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THE UNIVERSITY OF ALBERTA

VALIDATION BY RAINFALL SIMULATOR OF AN EROSION HAZARD RATING SYSTEM FOR WESTERN CENTRAL ALBERTA

by

© HAO ZHANG (HAO CHANG)

A THESIS
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FACULTY OF GRADUATE STUDIES AND RESEARCH

The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research, for acceptance, a thesis entitled VALIDATION BY RAINFALL SIMULATOR OF AN EROSION HAZARD RATING SYSTEM FOR WESTERN CENTRAL ALBERTA submitted by HAO ZHANG (HAO CHANG) in partial fulfilment of the requirements for the degree of MASTER OF SCIENCE.

Richard L. Rothwell

Supervisor

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Date June 12 1987

Abstract

Soil disturbance from forest harvesting which increases ~~soil~~ erodibility and water quality deterioration is a critical factor influencing forest management practices. Although erosion hazard rating techniques are important planning tools for land managers and foresters, the lack of field testing and practical validation has limited the application of most erosion hazard rating systems. This study was undertaken in an effort to assess the validity of a newly proposed erosion hazard rating system for Western Alberta (Singh 1983), and in particular to determine its applicability to post-logging sites where soils were disturbed by logging and soil scarification.

The validation was carried out in the area where the system was developed. A nested factorial experimental design with sixty 61cm x 61cm erosion plots was employed in compliance with the system classification. Overland flow and surface soil erosion from each plot were generated by the Tahoe Basin Rainfall Simulator (Munn 1976) with a 2.5m falling height and approximately 100mm/hr rainfall intensity. The results of soil loss were analyzed and compared directly or indirectly to the predicted ratings of the system. The comparisons showed no agreement. Small differences in soil loss among Singh's soil by forest stratifications, and great variability within the stratifications suggested that the system is weak in predicting soil erosion hazard.

Additional efforts were also made to improve the system. A series of multivariate expressions were derived by stepwise regression to relate soil loss with eight site and soil physical properties. The equations were tested against the observed soil loss and found to be more accurate and reliable in prediction of soil erosion hazard than the solitary infiltration index. An easily applicable expression with two variables was suggested to replace Singh's erosion hazard ratings.

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I would like to express my sincerest appreciation to my supervisor Dr. R.L. Rothwell for his immeasurable assistance throughout my graduate program. My special thanks for his time, his trust, his patience and his valuable counsel.

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Table of Contents

List of Tables

TABLE . PAGE

List of Symbols

L = soil loss in grams resulting from both splash and wash impacts of the simulated rainfall.

R = runoff volume in liters collected in the field.

I = overall infiltration rate in mm/hr.

D_b = bulk density in g/cm^3 of the surface soil.

M = soil particle-size parameter used in the Universal Soil Loss Equation (USLE, Wischmeier *et al.*, 1971) which equals (silt%) x (sand+silt%), where very fine sand (0.05-0.1mm) was included in silt.

S = slope of the simulation plot in percent.

R^2 = coefficient of multiple determination.

$S_{y.x}$ = standard error of multiple regression.

F = F value of the last step regression.

SE B = standard error of regression coefficient.

Beta = standardized regression coefficient (without physical unit).

R^2 change = change of R^2 with respect to each new variable selected into a stepwise multiple regression equation.

Sig. T = significant value (α) of regression coefficient by T test.

PPT = rainfall intensity (mm/h).

STO = stoniness index (frequency of occurence out of 2304 grids).

SMC = soil moisture content (%).

Chapter 1

INTRODUCTION

1.1 FOREST MANAGEMENT AND SOIL EROSION

Soil erosion seldom occurs on undisturbed forest land, because mineral soil is fully protected by a cover of litter and humus. Studies show that erosion from the undisturbed forest occurs almost entirely within the stream channel as discharge detaches soil particles and carries them downstream (Reinhart *et al*. 1963; Dils 1957).

Forest cutting, *per se*, causes little or no erosion (Hoover 1945). But soil disturbance which may accompany or follow cutting often results in erosion. Erosion control or prevention begins with planning. Considering that 90% of the sediment produced by erosion on timber-sale areas comes from roads (Packer and Christensen 1964), planning begins with those measures that will hold road mileage to a minimum. This involves careful selection of a logging method and road location.

Advance planning of road location can reduce both road area and gradient. Control of road erosion also requires adequate drainage systems to prevent overland flow from developing enough depth and velocity to seriously erode the road surface (Packer and Christensen 1964).

The method of logging can have a significant impact on the amount of soil disturbance and erosion. Tractor logging causes far greater soil disturbance than other methods

(Dyrness 1967; Rothwell 1978; Klock 1982). Post-logging treatments for site preparation create high amounts of soil disturbance as well. Depending on the method of measurement, the area of mineral soil exposed by mechanical scarification in Alberta ranges up to 40% to 65% (Ferdinand 1983).

1.2 EROSION HAZARD ASSESSMENT

Advance planning requires background knowledge about local erodibility and erosivity. From a practical viewpoint, erosion hazard ratings are important planning tools for land managers and foresters (Dunne and Leopold 1978; Rice and Gradek 1984). Erosion hazard rating techniques have developed, as understanding of erosion processes has expanded. The understanding and prediction of erosion processes have evolved from qualitative and single-independent variable estimates to multivariate expressions and various models now in use. Among them, the most popular model is the Universal Soil Loss Equation (USLE) developed by Wischmeier (1978) for agricultural soils. It has been modified for forest soil application and is entitled as the Modified Soil Loss Equation (MSLE, Warrington *et al*. 1981). However, its application on steep forest lands is not very successful (Kirkby 1980; Swanson *et al*. 1982), because surface erosion processes in forested lands have different relationships between transfer rate and slope length, rainfall and soil characteristics than those described for agricultural soils by the USLE.

There is still much that remains to be understood about erosion in the forest, and at present it is not possible to construct a convenient and realistic technique for predicting erosion without fieldwork (Dunne 1984). Therefore, the best way of predicting soil loss is using local field data representative of the range of conditions in the area of interest (Dunne and Leopold 1978). An example of this can be found in a study by Rice and Gradek, (1984) which was an effort to validate three untested erosion hazard ratings in California. Validation showed they were inadequate in most cases.

A common characteristic of various erosion hazard rating systems proposed or adopted today is their lack of field validation. Information from surveys or studies on hydrology, geology, soil properties, or even codified professional opinion is the backbone of most of these rating systems. The situation in Alberta is no exception. Dumanski *et al*. (1972) presented a local potential erosion classification for the Hinton-Edson area based on observations of natural precipitation and permeability of soil parent material. The classification has been used as a model by several other researchers. Kathol and McPherson (1974) rated erosion susceptibility of geologic deposits in the House Mountain area from least erodible to most erodible as follows: muskeg, gravel, coarse sand, till, clay, shale, fine sand, and sandstone. A recent study on erosion hazard by Anderson *et al*. (1986) presented an erosion-hazard chart based on studies of slope angle and soil moisture content. No field observations were made. None of these systems has been tested in a rational or quantitative way. As a result, few of these systems are adopted by land managers. Actual field examination of erosion hazard rating systems is important for their application in land management.

1.3 A PROPOSED SYSTEM FOR WEST-CENTRAL ALBERTA

A new regional erosion hazard rating system was recently proposed by Singh (1983) for west-central Alberta. The system uses forest cover types as indicators of erosion hazard. Three forest types were identified in Singh's system which in turn were stratified into 18 soil associations, for which steady state infiltration rates were determined. Erosion hazard was identified on the basis of infiltration rates, where high hazard was equated to low infiltration rates and low hazard to high infiltration rates (Llerena 1987). The system is simple in form, which makes it a potential tool for land use and management planning in west-central Alberta.

Infiltration rates in Singh's study were determined with a double-ring constant head infiltrometer under each forest cover on undisturbed litter surfaces. Six runs were made for each soil association in each forest cover type. Steady state infiltration rates were found to vary under different forest cover types, presumably due to the modifying influence of vegetation. The three forest types utilized in the system were lodgepole pine, spruce-fir and aspen. The results suggested low erosion susceptibility for lodgepole pine sites, very high susceptibility for spruce-fir sites and moderate susceptibility for aspen sites.

Singh recognized the simplicity of his system and the influence of other site and climatic factors on erosion, but considered that, reasonable estimates and rating of erosion susceptibility could be obtained from the infiltration capacities of the soil types under a dominant vegetation cover, and that such rating of land units could serve as a first approximation for planning purposes.

However, Singh's method employs a number of assumptions that are questionable. For instance, the steady state infiltration rates used in Singh's system were obtained for conditions where the litter layer was left intact. Under such conditions, the occurrence of overland flow, raindrop impact and erosion is limited. Furthermore, such infiltration rates may not be representative of the same soil when disturbed and exposed.

Soil stability is the resistance of soil particles to detachment, dispersion and transport from the force of raindrops and flowing water (Rothwell 1978), which is intimately related to soil structure and soil texture (Wischmeier 1969, Hillel 1980). A given soil association, defined as a group of closely interrelated soil series developed on similar parent materials and under essentially similar climates, is named according to lithologic differences in soil parent materials (Dumanski *et al.* 1972). Soils in a given association may undergo different weathering under various topographic, slope and drainage conditions and therefore may not necessarily be the same in terms of stability. Consequently, soil associations may be poor indicators of soil erodibility which may vary widely from site to site. Many studies have shown that soil erosion can be better denoted by a multivariate expression, integrating the interactions of local erosivity and relevant soil physical properties (Wischmeier 1969; Rice and Gradek 1984), than by an univariate expression.

To summarize, the primary assumptions in Singh's system are:

(1) The combination of vegetation and soil association serves as an index integrating soil and weathering factors affecting erodibility.

(2) Steady state infiltration for undisturbed conditions can serve as an index of erodibility of disturbed soils.

(3) Infiltration rate governs overland flow and the consequent possibility of induced erosion.

Some other points important to soil erosion but not included in Singh's system are:

(1)The importance of raindrop impact or splash erosion as one of the primary causes of soil loss (e.g. Brown 1980; Bryan 1974).

(2)The influence of soil disturbance and exposure on soil erodibility and soil loss.

(3)The potential for differences in erodibility within a given soil association.

An exploratory study (Llerena 1987) by erosion pins was undertaken to validate Singh's system. Abnormal rainfall pattern and amount during the field experiment confounded the results with uncontrollable errors, and made it difficult to draw a conclusive judgement on the effectiveness of Singh's system. Therefore, this study was conducted in an effort to refine the validation of the system.

1.4 STUDY OBJECTIVES

The purpose of this study was to assess the validity of Singh's erosion hazard system, in particular to determine its applicability to post-logging sites where soils were disturbed by logging and scarification. Actual measures of erosion generated from simulated rainfall were compared to Singh's ratings of erosion hazard. Further improvements to the system were suggested based on a series of multiple regression calculations. The null hypotheses proposed for testing were:

(1) There was no similarity in soil loss among the soil-vegetation groups described by Singh's method.

(2) There was no variability in soil loss within any single soil-vegetation group described by Singh's method.

(3) Erosion hazard was not related to the interactions of local erosivity and relevant soil physical properties as expressed by multivariate analyses.

Chapter 2

METHODOLOGY

2.1 STUDY AREA

The area selected for study was in the Hinton-Edson region of Alberta, on the forest management area (FMA) operated by Champion Forest Products (Alberta) Ltd. The FMA is located 286km west of Edmonton, between 116°00' and 118°00' west longitude and between 53°00' and 54°00' north latitude (Fig. 1). Elevation ranges from 853m in the eastern portion to about 2621m in the southwestern part (Hillman *et al.* 1978). It spans two physiographic subdivisions (Alberta Plateau Benchlands and Rocky Mountain Foothills) and, apart from a small area near the town of Hinton, the area is forested with spruce-lodgepole pine and aspen forests typical of the foothills section of the Boreal Forest Region (Dumanski, *et al.* 1972).

The study was carried out on Champion's McLeod and Athabasca management units, and on the Cache Percotte Watershed which is administrated by the Hinton Forest Technology School. The area has been extensively logged. After logging, scarification operations were carried out to facilitate regeneration. The harvest history offers a wide range of cut-blocks (harvesting units) on different topographic, vegetative and soil conditions for study. This is also the study area used by Singh to develop his erosion hazard rating system.

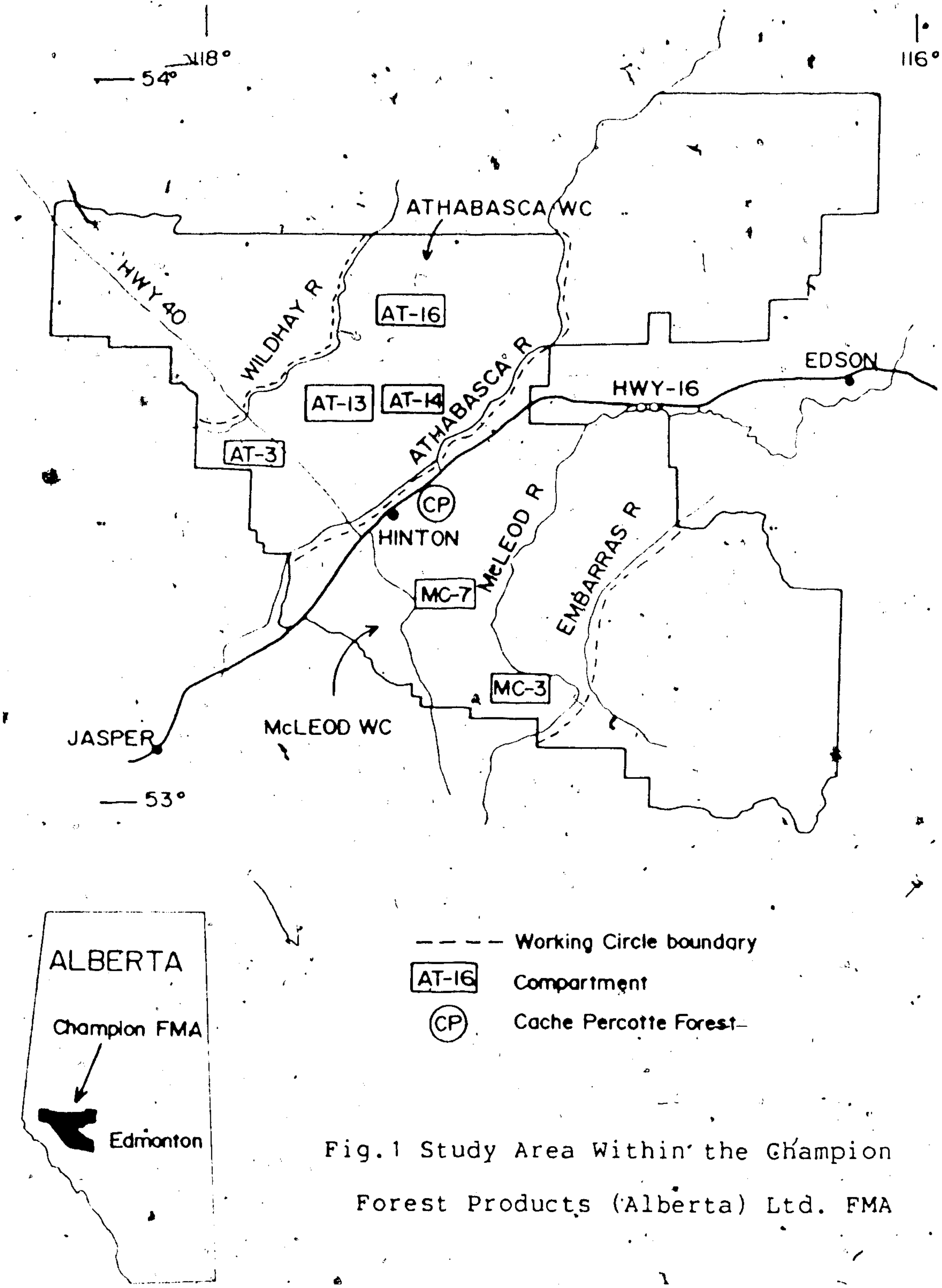

Fig.1 Study Area Within the Champion Forest Products (Alberta) Ltd. FMA

2.2 STUDY DESIGN

Two forest cover types (lodgepole pine and spruce-fir) and three soil associations (Marlboro, Obed and Robb) were selected for study. Sampling a large number of soil associations was impractical because of the spatial difficulties in identifying similar cut-block soil vegetation combinations and logistical problems in sampling a larger number. This sampling design gave six soil and vegetation combinations, roughly representing 80% of Champion's forest management area. Two cut-blocks were

TABLE 1. EXPERIMENTAL DESIGN

	MARLBORO	OBED	ROBB
PINE	AT(7) AT(3)	CP(7) AT(3)	MC(7) MC(3)
SPRUCE-FIR	AT(7) AT(3)	CP(7) AT(3)	MC(6) MC(4)

AT, CP, MC = Athabasca, Cache Percotte and McLeod management units.
(number) = number of observations in a cut-block.

selected within each of the six combinations to serve as experimental units. There were 3 to 7 observations of simulated rainfall erosion per cut-block (Table 1). The total number of observations for all cut-blocks combined was

60. Statistically, this was a hierarchial design with rainfall simulation plots nested in the experimental unit (i.e. cut-blocks).

2.3 CUT-BLOCK SELECTION

Selection criteria for the cutblocks were:

Vegetation. Two forest cover types were identified in the field. The first was lodgepole pine (*Pinus contorta Dougl.* var. *latifolia* Engelm.), and the second was spruce-fir consisting of white spruce (*Picea glauca* (Moench) Voss.), black spruce (*Picea mariana* (Mill.) B.S.P.) and alpine fir (*Abies lasiocarpa* (Hock.) Nutt.).

Soil Association. Three soil associations were identified by using soil survey maps of the region (Dumanski, *et al.* 1972) for testing of the system: Marlboro (chiefly Luvisolic soils developed on medium-to fine-textured Marlboro till of Cordilleran source); Obed (a collection of Gray Luvisol soils developed on medium-to coarse-textured Obed till); Robb (a collection of Gray Luvisols and Eutric and Dystric Brunisols developed on mixtures of till and colluvium).

Cut-block Age. All cut-blocks were less than 8 years in age and had similar levels of disturbance and post-logging vegetation.

Furthermore, cut-blocks with easy vehicle access were given priority in the study.

2.4 RAINFALL SIMULATION

Within each cut-block, 3 to 7 rainfall simulation plots were established on uniform, unbroken slope sections, away from skid trails, landing areas and depressions. The slopes of the plots varied from 8 - 15% in steepness. All surface debris and litter were removed from each plot to expose bare mineral soil to simulate newly disturbed conditions and to dampen any variability between plots resulting from different post-logging treatments, cutblock ages and harvesting season. All erosion plots were 61cm by 61cm in size. The plot perimeter was formed by pushing sheet metal edging 1 - 2cm into the ground and was sealed by placing soil against the outside surface to assure runoff collection and to prevent surface and subsurface leakage. Great care was given to plot surface levelling to insure similar microtopography for all plots.

The Tahoe Basin rainfall simulator (Munn 1976) with 3.2mm drop-former and 2.5m falling height was employed to simulate artificial rainfall at an intensity of approximately 100mm/hr onto the plot. The simulator was shielded from the wind and was air-tight to assistant in control of rainfall intensity. The flowmeter reading and initial and final water levels (20 litres in volume) in the water supply tank were held constant to achieve identical hydrostatic head (i.e. constant head) across the rainfall chamber for all runs. Each plot was sampled only one time. All overland flow generated during the process was collected from a triangular trough, oven-dried and weighed in the laboratory to calculate the amount of soil loss and volume of flow from each plot. These data were used as a relative index of inherent soil erodibility and were compared with ratings derived from Singh.

2.5 SOIL SAMPLING

Around each plot, two to three undisturbed soil samples, 5.4cm in diameter and 3cm in depth, were collected from the surface soil. The soil samples were used to determine bulk density and soil moisture content. Each core sample was weighed and sealed with a plastic bag in the field immediately after sampling. The soil moisture content was calculated on an oven-dry weight basis. In addition, disturbed soil samples were obtained from each plot for mechanical analysis of soil texture (McKeague 1978). The results were used to determine USLE's M factor (Wischmeier *et al.* 1978).

The stoniness (surface area of exposed stone) of each plot was evaluated in terms of frequency. A steel screen, with 1cm x 1cm grid, was placed on each plot surface. The total number of stones greater than 0.5cm^2 in surface area was recorded as an index of stoniness.

2.6 DATA ANALYSIS

A nested factorial design (Hicks 1973) was employed to test for significant variation among soil, forest type, soil-by-forest and cut-block strata. Before the analysis was started, the erosion data (in grams - g) were subjected to tests of normality (Anderson and McLean 1974) and Bartlett's test for homogeneity of variances (Sokal and Rohlf 1981). The results of these tests were positive at the $\alpha=0.05$ significant level.

To identify possible improvements to Singh's system, multivariate analyses were performed to identify environmental and site factors important to soil loss. A series of stepwise multiple regressions was performed, using linear polynomial and exponential models of the same forms as those employed in a successful California study by Rice and Gradek (1984).

$$Y = A_0 + A_1X_1 + A_2X_2 + \cdots + A_nX_n, \qquad (1)$$

$$\ln Y = A_0 + A_1X_1 + A_2X_2 + \cdots + A_nX_n; \qquad (2)$$

where Y is soil erosion generated by simulated rainfall.

Independent variables selected for analyses included: runoff, infiltration, rainfall intensity, slope, stoniness, bulk density, soil moisture content and USLE's M factor. Infiltration rate was obtained indirectly by subtracting runoff from the 20-litre of water used to simulate rainfall.

Rainfall intensity was included for analysis, because it varied slightly between runs due to installation and momentary wind turbulence. Theoretically rainfall intensity should have been constant for all runs.

Chapter 3

RESULTS AND DISCUSSIONS

3.1 MEASURED SOIL LOSS

Average soil loss caused by simulated rainfall for all plots combined was 237g, with a standard error of mean (SEM) of approximately 10g. Subdividing the samples by soil associations and forest cover types (Table 2) revealed similar level of soil loss between soil associations and forest types. The average soil losses by row or by column in Table 2 did not show [illegible] differences either.

TABLE 2. AVERAGE SOIL LOSS (in gram) AND VARIATION

FOREST COVER	SOIL ASSOCIATION			RQW MEAN
	Obed	Robb	Marlboro	
Pine	227±22	240±25	265±25	244±14
Spruce	245±37	226±19	218±18	230±15
COLUMN MEAN	236±21	233±15	241±16	237±10

The results from Table 2 brought into question the fundamental stratification of Singh's system. If the stratificaion of soil by vegetation is to make sense in differentiating soil loss, noticeable differences in soil loss between treatments (i.e. soil associations or forest types) should be apparent. Unfortunately, this was not the case.

3.2 ANALYSIS OF VARIANCE

To thoroughly evaluate the effectiveness of Singh's system, an analysis of variance (ANOVA) was performed on soil loss from each rainfall simulation run. A nested design was used to see if Singh's stratifications significantly explained variation in the data and to determine potential

TABLE 3. ANOVA OF SOIL EROSION

SOURCE	D.F.	MS	F
soil (S)	2	492.452	0.033 ns
forest type (F)	1	57.270	0.004 ns
S by F	2	8163.684	0.544 ns
B/SF	6	15005.551	2.808 **
ERROR	48	5343.723	
TOTAL	59	6109.590	

ns. non-significant at the α = 0.10 level
** significant at the α = 0.05 level

sources of variation for future study.

Results from the ANOVA (Table 3) confirmed initial observations and further developed my arguments. First, there were no significant differences in erosion between soil associations, forest types or interactions between them. The lack of significant differences between soil associations and forest cover types and their interactions indicates Singh's system was not sensitive enough to identify differences in erosion hazard. Furthermore, the test of the nested cut-block (B/SF) indicated that within single soil association-forest types, there was significant variation in soil loss. Table 4 shows that all of the cut-blocks within a given soil by forest combinations in this study were located on different soil subgroups

TABLE 4. SOIL SUBGROUPS IN EACH CUT-BLOCK

	MARLBORO	OBED	ROBB
PINE	MLB6 MLB5	OBD1 OBD2	RBB1 RBB3
SPRUCE-FIR	MLB6 MLB5	OBD1 OBD2	RBB4 RBB3

MLB, OBD, RBB = Marlboro, Obed and Robb soil mapping units, where each number suffixed to a mapping unit represents a distinct soil subgroup.

(Dumanski *et al*. 1972). This implies that the real source of variation might originate with the soil subgroups (mapping units). Nevertheless, this does not meet Singh's assumption that erodibility within a given soil association-forest cover type is uniform. Therefore, these observations lead to the rejection of hypotheses 1 and 2. Furthermore, even a qualitative comparison of Singh's erosion hazard ratings to measured erosion ranked by order of magnitude showed no agreement.

3.3 MULTIVARIATE ANALYSIS

The results from the previous sections indicated that Singh's system was weak in predicting soil loss. To find better parameters for expressing soil loss, a series of stepwise multiple regressions were performed using linear polynomial and exponential models.

The best linear (Eq.3) and exponential models (Eq.4) were ones which isolated runoff, bulk density, USLE's M factor and plot slope as the most important variables for describing soil loss (Tables 5 and 6). A confidence level of 95% was used for all stepwise regression calculations.

$$L = -30.876196 + 29.748577\ R - 108.605837\ D_b + 0.011496\ M + + 6.982186\ S \qquad (3)$$

$R^2 = 0.63800$ **

$S_{y.x} = 48.70728$

$F = 24.23351$ **

TABLE 5. MULTIPLE REGRESSION WITH LINEAR MODEL
(with all of the variables)

VARIABLE	SE B	Beta	Partial R	R^2 change	Sig.T
R	3.558	0.898	0.748	0.445	0.0000
D_b	37.883	-0.325	-0.361	0.1198	0.0059
M	0.004	0.218	0.332	0.0358	0.0117
S	2.931	0.217	0.306	0.0374	0.0207

** significant at the $\alpha = 0.05$ level

$$\ln L = 4.712495 + 0.176308R - 0.838844D_b + 0.000043M \quad (4)$$

$R^2 = 0.73714$ **

$S_{y.x} = 0.21299$

$F = 52.34816$ **

TABLE 6. MULTIPLE REGRESSION WITH CURVILINEAR MODEL

(with all of the variables)

VARIABLE	SE B	Beta	Partial R	R^2 change	Sig.T
R	0.016	1.028	0.834	0.561	0.0000
D_b	0.155	-0.484	-0.587	0.153	0.0000
M	0.00002	0.158	0.288	0.024	0.0283

** significant at the α = 0.05 level

The exponential model was more efficient in describing soil loss (with 3 independent variables and an R^2 of 0.74), compared to the linear model (with 4 independent variables and an R^2 of 0.64). Curvilinear models are reported to better describe how site and physical variables interact naturally to affect erosion than linear models (Rice and Gradek 1984). All regression calculations by the exponential model showed higher correlation coefficients and more significant statistical results (Table 6).

Both equations and independent variables used were significant at $\alpha \leq 0.05$ level (R^2, $S_{y \cdot x}$, F and Sig.T). The order of importance of the variables in the equations was assessed by either *Beta* or *Partial*. Runoff alone was the most important variable, explaining 45 - 56% of the variation in erosion. The importance of surface runoff to induce soil erosion has been recognized in many studies (e.g. Bethlahmy 1967; Farmer 1973; Luk 1977). It is well known that rainfall intensity must exceed soil infiltration capacity to produce runoff, and consequently to wash surface soil away. However, the role of runoff in soil erosion is often easier to visualize tha[illegible] to measure in the field, not to mention be [illegible]ized to improve Singh's system.

As mentioned in the method section, plot runoff and infiltration rate were highly negatively correlated ($r^2 = -0.93$) because of the method employed to obtain the latter. This high correlation induced rejection of infiltration in the stepwise regression calculations when both variables were included. Although the results showed unanimously that plot runoff gained number one priority, it does not mean that infiltration rate was not important. Actually, infiltration should be equally descriptive to soil loss since the variable itself was inherently correlated with surface runoff. In addition, infiltration rate is a more practical parameter to use for erosion prediction because it is easier to measure. Fortunately the rejection effect can be avoided by subjectively selecting independent variables.

Based upon this idea, further stepwise regression calculations were made without runoff and rainfall intensity data to derive a practical empirical equation. As expected, infiltration rate became the most important single variable.

The results (Table 7) were still statistically satisfactory ($\alpha = 0.05$ level) though less precision was achieved. The regression equation (Eq.5) was simple in form and easy to apply. Only bulk density was needed in addition to the infiltration rate which alone explained 48% of total variance. However it should be kept in mind that the infiltration rate in equation 5 was measured on a harvested site (i.e. disturbed bare mineral soil). This supports Singh's idea of using infiltration rate as a measure of soil erosion, but not the site conditions involved in getting it.

$$\ln L = 7.120325 - 0.023818\ I - 0.662574\ D_b \qquad (5)$$

$R^2 = 0.56309$ **

$S_{y.x} = 0.27471$

$F = 36.73104$ **

TABLE 7. MULTIPLE REGRESSION WITH CURVILINEAR MODEL

(without runoff and rainfall intensity terms)

VARIABLE	SE B	Beta	Partial R	R² change	Sig.T
I	0.003	-0.931	-0.737	0.4771	0.0000
D_b	0.198	-0.379	-0.406	0.0860	0.0014

** significant at the $\alpha = 0.05$ level

Most of the complications arising from soil erosion studies stem from the technical difficulty of directly evaluating soil erodibility itself. Numerous factors have an effect on erodibility, but no single factor can be ranked as most significant. Generally speaking, soil strength, (i.e. erodibility) can be ultimately denoted by the characterstics of soil structure and soil texture as well as their interactions. In this study, parameters of soil structure and soil texture were selected and found to be the significant soil physical properties affecting soil erosion regardless of the kind of mathematic model employed.

This study showed that soil bulk density was the single most important soil physical property in explaining soil erosion. It explained 12 to 15% of residual variance after surface runoff. It is easy to obtain and often used to indirectly describe soil structure (Hillel 1982). A high bulk density indicates a closely interlinked, compact soil body which often exhibits greater resistence to breakdown resulting from raindrop impact or surface runoff. Along with some other structural parameters such as water-stable aggregate index, bulk density is often selected in various multivariate soil loss equations (Wischmeier and Mannering 1969; Klock 1982).

A soil with either high sand or clay content usually tends to be less erodible, because it needs greater dynamic force to move the sand or to separate the sticky clay. Therefore, silty soil is most erodible. Wischmeier *et al.*

(1971) developed a soil particle-size parameter for their USLE (M = product of silt% and sand+silt%). Through repeated studies, they found that the fine portion of sand acted much like silt in promoting water entrainment. Therefore, he reclassified the USDA particle-size classification by redefining silt (0.002 - 0.10mm) and sand (0.10 - 2.00mm) which led to the creation of the M factor and greatly simplified the original complex multivariate equation (Wischmeier 1969). The new classification is widely accepted for evaluation of soil erodibility. Application of the M factor to soils in Alberta is generally successful (Tajek *et al.* 1985). This study showed that the M factor was the third most important parameter in the first two equations. The partial correlation with soil loss varied from 0.29 to 0.33, which demonstrated the important contribution of soil texture to the variance of soil loss.

It seems to be common sense that soil erosion is directly related to slope angle since it increases the downslope component of forces acting on soil particles or a water body. However, slope angle showed less significance in this study than other factors, especially in the exponential models. The main reason for this is probably that all plot surfaces were well landscaped to reduce variability. Plot slope steepness only varied between 8 and 15% in this study. Therefore, it is understandable that such small variations in slope would tend to be of lesser significance.

Other independent variables excluded by stepwise regression were surface stoniness and soil moisture content. Stoniness was expected to be eliminated since it was zero on most cut-blocks of the Obed and Robb soil associations. But soil moisture content was excluded by the stepwise regression because of errors in soil moisture content determination. Plastic bags were used to transfer soil samples from field to measuring pans in the laboratory. Some soil stuck on the inside of the bag even after washing by water, which introduced an evident additional error to the measurement since the initial volume of each sample was small. This could have been avoided by using aluminium tins.

Nevertheless, all equations were highly significant in determining soil erosion. Compared with the results from ANOVA by using the solitary infiltration rate, the advantage of a multivariate expression was obvious to perceive. As such, hypothesis 3 was rejected as well.

3.4 WEAKNESS OF THE RATING SYSTEM

Soil erosion hazard is a function of complex interactions of such factors as erosivity, erodibility and site conditions. The main shortcoming of Singh's system lies in the fact that infiltration capacity obtained from the undisturbed forest floor was utilized as an index of soil erodibility. This affects the system in two ways. First, numerous studies (e.g. Meeuwig 1970, Siddle 1980 Donnelly and Shane 1986) show that forest cover and its litter cover are vital in maintaining infiltration capacity and soil stability. Under forested conditions or even after forest cutting, soil erosion will not usually occur as long as the litter layer is left intact. But once the forest floor is disturbed (i.e. by logging or soil scarification), soil physical properties including the infiltration capacity will usually be significantly altered. Since forest harvesting can create an entirely new microenvironment, it does not make sense to assume that relative differences among disturbed soil units (i.e. soil association in Singh's system) will follow the same pattern as before harvesting. Proof of this was offered by the previous regression results (Table 7). Since infiltration rate obtained on disturbed forest floor explained approximately 50% of soil loss variance in this study, a much better agreement between Singh's erosion hazard ratings and the actual ones would have been obtained if the data of infiltration capacity in Singh's system had been collected on harvested sites (i.e. disturbed bare mineral soil surfaces). Secondly, soil disturbance caused by silvicultural practices often exposes mineral soil to direct raindrop impact which results in splash erosion and surface crust, which tend to further impede infiltration. Raindrop impact, which was not covered in Singh's system, is considered a more important cause of erosion on logged areas than surface runoff (Brown 1980).

Forest type has been examined and used as an environmental indicator in many studies (Rice 1977, Winkler and Rothwell 1983). Singh in his system assumes forest cover, or vegetation in general, integrates and expresses the net interaction of climate and site. An example of this is the correspondence of vegetation with different climatic or physiographic zones. These kind of associations are useful when defining large regional zones, but become less precise for small scale applications such as soil typing for individual properties like erodibility. For instance, studies in Alberta (Dumanski *et al.* 1972) show lodgepole pine is indicative of dry, well-drained sites, and spruce of wetter sites. These are only relative differences between the species, both of which occupy a wide range of sites singly and jointly, where soil physical properties like erodibility vary greatly. Furthermore, the differences in site "wetness" between the species can be overshadowed by high soil moisture contents on most harvested sites.

As mentioned earlier, a soil association, defined as a group of closely interrelated soil series developed on similar parent materials and under essentially similar climates, was named according to lithologic differences in soil parent materials (Dumanski *et al.* 1972). Soil associations, like forest cover types, are broad classifications based on lithologic materials (parent materials), but not weathering processes, which can produce similar soils among and within associations. Soil associations are good at reflecting certain pertinent aspects of the landscape (Dumanski *et al.* 1972), but are very limited in distinguishing other environmental parameters affecting soil profile development. As such, soils in a given association may undergo different weathering under various topographic positions, different kinds of slope and drainage conditions and may not necessarily be the same in terms of erodibility. Consequently, soil association is not a strong indicator of soil erodibility which varies widely from spot to spot.

3.5 IMPROVEMENT OF THE RATING SYSTEM

Singh's method probably could be improved by increasing the degree of stratification. Consideration of subgroups within the Dumanski *et al*. soil associations would be good, as they are classified on the basis of relative proportions of dominant and significant soils. These subgroups are often indicative of landscape types as various soil profiles are often associated with differences in topographic position and related drainage conditions, and the kind and frequencies of slope. Since forest cover type in Singh's system proved to be least important (Section 3.2, Table 3), it would be wise to shift attention to soil subgroups or other site conditions. Unfortunately, further confirmation of this point can not be made from this study because the replicates on soil subgroups were insufficient to make a valid comparison.

Another step would be to use multivariate expressions of erosion as a substitute for the solitary infiltration index. In section 3.3, three empirical equations (Eq.3 and Eq.4) were offered to express soil erosion. Because difficulty in obtaining plot runoff data would hinder their application to improve Singh's system, Eq.5 was suggested as the final multivariate expression.

Once infiltration rate on bare mineral soil and bulk density are known, Eq.5 can be readily applied to give an approximate assessment of erosion hazard. Doubtless, increasing sample size could improve the precision and the reliability of soil hazard prediction. No matter where Eq.5 is applied (eg. on a further stratified unit or simply a cut-block), an adequate sample size is always imperative to draw the correct inference. Further studies by testing Eq.5 to various sites are required to increase the database and improve the prediction of erosion hazard.

Chapter 4

CONCLUSIONS

Field experiments with a hierarchial design were conducted in compliance with Singh's erosion hazard rating system in Hinton, Alberta. A portable rainfall simulator was employed to generate soil splash and wash erosion on sixty deliberatly prepared, bare mineral soil plots. Comparisons between observed soil loss and predicted by Singh's method showed no agreement. Little difference between Singh's soil-by-vegetation stratifications but great variability within the single stratification were found. The analysis of variance further confirmed these observations and led to the rejection of Singh's method.

Although Singh's idea of equating soil loss to the inverse of infiltration rate was supported by the multivariate analyses, the site conditions involved in obtaining infiltration data were found to be inadequate and were believed mainly responsible for the failure of the system.

Improvements to the system were studied by deriving a series of multivariate expressions which all gave much better estimates of the real soil loss, and by measuring infiltration rate on disturbed sites with bare mineral soil. Major conclusions drawn from the study were twofold:

(1) The current erosion hazard rating system for western

central Alberta (Singh 1983) is quite weak in terms of predicting soil erosion hazard. Great unexplained variation in erosion hazard is anticipated when applying the system.

(2) Multivariate expressions with better descriptive variables can significantly increase the accuracy and the reliability of erosion hazard rating.

The study also calls for a higher level of stratification upon the system itself. A concise multivariate empirical equation with two easily obtainable independent variables (infiltration rate and bulk density) was recommended to replace the erosion hazard ratings in Singh's system. The equation was statistically significant.

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Appendices

(1) BRIEF DESCRIPTIONS OF 3 SOIL ASSOCIATIONS.

Descriptions are excerpted from Soil Survey and Land Evaluation of the Hinton-Edson Area, Alberta (Dumanski, *et al*. 1972).

The **Marlboro association** consists chiefly of Luvisolic soils developed on medium-to fine-textured Marlboro till of Cordilleran source. The parent material of the Marlboro association is an olive brown to yellowish brown colored till which is friable and moderately stony. Most of the Marlboro association occurs on topography which varies between moderately rolling and strongly rolling. Soils of the Marlboro association are mapped as having loam, sandy loam or sandy clay loam surface horizens, and clay, clay loam or sandy clay loam subsurface horizens. There are seven mapping units for the Marlboro association.

The **Obed association** is made up of a collection of Gray Luvisol soils developed on medium-to coarse-textured Obed till. The till is of Cordilleran origin. It is sandy, olive brown to grayish brown in color and slightly plastic when moist. It is commonly very stony, containing pebbles and cobbles which are generally well rounded, less than two inches in diameter. Topography of the Obed association usually varies between gently rolling and strongly rolling. Isolated, eroded cliffs and scarps exhibit very steeply sloping to extremely sloping topography. Obed soils generally have sandy loam textures in the surface horizens and sandy clay loam textures in subsoil. There are four mapping units for the Obed association.

The **Robb association** consists of a collection of Gray Luvisols and Eutric and Dystric Brunisols developed on parent materials that are generally shallow and made up of mixtures of till and colluvium. It is grayish brown to olive brown in color, friable, and slightly plastic when moist. It is generally moderately to very stony. Topography commonly varies from moderately rolling and strongly rolling to hilly, but local areas may be as smooth as gently rolling, or as rough as very hilly. The Robb soils have sandy loam to loam surface horizens and clay loam to sandy clay loam subsoil horizens. There are six mapping units for the Robb association.

(2) FIELD DATA AND SOIL ANALYSES

Plot numbers were composed of 3 parts. The first part is name of working circle (CP = Cache Percotte, AT = Athabasca, MC = McLeod). The second part is soil by forest combination (O = Obed, R = Robb, M = Marlboro, S = spruce-fir, P = pine). The third part the serial number. The meaning and units of the symbols were specified in the List of Symbols.

PLOT NO	t	RO	I	PPT	S	STO	DD	SMC	M
CP-OS-1	67.1	4.2	61.2	88.3	15	0	1.30	58	3961
CP-OS-2	189.2	7.7	40.3	88.7	15	0	1.29	65	4096
CP-OS-3	80.8	2.8	82.5	102.1	15	0	1.23	112	3136
CP-OS-4	206.4	9.4	40.7	106.7	15	0	1.44	43	4761
CP-OS-5	159.2	4.5	65.0	95.7	9	0	1.03	106	2809
CP-OS-6	365.6	9.5	34.7	102.3	12	0	1.31	85	8280
CP-OS-7	337.4	10.0	28.9	101.1	14	0	1.22	69	4761
AT-OS-8	355.5	11.6	21.4	105.0	10	58	1.82	25	7275
AT-OS-9	334.3	11.8	17.4	103.1	1[illegible]	38	1.73	34	7462
AT-OS-10	353.6	11.8	17.3	102.0	11	2	1.70	35	7110
CP-OP-1	115.2	8.0	56.1	112.9	9	0	1.28	54	6734
CP-OP-2	201.0	9.1	31.9	96.4	13	0	1.25	45	5888
CP-OP-3	229.1	10.6	25.0	100.8	9	0	1.56	35	4785
CP-OP-4	214.9	10.6	24.2	99.5	10	22	1.51	49	6786
CP-OP-5	319.3	12.2	14.8	100.8	13	22	1.56	35	4970
CP-OP-6	336.4	11.8	17.0	100.8	10	0	1.51	49	6800
CP-OP-7	178.9	9.1	36.2	102.0	13	1	1.51	49	5130
AT-OP-8	300.6	11.1	25.2	105.1	9	112	1.74	18	6696
AT-OP-9	166.7	10.9	25.2	103.5	4	18	1.77	26	7680
AT-OP-10	212.1	11.1	24.4	101.7	7	7	1.65	9	5032
MC-RS-1	237.4	11.0	48.0	127.1	5	0	1.79	29	3364
MC-RS-2	307.3	11.6	26.3	108.8	10	0	1.72	27	6557
MC-RS-3	307.2	12.1	20.8	106.6	11	0	1.72	29	6723
MC-RS-4	175.6	10.4	27.2	101.7	10	0	1.89	29	7056
MC-RS-5	244.4	12.3	17.9	106.1	8	0	1.97	24	6384
MC-RS-6	165.7	10.9	32.4	110.9	8	0	1.94	25	7221
MC-RS-7	122.4	5.5	62.3	101.7	13	117	1.71	38	3900
MC-RS-8	196.9	12.6	11.4	95.6	11	86	2.10	16	4048
MC-RS-9	262.6	12.0	16.9	102.9	13	133	1.78	21	4050
MC-RS-10	249.3	11.6	18.6	101.4	12	102	1.79	26	5096
MC-RP-1	154.6	11.1	30.1	100.9	9	0	1.86	30	4096
MC-RP-2	58.3	4.2	48.3	78.1	9	0	1.83	32	4356
MC-RP-3	267.5	13.5	11.8	108.1	10	0	1.83	31	4356
MC-RP-4	260.4	11.0	25.4	103.0	9	0	1.86	27	2601
MC-RP-5	219.8	11.7	22.0	100.7	9	0	1.76	29	1681
MC-RP-6	262.9	12.4	12.1	97.4	12	0	1.72	41	4900
MC-RP-7	238.8	13.3	6.3	98.6	11	0	1.80	58	4154
MC-RP-8	286.2	12.0	14.3	100.1	11	6	1.62	38	5952
MC-RP-9	322.0	12.2	13.3	101.0	11	0	1.67	28	6603
MC-RP-10	314.5	12.3	11.7	93.4	11	3	1.95	24	7008
AT-MS-1	248.1	12.6	14.2	103.6	9	31	1.82	26	5544
AT-MS-2	161.7	11.6	15.1	98.4	9	48	2.03	17	4312
AT-MS-3	167.3	11.9	13.7	99.4	9	61	2.03	16	4624
AT-MS-4	221.2	12.4	15.7	100.6	9	29	1.92	18	4005
AT-MS-5	132.6	11.1	20.9	100.9	7	82	1.79	24	4508
AT-MS-6	175.1	12.0	11.9	96.2	7	67	1.75	28	3102
AT-MS-7	261.0	11.0	20.2	99.6	8	3	1.95	18	5476
AT-MS-8	228.2	11.0	15.6	95.2	14	48	1.79	29	5418
AT-MS-9	323.2	11.6	14.7	97.8	10	63	1.76	35	6210
AT-MS-10	262.1	11.3	15.4	94.6	9	122	1.89	24	6480
AT-MP-1	255.4	11.5	23.1	106.0	13	211	1.83	23	5310
AT-MP-2	355.9	12.6	11.5	102.0	9	16	1.85	23	6956
AT-MP-3	347.6	13.6	4.4	89.4	13	131	1.92	19	2280
AT-MP-4	247.5	11.7	14.2	97.0	13	6	1.83	23	4186
AT-MP-5	277.1	12.9	9.2	100.0	9	33	1.85	23	4824
AT-MP-6	184.8	11.7	12.9	96.5	8	135	1.92	30	6188
AT-MP-7	328.8	12.6	16.4	106.4	9	31	1.96	22	4761
AT-MP-8	290.5	10.8	19.5	94.8	12	12	1.55	24	4761
AT-MP-9	260.1	11.9	12.9	95.9	12	46	1.61	20	3480
AT-MP-10	97.8	7.4	46.2	99.7	12	15	1.53	32	5808