.[3] These data were provided to us from Ministry of Forests.

Tools

ESRI ArcInfo and ESRI ArcView as well as Microsoft Excel were used as analysis tools. Digitizing was done at Ministry of Environment, Lands and Parks and University College of the Cariboo. GIS is a powerful tool that can enhance the establishment of a hazard classification system. However, it is a tool only and the user must be able to incorporate it correctly into the process.

The overlay analysis is based on the combination of layers. Each layer represents one specific factor, such as aspect or soil type, and divides the study area into polygons according to the values of its factor. By combining layers, a new layer is generated. The polygons of this newly generated layer contain one, and only one, attribute value of the layers it derived from. For instance, the combination of an aspect layer with a soil layer would generate a new layer that would divide the area into polygons in a way that each polygon contained exactly one aspect value and exactly one soil type value. Each polygon contains information about all factors at its specific location.

Based on this overlay analysis, two main approaches are used to implement a GIS into the establishment of a hazard classification scheme: the process-based approach and the stochastic approach. In the following sections, both methods are examined.

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[3] http://www.ocs.orst.edu/prism/gen_toc.html

Process-Based Approach

The processed-based approach is concerned with the physical processes involved in debris flows and takes geotechnical parameters, such as cohesion or angle of internal friction, into consideration. Its main focus lies on the determination of the safety factor. Sakellariou and Ferentinou (2001) employed a process-based approach in a study that treats of the estimation of slope stability. To begin with, a digital elevation model (DEM) was created that provided information about geomorphic factors such as slope angle, aspect, and elevation. A second layer was then created in which geotechnical data, such as cohesion, angle of internal friction, thickness of layers, or depth of groundwater, were stored. These data, before being evaluated, had to be transformed in a way that corresponded to the homogeneity of data structure, which is required for process-based models. For this reason, average values were used. The two layers were overlaid so that the newly generated layer contained information about both the geomorphic and geotechnical data for each polygon. The next step was the implementation of a "Landslide Hazard Assessment Tool." This tool automatically calculated the safety factory for each polygon. The calculation was based on the following equation:

$$F = 2.27 \cdot \frac{c \cdot \cos ec\,\psi_f}{\gamma \cdot H} + 1.54 \cdot (1 - r_u) \cdot \cot \psi_f \cdot \tan \varphi$$

The parameters involved in this equation are F = safety factor, γ = unit weight of soil, c = cohesion, φ = internal friction angle, ψ_f = slope angle, H = slope height, and r_u = pore water pressure ratio. The equation was proposed by Sah et al. (1994) in Sakellariou and Ferentinou (2001).

According to the values of these parameters, the program calculates a safety factor for each polygon. The spatial distribution of this safety factor can be visualized in a map identifying the risk of slope failure for every polygon. The user of this "Landslide Hazard Assessment Tool" can change the values of the parameters easily and, by doing so, create a set of maps representing different scenarios. These maps can be compared with a map representing real locations of slope failure. The combination of values that makes the best match can be determined.

The advantage of such a process-based method is that it is physically based. It is possible to identify a fine-scale pattern of instability. However, it can be difficult to acquire the input data necessary to use this method effectively. Geotechnical parameters often have to be measured in the field, which is time and cost consuming.

Therefore, the process-based method is well suited for the analysis of smaller areas (Lineback Gritzner et al. 2000). The study conducted by Sakellariou and Ferentinou (2001), for example, covered an area of 48 km^2.

Stochastic Approach

The stochastic approach is another way of implementing a GIS into the establishment of a hazard classification scheme. This method is based on the assumption that the conditions that triggered slope failures in the past are likely to cause future slope failures. In the stochastic approach used by Dhakal et al. (2000), the focus is not on the safety factor and the required geotechnical data, but on geomorphic, geologic, climatic, and vegetation factors, which are considered to be indices of the parameters of the safety factor. These factors are analyzed, generally employing multivariate statistical analysis techniques. As the stochastic approach is going to be employed for the project at Hunters Range, the study conducted by Dhakal et al. (2000) will be examined in detail.

The database for the study was built by taking the following steps. First, landslide locations were identified on 1:20 000 air photographs and plotted on a 1:12 500 topographic hardcopy map. This landslide distribution map was digitized. Next, a DEM was generated providing information about slope gradient, elevation, and aspect. To classify these data, the slope gradient was divided into five classes: < 15°, 15–25°, 25–35°, 35–45°, and > 45°. The elevation was divided into four classes: < 1800 m, 1800–2000 m, 2000–2200 m, and > 2200 m. The aspect was also divided into four classes: north (315–45°), east (45–135°), south (135–225°), west (225–315°). Moreover, ridges and valleys were identified from the DEM. Six classes were created based on the distance to these features. The next step involved the generation of (1) a land use/land-cover layer, which derived from a 1:25 000 land use/land-cover map; (2) a geology layer, which derived from a 1:50 000 geology map; and (3) a basin order layer (first, second, third order), which derived from a topographic map. Land use/land-cover data were divided into five classes, geology data into seven classes, and basin order into three classes. These layers will be referred to as factor layers.

The analysis of the database was based on a Q-S II analysis.[4] This combines a multidimensional quantification analysis and the equivalent of a discriminant analysis. The difference, however, is that this function incorporates nominal data instead of interval or ratio data. Nominal scaled factors, such as geology or land use/land-cover, are often crucial to discriminate between landslide and non-landslide groups. A discriminant analysis can be employed to determine whether the variables used are able to explain spatial differences, such as “landslide” or “non-landslide.” In addition, it can provide information to what extent each variable contributes to the spatial differentiation (Bahrenberg et al. 1992). For the purpose of determining a spatial differentiation, Dhakal et al. (2000) created a landslide group and a non-landslide group. The first question to be answered was which sampling method for the non-landslide group would provide more discriminant and thus meaningful results. The two methods in question were the aligned systematic sampling method and the unaligned stratified random sampling method. As only the results themselves could give an answer, the analysis was conducted for both sampling methods and their results were compared afterwards. This means that two samples were created using the aligned systematic method, and three samples were created using the unaligned stratified random method. The Q-S II analysis was made in the Japanese version of the SPSS[5] statistical package and used the attribute tables of the previously created factor layers.

The analysis started with the calculation of the correlation coefficients between the factors, which from now on will be referred to as variables. The aim was to see if any two variables vary in a similar way. For example, if the values of elevation and slope angle are highly correlated, then one of these two variables could be excluded from the analysis. In the case of the study conducted by Dhakal et al. (2000), however, no strong correlations appeared, which simply

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[4] Q-S II is a statistical analysis of quantification scaling type II used in a GIS application.

[5] SPSS Inc. is Statistical Package for the Social Sciences software system.

indicates that all eight variables contribute to the occurrence of landslides in their own specific way and therefore should be integrated in the Q-S II analysis.

The Q-S II analysis was supposed to provide information about (1) which sampling method leads to more discriminant results and (2) to what extent each variable contributes to the occurrence of landslides. To determine the efficiency of the discrimination between the two groups, the correlation ratio, η^2, and eta, η, were calculated. The correlation ratio is referred to as the "...proportion of variance between the groups to the total variance.…" and eta is referred to as "...the degree of difference between the group means." (Dhakal et al. 2000). Higher η^2 and η scores indicate a more efficient discrimination. Analysis results show that the unaligned stratified random sampling method led to a more efficient discrimination between the two groups, thus providing more meaningful results. The second aim of the Q-S II analysis was to determine the importance of each variable. For this purpose, the scores of all classes of all variables were compared. According to the Q-S II functions, a larger class score (CS) indicates a greater contribution of this class to landslides. In addition, the range of scores (RS) within every class was calculated and compared. As to the class scores themselves, a larger range of scores indicates a greater contribution of this variable to landslides. Hence, the analysis did not only determine the importance of each variable (RS), but moreover provided information about the importance of each class of every variable, too.

The stochastic approach made it apparent that geology is the most contributing variable (RS = 2.557) and that the class "granite" of this variable is the one most inclined to landslides (CS = –0.708). Geology is followed by elevation (RS = 0.835) with the highest class score for "2000–2200 m" (CS = –0.412). Other important variables are slope aspect (RS = 0.831) with the highest class score for "south" (CS = –0.358) and land use/land-cover (RS = 0.769) with the highest class score for "shrub land" (CS = –0.443). The analysis showed that the variables distance from ridge, distance from valley, and slope gradient only have a minor impact on the occurrence of landslides. Their range of scores is 0.081, 0.145, and 0.268, respectively. Their largest class score is –0.033, –0.097, and –0.194, respectively.

The next step of the study focused on the determination of hazard classes. Each previously generated factor resulting from the Q-S II analysis layer now contained data about the scores for its classes. The factor layers were overlaid so that one layer was generated, which contained a cumulative score for each polygon. Cumulative scores of the landslide group were compared with cumulative scores of the non-landslide group. A discriminant score was determined that divided the polygons into "stable" and "unstable" according to their cumulative score. In this study, the discriminant score was –0.13. A further differentiation between very unstable and marginally unstable, as well as very stable and marginally stable, respectively, was made. This differentiation was based on the accuracy of decision, meaning that the top 20% of each group were identified as being very unstable and very stable, respectively. These four categories were considered to be four classes of relative hazard: high, moderate, less, least. Landslide hazard maps were produced taking the ranked cumulative score of each polygon into account as the foundation.

The last step of the study involved the evaluation of these hazard maps. The method employed was to calculate the percentage of landslides for each hazard class by overlaying the landslide hazard map with the previously created layer representing real landslide locations. A high percentage of landslides in polygons, which had been ranked as high hazard, indicated a high accuracy of the hazard map. To determine to what extent the five different samples led to different results, two of the five hazard maps were overlaid in turn. Those polygons that had the same hazard class were counted. The proportion of these polygons to the total number of polygons was considered to be the “overall spatial agreement.” It became apparent that differences were minor between samples resulting from the same sampling method. Dhakal et al. (2000) inferred that one sample set would satisfy the analysis and hazard mapping requirements if the unaligned stratified random sampling method was employed.

Dhakal et al. (2000) employed a stochastic approach using the capabilities of a GIS in combination with the analysis capabilities of the statistic program SPSS. This method is appropriate especially for large areas. The study conducted by Dhakal et al. (2000) covered an area of 124 km^2. In light of the often difficult, if not impossible, data acquisition that comes along with process-based methods, the benefits of a stochastic approach are that it can be made rapidly and that site investigation costs are minimized. Moreover, the incorporation of a GIS has further enhanced this method (Dhakal et al. 2000).

Two aspects must be emphasized however. First, the validity of any statistical or GIS-based approach largely depends on how complete and accurate the input data are. For this reason, it is mandatory that the analysis be strictly based on variables for which appropriate data are available. Incomplete or inaccurate data can easily lead to invalid results. Second, although certain statistical analysis functions are part of every GIS, a sophisticated statistical analysis can be better undertaken employing a statistic program. It is important that the user of a GIS analysis understands which steps of a project can be conducted efficiently by using a GIS and which steps can be better carried out by employing other tools. This means that often a GIS is a powerful tool to establish a comprehensive database (overlay function) and a powerful tool to visualize and evaluate gained results (hazard maps). On the other hand, a statistics program can often carry out the analysis of the database more effectively.

From these tools, watershed characteristics were derived. These included watershed area, perimeter, basin relief, maximum and minimum elevation, fan area, fan slope, aspect, slope classes, and Melton's ruggedness, for each sub-basin. Melton's ruggedness (MR) is defined as:

$$\text{Ruggedness} = \text{Height of Basin} \times (\text{Area of Basin})^{-0.5}$$

$$MR = Hb(Ab)^{-0.5}$$

Melton's ruggedness provides a unitless number to compare basins. It has been used in the Canadian Rocky Mountains to help differentiate debris flow impacted fans from alluvial fans (Jackson 1987). Melton's ruggedness was also used in a study conducted by EBA Engineering (1999) following suggestions from Ted Fuller. This study provided an inventory of high consequence terrain in the Salmon Arm Forest District. An example to test this is from Camp Creek, the site of a 1968 debris flow in the Eagle River valley north of Hunters Range. The parameters used are $Hb = 1660$ m and $Ab = 15\ km^2 = 15\ 000m^2$, which give a Melton's ruggedness number of 0.429.

Graphical Methods

Basin area was plotted against basin relief for the watersheds as a log-linear plot (Figure 3). Melton's ruggedness number was plotted against slope of the fan (also logarithmic scales) (Figure 4). In this way, known fan impacts can be shown with their relationship to a few basin parameters. Speculations from these graphs suggest that large basins with lower relief are fluvial fan derived while smaller basins with high relief are debris flow fan derived. A suggestive curve is drawn through these data with debris flow above the curve and non-debris flow below. In addition, watershed area was plotted against fan area (Figure 5) and shows a wide scatter in the data.

Watershed slope distributions were determined from a digital elevation model (DEM) for selected watersheds. The slope classification was divided into 17 classes. The first class was 0–2%, the second 2–5%, the third 5–10%, and then in increments of 10%. Histograms were plotted to show slope distributions (Figures 6 and 7). Analysis of the slope data is in progress.

Debris Flow Runout

Debris flow runout is an important physical attribute to obtain and inventory. At present, there is limited information on debris flow runout in the Hunters Range. The runout of coarse rubbly size material or fine muddy matrix material will be different. In this study, the runout was determined from 1997 four (4) m pixel resolution orthophoto imagery by examining the extent of the debris flow path. By using examples from Hummingbird Creek, Fall Creek, Rogers Creek, Hunter Creek from Hunters Range, as well as Leonard Creek, Eagle Valley creeks near Malakwa, and Falkland Creek, generalities can be made. Typical debris flows are transported in channel gradients of 16° and higher and run out on fan slopes of 3° or higher. Large debris flows extend onto fans less than 3° such as the case of the Hummingbird Creek fan.

Conclusions

The aim of this paper is to create a platform for the project “Establishment of a GIS-based Hazard Classification Scheme for Debris Flows, Hunters Range, British Columbia.” For this purpose, the current status of research regarding debris flows and landslides was investigated. This investigation demonstrated that debris flow initiation is the result of basin morphometry, slope gradient, soil moisture, and roads.

Small and steep basins are highly vulnerable to debris flows. Determining Melton’s ruggedness number is a method for summarizing the interrelation of morphometric basin parameters. Slope gradients can be classified with respect to debris flow occurrence. It appears that there is a relatively higher concentration of debris flows on slopes with a gradient of approximately 30° or more. Furthermore, soil moisture significantly contributes to the initiation of debris flows. Increased soil moisture conditions can be the result of either severe storms or road construction.

Road construction affects the water regime of a basin in two ways: (1) relatively permanent gaps in the forest canopy lead to increased water storage in the soil and snowpack, and (2) the water routing to streams is spatially concentrated. The behaviour of landslides is strongly connected to initial soil porosity. Landslides initiated in loose soil show a sudden and fast motion, whereas the motion of landslides initiated in dense soil is dilative, episodic, and slow. In addition, the critical pore water pressure of dense soil is roughly twice as large as the one of loose soil.

Although engineers and geoscientists have been able to uncover many of the mechanisms of how single factors contribute to the occurrence of debris flows, there still remain unanswered questions. The major problem is the interaction of these factors, which is only poorly understood. This is the reason why prediction of debris flows is difficult.

In addition to the investigation of the factors causing debris flows, this paper examined two different approaches are used to implement a GIS into the establishment of a hazard classification scheme. The process-based approach seems to be a useful method for the analysis of small areas, as geotechnical data acquisition is time and cost consuming. The results gained this way, though, provide a high degree of precision (but not necessarily accuracy if modelled incorrectly). The stochastic approach, on the other hand, appears to be well suited for the investigation of larger areas, as geotechnical data are not required.

The debris flow phenomenon is the result of the complex interplay between various factors. Sophisticated methods for a reliable prediction of debris flows have not been able to be developed yet. Due to the progress in the field of GIS technology in the past two decades, this technology is bound to play a key role in the enhancement of methods for the prediction of debris flows.

GIS is a useful tool for calculating Melton's ruggedness, basin characteristics (slope, aspect), stream gradients, and long profiles of streams. However, GIS should not be the only method used for this type of investigation.

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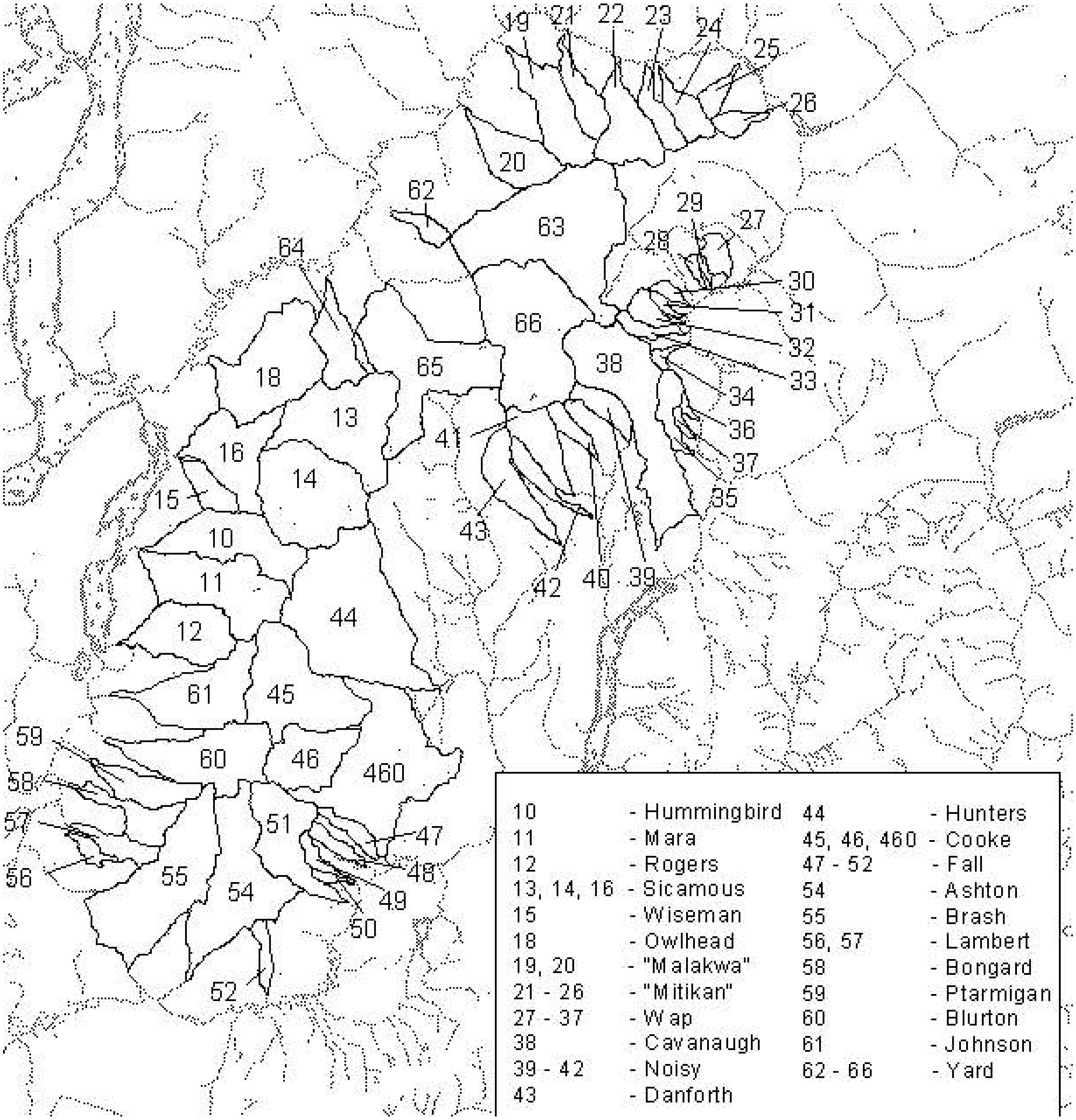

Figure 1. Location of 56 watersheds in Hunters Range.

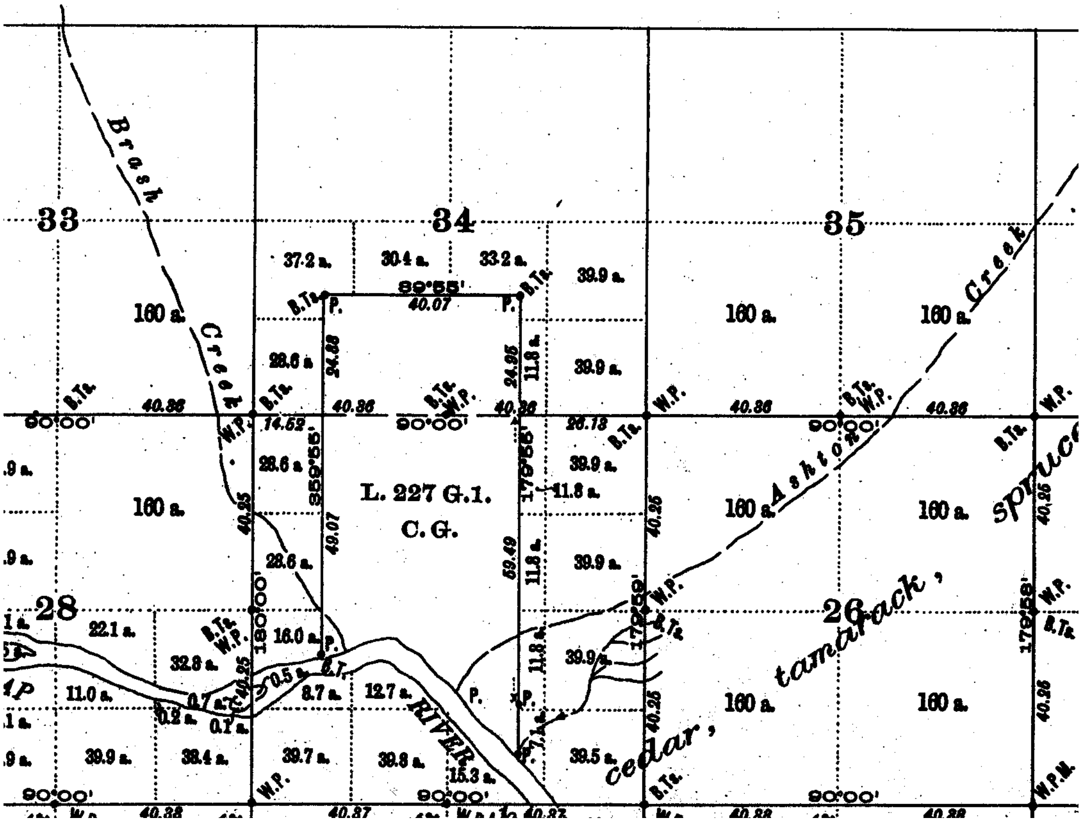

Figure 2. Historic Railway Belt map showing Brash Creek and Ashton Creek confluences with Shuswap River.

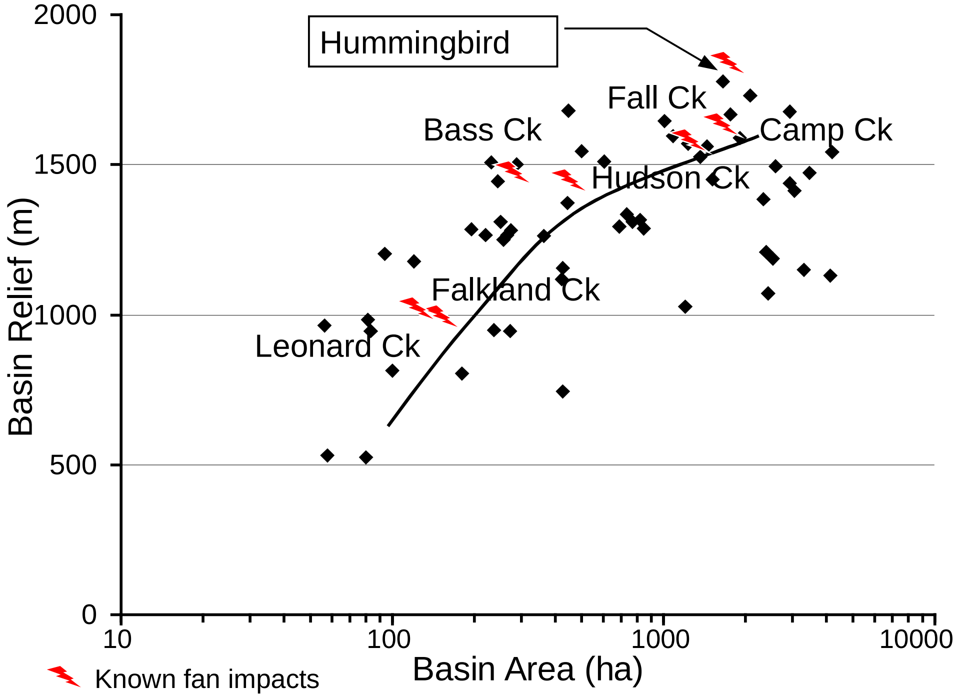

Figure 3. Basin area versus basin relief.

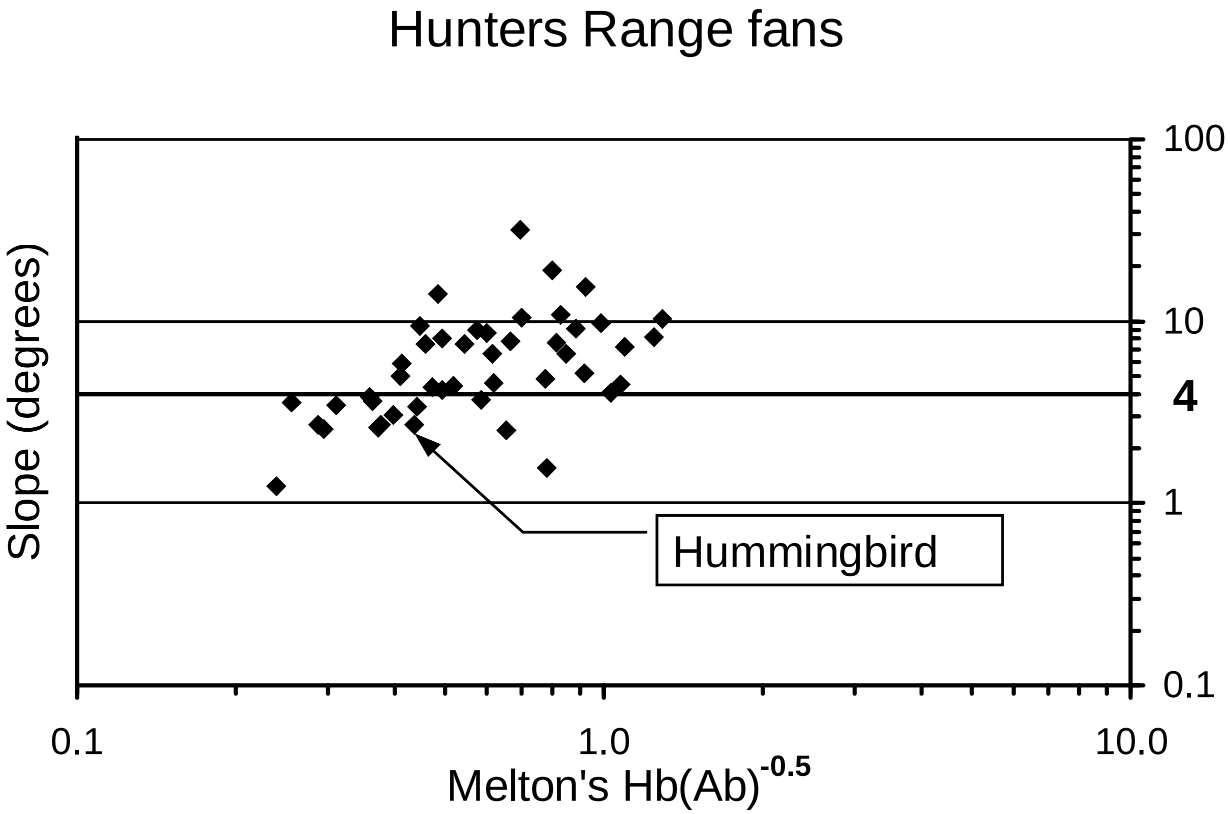

Figure 4. Melton's ruggedness versus fan slope.

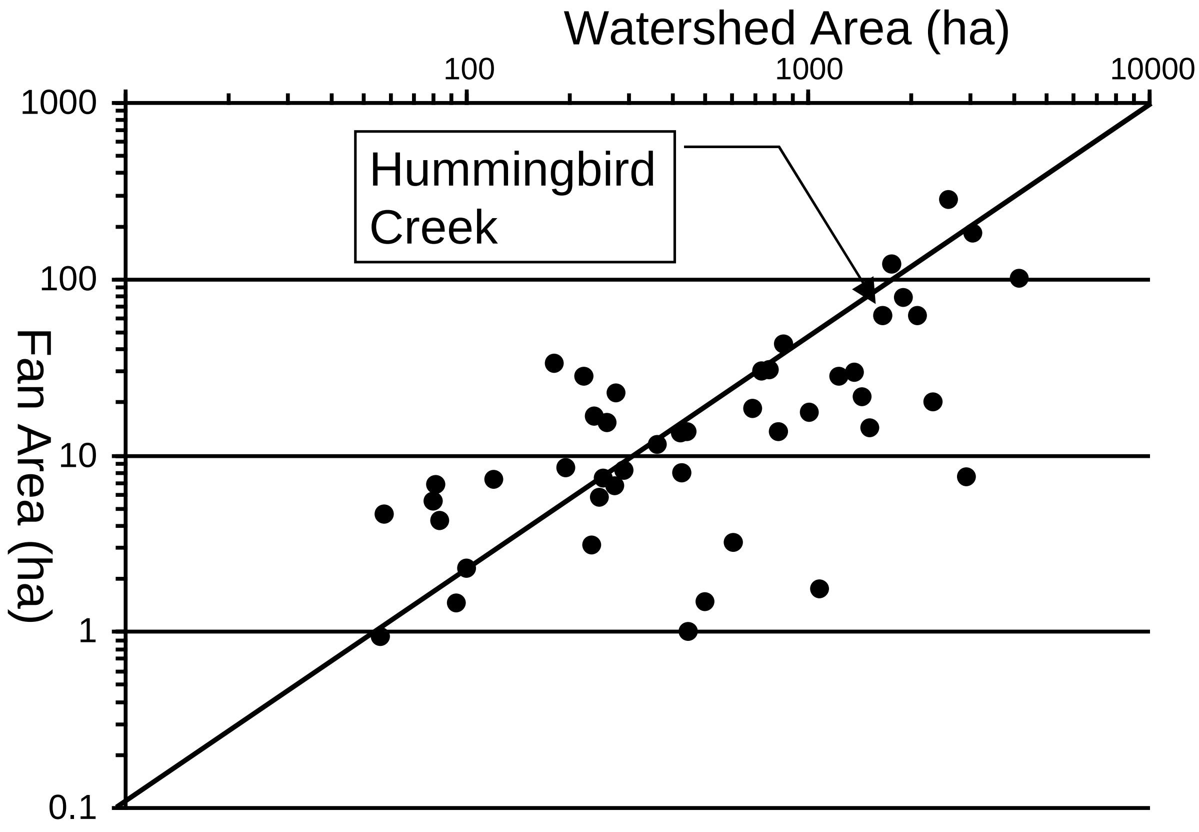

Figure 5. Watershed area versus fan area.

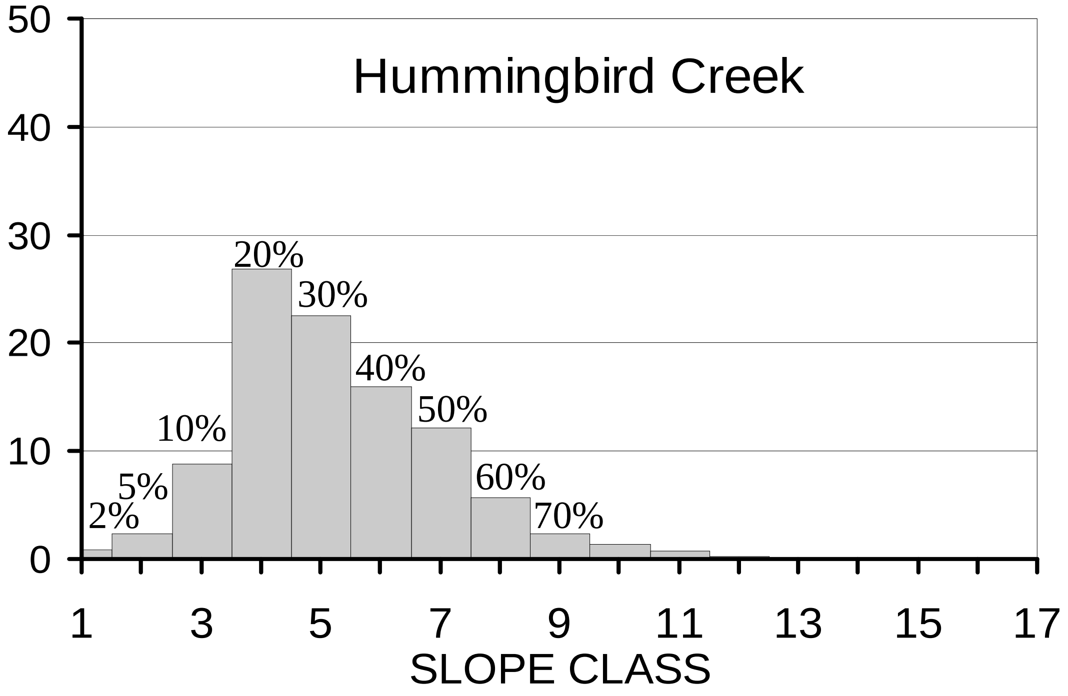

Figure 6. Slope classification for Hummingbird Creek.

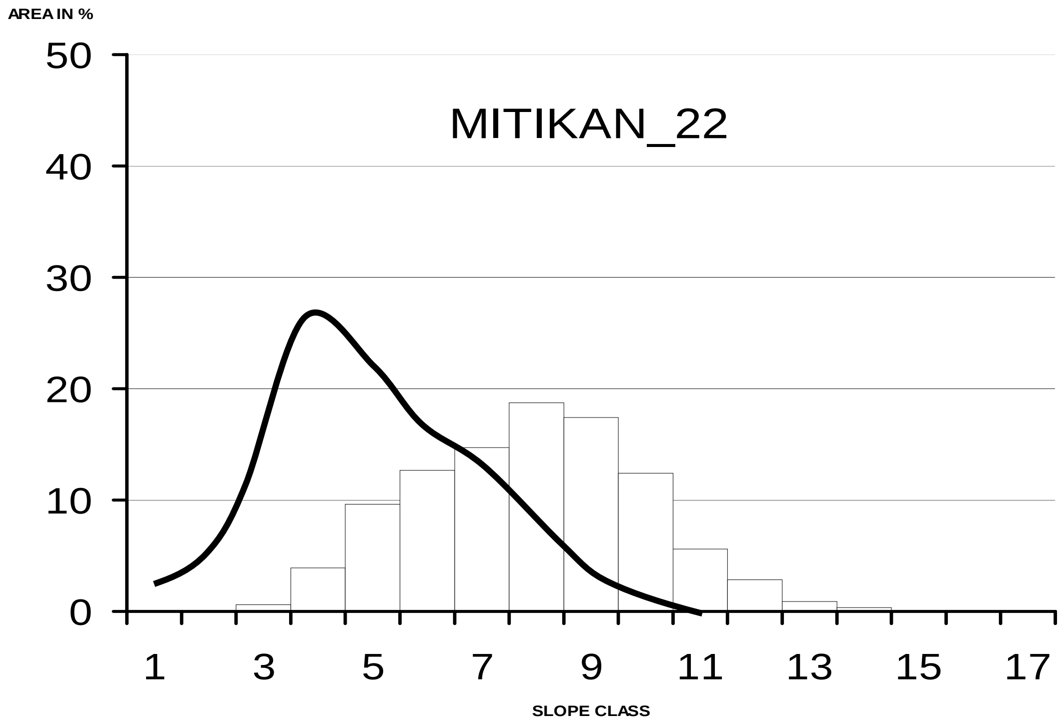

Figure 7. Slope classification of Mitikan_22 watershed with Hummingbird Creek watershed superimposed.