Research Technical Completion Report
Project A-070-IDA

FROZEN SOIL EFFECTS ON THE EROSION HAZARD

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ABSTRACT

An examination of past erosion events shows that erosion and sediment yield affected by frozen soil are usually worse than that occurring on unfrozen soil. The objectives of this project were to determine if these observed differences were real or not and also if the severity of erosion in the early winter had any effect on the severity of erosion in the late winter or spring. The changes in surface roughness of three plots were determined as a function of freeze thaw cycles.

Runoff energy and sediment yield were classified as to whether they occurred on frozen, thawing or unfrozen soil. It was found that there were significant differences in runoff energy and sediment yield from snowmelt or rainfall on frozen or unfrozen soil. Sediment yield from runoff occurring on thawing or frozen soils was the same and was significantly different from rain on unfrozen soil.

A principal component and cluster analysis of runoff energy, sediment yield and freeze index showed that there is no statistical relation between the runoff energy, freeze index or sediment yield in the spring and winter but that sediment yield in winter is affected by the runoff energy and freeze index (thawing ground tends to increase sediment yield) in winter with spring sediment yield is determined by the spring runoff energy.

Random roughness on south facing plots decreased to a base level faster than other aspect plots but all plots approached the same base level roughness regardless of orientation.

I. Introduction

Soil erosion affected by frozen ground is a major conservation problem in the Pacific Northwest. During winter and early spring, prolonged precipitation combined with low evapotranspiration losses results in high soil moisture in this region. During this non-growing season, when the temperature drops below freezing, most bare soils are inevitably frozen. Frost may penetrate to a depth of 30 cm or more, permeability is commonly decreased and runoff increased with implications for flooding and soil erosion.

Mass movement of this soil often occurs on supersaturated soils after the thaw when the lower soil profile is still frozen. This thawing layer is highly erodible and easily moved by gravity or runoff to the toe of a slope. Then stream flow can undercut these deposits and cause a very high downstream sediment yield.

If there is high erosion in the early winter, the chances of severe soil erosion in late winter might also be high because rill and runoff patterns become established early. On the contrary, if low erosion occurs in the early winter, there might also be low erosion in spring. This timing effect of soil erosion could be caused by the gradual formation of an erosion pattern such as rill network or soil clod breakdown by frost action, rainfall and runoff. If rill pattern development could be delayed or the clod breakdown slowed, then the onset of erosion could also possibly be delayed.

Temperature changes and frost action are often factors in the disintegration of soil clods. Freezing can produce frost expansion because of the growth of ice lenses between the soil particles. Thawing can soften the soil and reduce the shear strength of the soil. Alternate freezing and thawing of soil may cause either disaggregation or dispersion. As a result, the shear resistance of a soil clod will decrease. If rain or runoff occurs during the thaw cycle, dispersion of the soil clod may be accelerated.

Tillage practices create soil clods and affect the change of surface roughness during winter and spring. Soil clods are reduced in size by disking and harrowing and increased by moldboard or chisel plowing. The moisture content of the soil, frost action and different tillage practices play an important role in soil breakdown. The breakdown process through winter periods may influence the pattern of soil erosion in later spring because surface roughness can affect the amount of snow trapped, soil water storage, infiltration, soil temperature, and radiation balance. In this manner, surface roughness can influence runoff and soil erosion.

The basic principles of the soil erosion process are the same regardless of the presence of frozen soil. It consists of the processes of detachment, transport, and deposition. Frozen ground events are only one factor involved in these processes, but one which can create ideal conditions for runoff to cause severe soil erosion.

II. Objectives

Research on soil erosion on frozen ground is just beginning. Most frozen ground studies have concentrated on soil heaving and settlement while the studies of frozen ground and soil erosion are hard to find in the literature. This study will emphasize the finding and verification of facts and data dealing with soil erosion and frozen ground by analyses of historical data.

The purposes of this report are to analyze the various factors associated with soil erosion on frozen ground and to explain their effects. Specifically, the objectives are to determine:

A. The differences in soil erosion resulting from either snowmelt or rainfall events on either frozen or unfrozen soil.

B. The effect of the timing of a runoff event on the erosion resulting from that and subsequent events.

C. The change in surface roughness due to freeze-thaw cycles and moisture input with time.

III. Previous Studies

Jumikis (1977) defined frozen soil as a soil at or below the freezing temperature and with its voids completely or partially filled with ice and unfrozen water. So, frozen ground is a layer of frozen soil in the rooting zone of the soil profile. This layer is very active in freezing and thawing during the winter and early spring. It therefore plays an important role in the soil erosion process in the Pacific Northwest region.

A freezing index is calculated from the air temperature and can be used to predict frost pentration. It is defined as the accumulated sum of the daily average temperature below 0° C in degree days. A degree-day of soil freezing means that the average air temperature is -1°C for one day. The thawing index is defined as the inverse.

Snow is a good insulator to prevent frost penetration. Berggren (1943) showed that 10 cm of snow is sufficient to reduce the frost penetration into soil. When temperature rises above zero and persists for a period of time, the snowcover will melt and flow over frozen or thawing soil and can cause severe soil erosion.

There are different methods to predict frozen ground. U.S. Army Corp of Engineers (1949) developed a graphical relationship between the depth of freezing and the freezing index (degree-hour). Brown (1964) improved this graphical method by modifying it for different types of soil and soil moisture. Although the method is rough, it is easy to use and does not need many variables. Yen and others (1975) used a discriminant analysis with available climatological data input to identify frozen ground events but not penetration depth. Cary and others (1978) developed a physically based method to determine whether the soil was frozen or not using more weather variables than Yen and others (1975). Farnsworth (1976) used the frost penetration equation developed by the U.S. Army Corps of Engineers in a simulation model for predicting the depth of frost penetration but it requires much data. The frost penetration depth used by Farnsworth and used in the present research is:

$$D = \left[\frac{8.64 * 10^4 \ KF}{L + C\ (T_o + F/2t)}\right]^{1/2} \quad (1)$$

where:

D = frost penetration depth (cm)
K = thermal conductivity (cal/(cm sec C))
F = freezing index (degree-days)
L = average latent heat (cal/cm)
T_o = mean annual air temperature (C)
t = duration of the freezing period (days)
C = average volumetric heat capacity (cal/(C cm3))

The infiltration rate is also affected by frozen ground. Concrete frost especially can become a nearly impervious layer, reduce infiltration, increasing runoff, and possible causing soil erosion.

Soil moisture plays an important role in frozen ground. Willis and others (1961) reported that the soil moisture conditions in the fall under general winter weather conditions may affect depth of freezing, spring runoff, and moisture retention. Kuznik and Bezmenov (1964) reported that soil moisture greater than field capacity tended to reduce infiltration to zero when soil is frozen. Benoit (1973) showed that high soil moisture may decrease hydraulic conductivity due to freezing and thawing regardless of soil aggregate size or freezing temperature, but low soil water content will do just the opposite. But Hinman and Bisal (1973) found freezing and thawing tends to increase the hydraulic conductivity of high moisture contact clays and reduce the conductivity in loam soils. Also, they found that alternating freezing reduced the conductivity less in loam soils than a continuous freeze. Post and Dreibelbis (1942) showed that percolation decreased and ceased when frost depth was 8 cm or more because concrete frost usually developed below this depth.

There are three basic internal bonds in frozen soil. There is a purely molecular bond at the point of contact between the solid mineral particles of the soils, an ice-cement bond which is almost entirely responsible for the strength and deformation properties of frozen soils and structural-textural bonds which depend on the conditions of formation, shaping, and the subsequent existance of the frozen soils. There are contacts and cohesion between mineral particles and ice, and cohesion of the ice and film water. Therefore, ice-cement bonds are very important in the strength resistance in frozen soils. The internal bonds of ice are highly sensitive to changes in temperature. Above freezing temperatures can destroy the ice-cement bond and below freezing temperatures can increase the strength of frozen soil. Tsytovich (1975) showed that the mechanical-property instability of freezing, frozen, and thawing soils are due to:

A. The temperature variations in soils.

B. Changes in the state of stress in freezing, frozen, and thawing soils under the influence of internal and external factors.

C. Time under load, which governs stress relaxation and creep in frozen and thawing soils.

Two external forces exerted on frozen ground are rainfall and runoff. Rain or runoff not only transfers heat into frozen ground and gradually melts ice-cement bonds, but also transports soil particles by the impact of rain or tractive force of runoff. Lee (1979) used William's Modified Universal Soil Loss Equation in the Palouse Prairie and found that sediment yield in this region was underestimated when the soil was frozen or thawing (Table 1).

Thawing is accompanied by a drastic change in the texture of the soils. This affects soil permeability and compressibility. Tsytovich (1975) showed that the permeability of thawing ground with a high ice content is tens or hundreds of times greater than that of the same

Table 1: Predicted Measured Sediment Yields on Frozen Ground

(From Lee, 1979)

Watershed	Water Year	Year	Sediment Yield (Mg/ha) Predicted	Sediment Yield (Mg/ha) Measured	Condition
Missouri Flat Creek	1936	01/12-01/15	0.0895	0.2969	Soil froze at night & thawed during the day
	1936	02/25-02/29	0.2105	0.4557	
		03/01-03/06	0.5237	1.4678	Soil froze hard
	1937	03/06-03/09	0.2361	0.4649	Only part of watershed had frozen ground.
		03/10-03/11	0.1338	0.4369	
		03/12-03/14	0.0995	0.1821	
	1940	02/17-02/22	0.0024	0.0293	Ground frozen.
Thompson	1973	12/21	0.1518	1.1881	Ground frozen.
Pitzen	1940	02/08-02/11	0.1250	0.2497	Soil froze at night.
Naylor	1941	12/17-12/22	0.0672	0.2883	Ground frozen & mud on surface.
		12/26-12/28	0.0838	0.2218	Ground was frosty.

soils after thawing and it depends on the change in porosity due to compression. Soil thaws, becomes saturated, and will flow like a viscous liquid so that a thawing layer over a frozen layer can cause mass movement. Chamberlain (1974) showed that the deviation stress is least affected by changes in freeze-thaw cycles or time at low void ratios, but the greatest reduction in the deviation stress occurs during the first three freeze-thaw cycles.

Frozen ground is usually not uniformly distributed over a watershed. if it is present on 25 percent of the watershed, 12 percent of the total water equivalent in the rainfall and snowmelt becomes runoff and if 63 and 93 percent of frozen ground present in watershed, runoff increase to 41 and 53 percent of the total equivalent (Storey, 1955).

The soil temperature over a watershed can also vary considerably because of variations in soils, precipitation, wind, topography, etc. The southern slopes of a watershed receive more heat from solar radiation than northern slopes. Western slopes receive about the same energy as the eastern slopes. As a result of this, the southern slopes are drier than northern slopes. During the winter, north-facing slopes may be frozen for several months and soil on south-facing slopes experience freeze-thaw cycles almost daily. Shulgin (1957) showed that differences of soil temperature on southern and northern slopes increased with increasing slope, whereas on eastern and western slopes the reverse is true. He also showed that a soil surface with ridges is warmer than a level surface, but at night the ridges are cooler than a level surface.

Soil erosion by freezing and thawing may be accentuated by hillslope exposure, presence of swelling clays and density of vegetative cover. Mass movement can occur on all slopes, but is greater on the north-facing slopes because of the higher moisture content in the soil mantle and different soil profile. Haupt (1967) reported that a soil frost condition deteriorates rapidly during a rainstorm on bare soil. Soil losses from snowcovered plots are practically zero in the absence of soil freezing. Tigerman and Rosa (1951) in their observations of erosion from snowmelt in the mountains of Utah, also found that mass movement often occurred when the surface thawed over the frozen layer.

The Universal Soil Loss Equation (USLE) has been developed to predict average annual soil losses from sheet and rill erosion from individual fields. Hudson (1971) classified this equation into the power of the rain to cause erosion (Erosivity) and the ability of the soil to withstand the rain (Erodibility). The equation is:

$$E = RKLSCP \tag{2}$$

where:

E = average annual soil loss (tons/acre/year)
R = rainfall erosivity index
K = soil erodibility index
LS = topographic factor

C = cover and management factor
P = the support practive factor

Most conservationists try to fit this equation to their local conditions. McCool and others (1976) developed a modified R-index for snowmelt and rain on snow in the Pacific Northwest. They related the R-index to the 2 year, 6 hour precipitation, and the total December to March precipitation. Williams (1975) used runoff energy as an index to indicate erosion capability. His index is defined as the product of the volume and the peak flow of runoff for a single storm. He used this index to replace the R factor in the USLE and correlated it to sediment yeild instead of to soil erosion.

Soil erosion is the dynamic process of detachment and transport of soil by rainfall and runoff. The impact of raindrops and the flow of runoff are the major forces causing soil erosion. Meyer and Wischmeier (1969) divided the soil erosion process into a) soil detachment by rainfall, b) transport by rainfall, c) detachment by runoff, and d)transport by runoff. These four components are interrelated and constitute the upland soil erosion system. This model describes the soil erosion process on agriculture land and also can be expanded by introducing other components. Yoo (1979) expanded the model and connected it with the USDA Hydrograph Laboratory Runoff model. His erosion model can be used to help understand soil erosion on frozen ground. He used an index to indicate soil resistance and this index is a function of soil moisture. His equations are:

$$S = I_{PL} + (I_{WP} - I_{PL})[1 - (\frac{M - M_{WP}}{M_{PL} - M_{WP}})^{e1}] \quad M < PL \qquad (3a)$$

$$S = I_{PL} [1 - (\frac{M - M_{PL}}{M_{LL} - M_{PL}})^{e2}] \quad M \geq PL \qquad (3b)$$

where

S = soil erosion resistance index

I_{PL} = erosion resistance index at plastic limit (PL)

I_{WL} = erosion resistance index at wilting point (WP)

M = soil moisture content (volume percent)

e1 and e2 are exponents related to soil characteristics greater than one

LL = liquid limit (percent)

The corrected critical tractive force is expressed as:

$$T_{cc} = T_c (1 - e^{-S})$$

where T_c = original critical tractive force.

Freezing and thawing can detach soil particles but these remain on the interrill and rill areas. These particles in detachment storage can be transported by runoff water without requiring further detaching power. Some factors which affect the detachment storage are wetting and drying, freezing and thawing. When freezing soils may absorb moisture, the soil clods are broken down because of the changes of the soil resistance to detachment. Yoo

(1979) developed a model to evaluate the detachment storage capacity from freezing and thawing for rills and interrills. This model is:

$$D = D_{max} \left(\frac{T - T_f}{dh}\right) \Delta t \left(\frac{SM}{G1 + AWC}\right) CMCV \qquad T > T_f \qquad (4)$$

$$D = 0.0 \qquad T \leq T_f$$

where:

D = increment to detachment storage by thawing effect (Mg/ha)

D_{max} = maximum D by thawing at saturated soil moisture and no organic material effect

dh = degree-hour

T = temperature at the end of a time interval (C)

t = time (hour)

T_f = the thawing temperature of soil (C)

G1+AWC = total porosity in A horizon of soil profile (volume percent)

CMCV = overall effect of crop and mulch on erosion

If $T < T_f$, then thawing ends. He also used the average temperature of the previous seven days to identify the frozen ground and showed that the surface is frozen if the average temperature is below a critical temperature of surface freezing. The incremental detachment storage by thawing is added to total detachment in rills and interrill areas.

Soil erosion in upland areas is a major source of sediment yield downstream. Not all of the eroded materials are effectively delivered to the stream. The ratio of sediment yield to total sheet erosion is called the sediment delivery ratio. The rate of sediment delivery is dependent on sediment source, transport capacity of the stream and the distance of the sediment source from the stream, volume and velocity of water flow, the partical size distribution of eroded material, the deposition areas, and watershed characteristics. Frozen ground affects upland soil erosion and thus indirectly influences sediment yield downstream. The delivery ratio of the Pitzen watershed ranged from 10 to 29 percent, Naylor watershed from 9 to 18 percent, and Missouri Flat Creek from 5 to 12 percent (Lee, 1979).

Factors which affect the structure of soil are mainly dependent on the texture and moisture content of the soil. But temperature changes and frost action in winter are often the most important factors in disintegration of soil clods. Bisal and Nielson (1964) showed that large clods are broken down during winter by freezing and thawing. The net effect of frost action in most soils is that the final size of the clod is decreased and the erodibility of soil is increased.

Rainfall can transfer heat to frozen soil and accelerate soil clod breakdown. It also possess energy to detach and transport soil aggregates. Rainfall splash is mainly detachment of particles from clods which modifies the surface roughness. Ellison and Slator (1945) showed that the breakdown products can seal the pores of the soil surface and reduce infiltration. As a result, the amount of runoff increases.

There are two types of surface roughness formed by tillage practices. One is called oriented roughness which is characterized by furrows and ridges created by tillage and planting implements. The other is called random roughness which is characterized by the irregular occurrence of peaks and depressions (Burwell and others, 1966).

Surface roughness is directly reflected in the clod size and this can influence the exchange of energy and mass at the soil surface directly or indirectly (Linden, 1979). It also can cause resistance to water flow which would cause soil erosion. The depressions on a rough surface can store more water and trap more snow than a smooth surface so that infiltration is increased and soil erosion reduced. Conversely, increased roughness at higher wind speeds can enchance water losses because considerable turbulence and eddies develop within the roughened layer (Linden, 1979).

Burwell and Larson (1969) reported that moldboard plowing produced the highest random roughness and pore space on both Barnes and the Nicollet soils in Minnesota. The untilled treatment had the lowest random roughness and pore space. Therefore, infiltration affected by tillage practices should be considered if tillage is to reduce runoff and erosion.

Rain can detach and transport freshly tilled soil and make soil structure changes. It can decrease the roughness and total pore space of freshly tilled soils. Burwell and others (1966) reported that random roughness can account for 76 percent of the variation in precipitation excess required to initiate runoff.

A measure of random roughness can be computed from the microrelief data. Microrelief data are a mixture of the total effects of surface topography, tillage tool marks, and wheel tracks. Allmaras and others (1967) separated roughness into oriented and residual roughness. He defined the random roughness as residual roughness which is approximately equal to the standard deviation of the actual height measurement. Burwell and others (1963) found that the logarithms of microrelief heights approached a normal distribution more closely than using arithmetic heights. Allmaras and others (1967) split this logarithmical height into the components of the effects of slope, oriented tillage tool marks, and residual roughness. Their model is:

$$\ln (h_{ij}) = \mu + \alpha_i + \beta_j + e_{ij} \quad (5)$$

where:

μ = the average natural logarithm of height
α_i = the component of variation due to slope
β_j = the component of variation due to tillage tool orientation
e_{ij} = the residual variation among logarithmatic heights
h_{ij} = the height measured by rillmeter at the point (i,j)

The residual term is equal to:

$$e_{ij} = \ln(h_{ij}) - (\overline{\ln(h._j)} - \overline{\ln(h..)}) - (\ln(h_i.) - \ln(h..)) \quad (6)$$

where:

$\ln(h..)$ = the average of the logarithms of heights
$\ln(h._j)$ = the average of the height along tillage for the j-th tillage tool mark
$\ln(h_i.)$ = the average height perpendicular to the row for the i-th

The random roughness index, S2, can be computed by:

$$S2 = \bar{h}\ S1 \qquad (7)$$

where:

$S2$ = the standard error among unlogged heights

$S1$ = the standard error among logarithms of heights

$\bar{h}$ = the mean height.

The effect of surface roughness on runoff can be shown in the following equation.

$$\frac{V}{V^*} = 6.06 \log \left(\frac{R}{x}\right) \qquad (8)$$

where:

x = resistance parameter

V = the mean velocity

V^* = the shear velocity

R = hydraulic radius.

Kruse and others (1965) correlated x to the standard deviation of equally spaced measurements of roughness height along the longitudinal profile. They obtained:

$$x = 12.9S^{1.66} \qquad (9)$$

where S is the standard deviation of roughness height. Equation (9) still needs to be evaluated with field data at each site in order to meet local conditions.

IV. Study Areas

The historical data for this research were obtained from the Pitzen, Naylor, Missouri Flat Creek, Cow Creek, and Little Potlatch Creek watersheds which are in the Palouse region of Idaho and Washington. The University of Idaho Plant Science Farm was selected for the tillage and the surface roughness field experiment site. The location of these watersheds is shown in Figure 1.

A. Frozen ground and soil erosion in Palouse Basin.

The Palouse Basin of eastern Washington, northern Idaho, and northeast Oregon, is a highly productive dryland agricultural region. It has a steep rolling, dune-like topography. The south and southwest facing slopes are longer and not as steep as the north and northeast facing slopes. Winter is cool, cloudy, and wet. A minimum temperature of -37C has been recorded but the minimum temperature drops below -20C on only a few days each winter; lengthy cold periods are rare. Frequent subfreezing temperatures often cause the top several cm of soil to freeze. Over 60 percent of the annual precipitation of 501 mm (1936-42) occurred during November to March and one-sixth fell as snow. With these conditions, high soil moisture results each winter. Concrete frost develops easily under the unprotected soil surface when the temperature is below

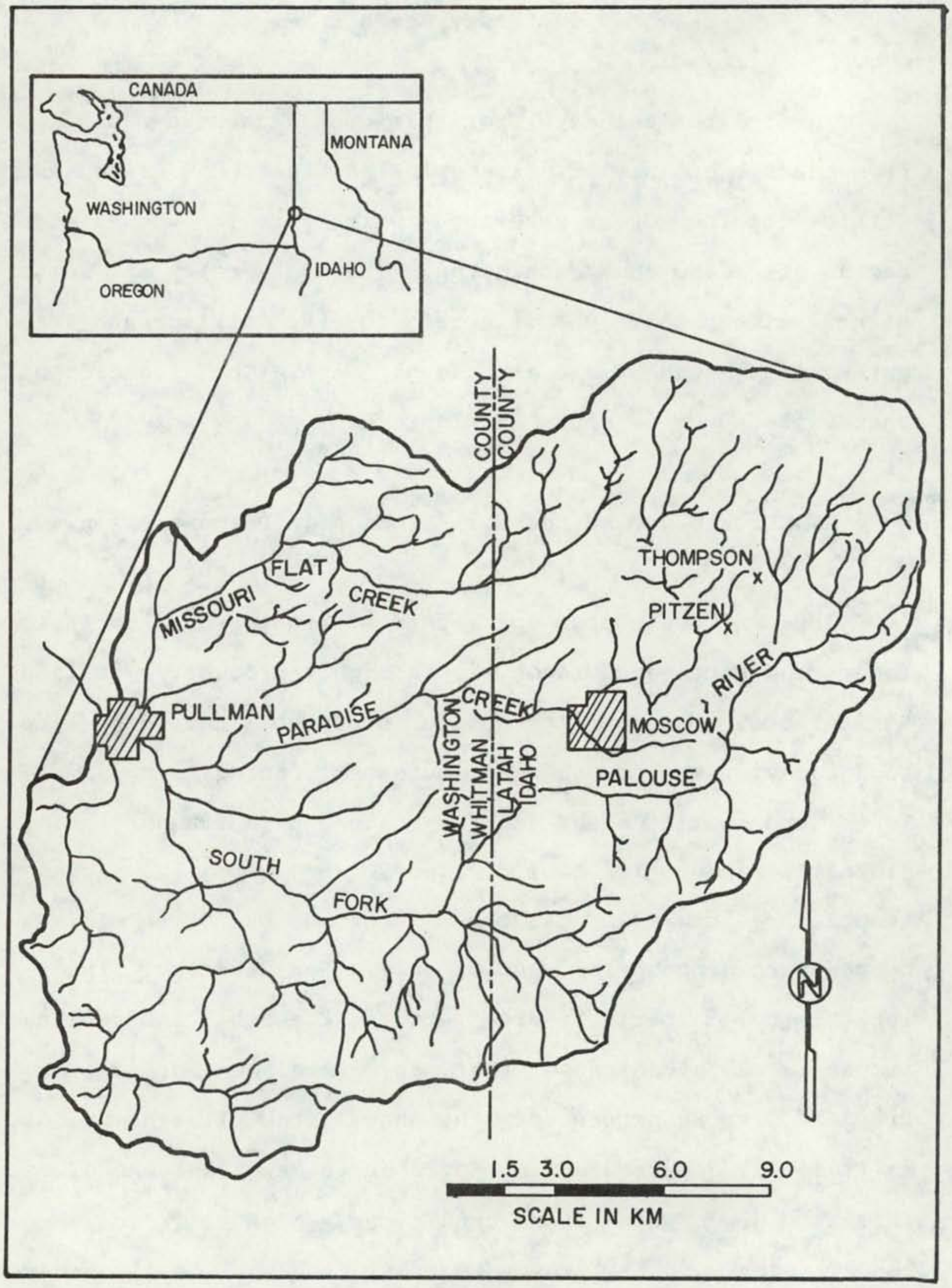

Fig. 1 --Location map of the test watersheds

freezing and persists for any length of time. When warm, moist air masses move through the area in early spring or late winter, the rain or melting snow or both on frozen ground causes soil erosion. The most critical period for soil erosion is during the late winter or early spring when melting snow or storms of high rainfall intensity occurs on these wet and thawing soils.

The amounts of soil erosion are influenced by the steep topography, temperature, rainfall intensity, and farming systems. Sheet and rill erosion on cropland account for over 90 percent of the basin's erosion (USDA, 1978). Annual erosion rates in the western (300-380 mm precipitation zone) and eastern (over 460 mm precipitation zone) portions of the basin average over 4.4 Mg/ha while the central portion averages 4.3 Mg/ha. An average of 12.7 Mg/ha/yr was eroded from the hilltops and upper parts of the south-facing slopes, where the soils are shallow. These steep areas, which account for only 25 percent of the cropland, produce over 50 percent of the erosion in the basin. Erosion rates on rangeland areas average less than 1/2 Mg/ha/yr and forested areas in the mountainous eastern Palouse average less than 180 kg/ha/yr. Gully erosion, though locally serious, accounts for less than one percent of total erosion. Mass movement occurring after a spring thaw may remove as much as 270-540 Mg/ha of soil from a limited spot and cause farming difficulty.

B. General description of study watersheds.

The mean monthly temperature, precipitation, and snowfall for winter and spring for the period 1931 to 1960 at Pullman are shown in Table 2. Pullman data were used for all analyses for Missouri Flat Creek while Moscow data (Table 2) were used for all other analyses.

Table 2: Winter Climate of the Palouse

Month	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	April
	Pullman, Washington (1931-60)						
Temperature (C)	9.6	2.8	-0.1	-2.6	-0.3	3.4	7.9
Precipitation (mm)	30	63	70	68	53	54	38
Snowfall (cm)	0.8	9.6	23.4	35.0	24.6	14.0	2.0
	Moscow, Idaho (1938-1979)						
Temperature (C)	9.4	3.0	-0.3	-2.2	1.1	3.7	7.8
Precipitation (mm)	50	74	81	74	57	51	49
Snowfall (cm)	0.8	13.7	33.3	43.4	23.1	12.7	2.0

Table 3. Physical characteristics of the study areas.

	WATERSHED				
	Pitzen	Naylor	Cow Creek	Missouri Flat Creek	Little Potlatch Creek
Area (ha)	59.4	71.8	2468	7123	551
Aspect (°)	210	202	170	225	100
Slope (%)	11.7	10.4	8.0	10.8	17.0
Drainage density (m/ha)	46.2	40.8	5.7	9.2	5.9
Relief/ length (m/km)	61	34	33	22	76
Shape factor	0.59	0.40	0.26	0.32	0.41
Maximum elevation (m)	867	856	1130	975	1080
Minimum elevation (m)	808	810	830	731	855

The coldest months are December, January, and February. Snowcover remains on the ground more than half the time between the middle of December and the end of February. Sunshine duration during each month ranges from 20 to 30 percent in winter and 50 to 60 percent in spring and fall. In winter, relative humidity ranges from 90% at night to 80% during the day (Horner & others, 1944). Some characteristics of all study watersheds are shown in Table 3.

1. Pitzen and Naylor Watersheds.

Pitzen watershed is located 4.8 km northeast of Moscow. Naylor watershed is west of Pitzen and located 2.8 km north of Moscow.

The predominant soil type on these two watersheds is Thatuna silt loam. During 1937-1941, tillage was mainly disc-plow, which left considerable straw on the surface. The use of a moldboard plow on dry ground in the fall of 1940 left big clods and some stubble cover. The tillage between these two watersheds was much the same except Naylor had more stubble standing during the winter.

2. Cow Creek and Little Potlatch Watersheds.

Cow Creek watershed is located approximately 8 km southeast of Moscow, Idaho and south of Paradise Ridge. It flows in a southerly direction through the town of Genesee. Then it turns to a westerly direction and joins Union Flat Creek in Washington. The Little Potlatch watershed lies adjacent to the northeastern boundary of the Cow Creek and is tributary to the Potlatch River.

The soils in the Cow Creek and Little Potlatch Creek watersheds are the Naff-Thatuna-Palouse-Tilma group and are considered to be well drained and highly suitable for agriculture.

3. Missouri Flat Creek Watershed.

Missouri Flat Creek is located northeast of Pullman, Washington. It originates on the western slope of Moscow Mountain, north of Moscow, Idaho, and flows in a westerly direction, joining the South Fork Palouse River at Pullman. The length of the principal drainage way is 25.75 km and consists of Palouse silt loam soils.

4. Plant Science Farm.

The field plots are located on the University of Idaho Plant Science Farm, east of Moscow. The average annual precipitation is 533 mm; annual air temperature is about 8.9 C, and average frost-free period is about 140 days. The soil is a Palouse silt loam. The surface layer is dark grayish brown silt loam 38.1 cm thick. The wilting point of 0-20.3 cm depth is 11.1%. Field capacity in this depth is 25 percent. The porosity is 47%. Permeability is moderate. Available water holding capacity is high. Effective rooting depth is 152 cm or more. The potential frost action is high. The slope in this area is 5-7 percent.

The experimental plots are arranged as 4 treatments and 3 plots in each treatment. The four treatments and plot aspects are:

1.	Moldboard plow-disk-harrow	east
2.	Moldboard plow-disk-harrow	south
3.	Chisel plow	northeast
4.	Moldboard plow	north

V. Methods and Procedures

The events on Pitzen, Naylor, and Missouri Flat Creek were used for comparing the differences in sediment yield from rain, snowmelt, or both on frozen or unfrozen ground. The sampling periods for the watersheds range from 1939 to 1941 for the Pitzen and the Naylor watersheds and from 1935 to 1942 for the Missouri Flat Creek. The basic units used for this study were the runoff volume, peak flow, and sediment yield for a single event. The volume and the peak of runoff are considered as a potential factor causing the sediment yield as outlined by Williams, 1975. The various combinations of soil and moisture sources are given in Table 4. Of the nine categories shown, only seven were found in this study. The purpose of this classification was to determine the differences of the sediment yield among the seven categories so that Objective 1 can be answered. The data used for the classification were obtained from the reports of Pitzen, Naylor, Missouri Flat Creek, and other references (Potter and Love, 1942; Horner and others, 1974). Portions of the frozen ground data were obtained from field observations as recorded in non-published notebooks, and portions were computed by using the Corps of Engineers (1949) frost penetration equation. Whether the runoff is from snowmelt or not was judged from the snowcover and the air temperature. Precipitation, air temperature, and snowfall were obtained from the State Climate Data Base. A total of 124 events for Pullman, Washington and Moscow, Idaho were used for the multivariate analysis of variance.

Table 4. Event Type Classification and Frequencies.

Source of Runoff	Frozen	Ground Conditions Thawing	Unfrozen
Snow Melt	19	--	24
Rain	6	19	16
Rain-on-Snow	30	--	10

A. Multivariate Analysis of Variance.

The severity of erosion on a watershed is affected by frozen ground, rainfall, runoff, steepness, length of slope, soils, and land. Frozen ground can create a favorable environment for rain, runoff, or gravity to detach and transport soil. The separation of the various causative factors from other associated factors is one of the objectives of this study.

The model which is subjected to the multivariate analysis of variance is:

$$X = A\ \mu + \varepsilon \tag{10}$$

where:

$X = N \times 2$ matrix. 2 variables (runoff energy and sediment yield), N observations ($N = 124$).
$A = N \times (K+1)$ design matrix

(K = 7) containing only ones and zeros.
μ = (K+1) x 2 matrix, each containing the effects of 7 categories; 1 general mean for each category.
ε = N x 2 error matrix.

If a significant difference is found anywhere among the seven catagories, then a pairwise test among the seven catagories must be made. The pairwise test was done by constructing a confidence interval around each point using the method described by Morrison (1967).

The advantage of multivariate analysis of variance is that it can separate the covariance of the sediment yield and the runoff energy. This helps avoid interference between these two variables.

B. Principal Component, Cluster and Causal Analysis.

Principal component analysis is used here to reduce 6 variables (Table 5) into two variables or principal components so as to plot a scatter graph in two dimensions. Then from the scatter graph, initial clusters or groupings can be determined for cluster analysis. Cluster analysis can also help explain the implicit meaning of each principal component from the factor score of the variables.

Cluster analysis is used to find possible patterns in the 16 station years of available data, each year being described by the six variables of Table 5. The desired pattern is the possibility that higher than normal fall runoff or sediment yield will be followed by higher than normal spring runoff or sediment yield. Then, principal components and causal analysis can be used to determine the physical implication of this finding.

Table 5. Variables for the timing study.

	SEASON WINTER	SEASON SPRING
Sediment Yield	Sw	Ss
Runoff Energy	Ew	Es
Freeze Index	Fw	Fs

1. Principal Component Analysis.

Principal Component Analysis has as its purpose to do an orthogonal transformation from highly correlated original variables to a smaller number of the uncorrelated or poorly correlated variables (principal components) and still retain the largest portion of the total response variance. More detail information can be found in Morrison (1967).

2. Cluster Analysis.

Cluster analysis is defined as the classification of objects or observations according to indices of alikeness or affinity between pairs of observations.

The index of alikeness can be expressed in different ways. The covariance distance matrix was used in this study. This equation is:

$$d_{ij} = (X_i - V_j)\ A_j\ (X_i - V_j)' \quad (11)$$

where:

d_{ij} = the closeness between the ith observation and the jth centroid of cluster.
X_i = the ith object vector and contains 6 elements in this study. It is a column vector.
V_i = the centroid of the jth cluster.
A_j = the covariance matrix for the jth cluster.

The variables used in this analysis are listed below.

Ew is the runoff energy in winter.
Es is the runoff energy in early spring.
Sw is the sediment yield in winter.
Ss is the sediment yield in early spring.
Fw is the freezing index in winter.
Fs is the freezing index in early spring.

There are many methods of cluster analysis. The selection of a suitable method is dependent upon the structure of and the knowledge of your own data. According to Dubes and Jain (1980), classify clustering into nonexclusive and exclusive processes.

Exclusive classification is defined as a pattern belonging to only one cluster such as a person in either a male or female. Nonexclusive classification allows each pattern to belong to several clusters such as one person can have several diseases. Fuzzy clustering is a combination of these two where there is a probability of being assigned to either method.

Fuzzy clustering was used in the classification of the pattern for the 16 observations. In conventional clustering, each pattern belongs to exactly one cluster in a partition, but in fuzzy clustering, each pattern is allowed to belong to several clusters. The original fuzzy set concept was introduced by Zadeh (1965). It is a method for modelling imprecise, vague, ambiguous phenomena such as hydrologic data which have overlapping or fuzzy classification possibilities.

The iterative algorithms used for fuzzy clustering were obtained from Gustafson and Kessel (1979). The initial cluster center is estimated from principal component graphs and the initial covariance matrix is taken as an identity matrix. The distance between any ith object and the jth cluster can be computed from Equation 11. Then d_{ij} can be used to calculated the membership function W(X_{ij}) (or W_{ij}). The equation is:

$$W_{ij} = \frac{1}{\sum_{n=1}^{K} (d_{ij}/d_{in})^{1/(\alpha-1)}} \qquad \alpha \geq 1 \tag{12}$$

where:

k = number of clusters
α = called "fuzziness" of the clusters ($0 < \alpha < \infty$)
d_{ij} = distance from eq. 11.

The range of α is 0 to ∞, but for all practical purposes, α will seldom be greater than 4. As α increases from 1 to 2 to 3, the fuzziness increases and the partioning becomes increasingly difficult. In this study, $\alpha = 2$ was used because it gave acceptable clustering. When approaches 1 each observation must be assigned to a single cluster (hard clustering). In this report, an observation (one station year) may have the characteristics of several classes. The class boundaries are not "hard" but rather are fuzzy. Fuzzy clustering gives recognition to the troublesome or outlying members of the data set because the degree of membership is continuous rather than discrete. Hard clustering is defined as:

$$W_{ij} = \begin{cases} 1 \text{ for } j = m \\ 0 \text{ for } j \neq m \end{cases} \qquad (13)$$

Here W_{ij} equals a membership function which is the weighting factor of observation i belonging to cluster j. If observation i belongs to cluster m, then W_{ij} is equal to 1, otherwise W_{ij} is zero.

Hard clustering assigns an observation to only one cluster. The sum of the total observations of the membership function is therefore equal to the number of observations for that cluster, N_j. The sample mean for a cluster, M_j, is computed in the standard manner.

Fuzzy partitioning, used in this study, is when $\alpha > 1$. K membership functions can be computed from Equation 12 for each observation so that

$$0 < W_{ij} <= 1 \text{ for all observations, } X_i \text{ and } 1 <= j <= k.$$

$$\text{then} \quad \sum_{j=1}^{k} W_{ij} = 1$$

The value of the membership function then determines the most probable cluster membership for that observation.

The objective function which is subject to $|A_j| = \rho_j > 0$ where A_j is the covariance matrix of 6 variables in Cluster 1 or Cluster 2 and is expressed in Lagrange form as:

$$F(W,M,A) = \sum_{i=1}^{N} \sum_{j=1}^{K} W_{ij}^{\alpha} d_{ij}(M) + \sum_{i=1}^{N} \lambda_i [\sum_{j=1}^{K} W_{ij} - 1] + \sum_{j=1}^{K} \beta_j [|A_j| - \rho_j] \qquad (14)$$

where λ_j and β_j are the Lagrange multipliers.

The minimization of function F with respect to membership function W, the centroid of the cluster, M, and the covariance distance matrix, A, will result in new weights, W_{ij}.

The fuzzy mean for j-th cluster is:

$$M_{fj} = \frac{\sum_{i=1}^{N} W_{ij}^{\alpha} X_i}{\sum_{i=1}^{N} W_{ij}^{\alpha}} \qquad (15)$$

The covariance, A_j, can be estimated by:

$$A_j = \left(\frac{1}{\rho_j |P_j|}\right)^{-1/n} P_j^{-1} \tag{16}$$

where:

n = number of variables in the observation matrix (6).

$|P_j|$ = the determinant of matrix P .

$$P_j = \frac{\sum_{i=1}^{N} W_{ij}^{\alpha} (X_i - M_j)(X_i - M_j)^T}{\sum_{i=1}^{N} W_{ij}^{\alpha}} \tag{17}$$

After this is computed, return to equation 11 and use the new M_j and A_j until convergence is reached.

3. Causal Analysis.

The causality of natural phenomena has two components: a cause and an effect. For example: sediment yield is a result of runoff energy. But it is ridiculous to state that runoff energy is a result of sediment yield. Therefore, the cause-effect is unidirectional and can be expressed as:

$$X \xrightarrow{p} Y \tag{18}$$

where X = a cause, Y = an effect, and p is the path coefficient.

If variables X and Y are standardized $((X-\overline{X})/S)$ then p can be determined by a correlation between X and Y. The regression form is:

$$Y = pX \tag{19}$$

Then

$$r_{xy} = \frac{1}{N} \sum^{N} XY \tag{20}$$

and

$$\frac{1}{N} \sum^{N} X^2 = 1 \tag{21}$$

and

$$P = r_{xy} \tag{22}$$

r_{xy} is the correlation and X's are define as in the cluster analysis.

These six variables shown in Table 5 are standardized individually. A positive freezing index means that the cummulative temperature is below freezing and a negative freezing index means that there is thawing taking place.

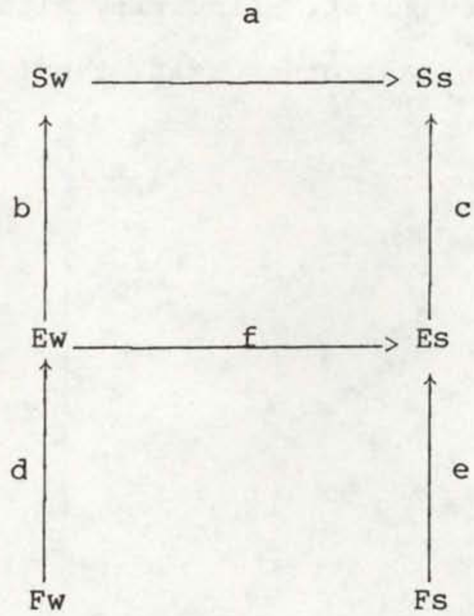

Figure 2. Causality model structure.

Four equations, derived from Figure 2, are shown below.

$$Sw = bEw \tag{23}$$

$$Ew = dFw \tag{24}$$

$$Ss = aSw + cEs \tag{25}$$

$$Es = fEw + eFs \tag{26}$$

Such variables as sediment yield during the winter (Sw) and the freezing index in the spring (Fs) cannot be related but may be considered only as instrumental or dummy variables if desired.

Outliers can affect the casual analysis. This is why cluster analysis is used first. Linearity also is a problem for this method as with many other statistical methods.

VI. Results and Discussion

The results of the procedures to attain the three objectives are given in this chapter each in a separate section.

A. Effect of Event Time on Sediment Yields

The event frequency is shown in Table 4. As an example, 19 events were caused by snowmelt on frozen ground.

The correlation coefficient between runoff energy and sediment yield was found to be 0.80. This correlation between the error of sediment yield and error of runoff energy is highly significant and shows that the covariance between these two variables should be separated.

Three methods were used to test for significant differences among the seven categories. The result of these three tests is given below.

(i) Hotelling - Lawley's trace test.
$F(12,230) = 28.76^{**}$

(ii) Pillai's trace test.
$F(12,234) = 12.67^{**}$

(iii) Wilks' criterion test.
$F(12,232) = 19.94^{**}$

** All three show highly significant differences among the seven categories at the 0.01 level.

The conclusion is that at least one of the seven categories is different from the other categories. It then becomes a question as to which two pairs among the seven have significant differences in sediment yield and in runoff energy. To answer this question, a multiple comparison test among the seven catagories was used.

Table 6. Multiple Test of Sediment Yield and Runoff Energy

	Log (S)	Log (E)
Snowmelt on frozen ground	-5.46bcd	-9.15cd
Rain on frozen ground	-5.99bcde	-9.58bcde
Rain-on-snow on frozen ground	-2.88a	-5.63a
Rain on thawing ground	-3.26ab	-6.33ab
Snowmelt on unfrozen ground	-10.29f	-15.32f
Rain on unfrozen ground	-8.06e	-11.78de
Rain-on-snow on unfrozen ground	-5.14bc	-7.96bc

S - sediment yield
E - runoff energy

Means with the same letter are not significantly different at the 0.05 level.

Table 6 shows that sediment yield and runoff energy resulting from rain-on-snow on unfrozen ground are not significantly different from those resulting from rain on thawing ground. The reasons probably are that rain on snow causes much runoff because the unfrozen ground is saturated. Infiltration is reduced by either frozen or saturated unfrozen ground and results in approximately the same sediment yield and runoff energy. Rain on thawing ground results in a saturated thawing layer lying above a frozen layer. As a result, the ranges of the sediment yield and the runoff energy in the above two cases overlap. But rain-on-snow on frozen ground has a significant difference in sediment yield and runoff energy from either snowmelt or rain on unfrozen or frozen ground.

The sediment yield caused by rain on thawing ground is not significantly different from that of snowmelt or rainfall on frozen ground or rain-on-snow on frozen ground but does have a significantly different runoff energy from snowmelt on frozen ground. The reasons might be that runoff from snowmelt is mostly of low intensity and low volume and the erosion resistance of frozen or thawing ground in these three cases is not statistically different. Rain on thawing ground shows significant differences in sediment yield and runoff energy from rain or snowmelt but not rain-on-snow on unfrozen ground. This confirms our expectations because the resistant strength and infiltration rate of the thawing ground are less than those of rain or snowmelt on unfrozen ground while the snow on the ground protects the soil from raindrop impact.

Runoff energy and sediment yield from rainfall on unfrozen ground is significantly higher than the case of snowmelt on unfrozen ground. The reason is that snowmelt for an event releases less volume of runoff at a lower rate than rain on unfrozen ground.

The sediment yield and the runoff energy caused by rain-on-snow on unfrozen ground shows no significant difference from that of snowmelt or rainfall on frozen ground. This might be due to the fact that rain-on-snow typically occurs on a nearly saturated soil just as in the case of rain on thawing soil.

Sediment yield and runoff energy from snowmelt on frozen ground is significantly different from snowmelt or rain on unfrozen ground because the resistance to erosion is lower and infiltration is higher in the latter two cases.

Another result of this analysis is that rainfall on frozen ground is not found to be significantly different from rainfall on unfrozen ground. This does not seem logical but can be explained by noting that unfrozen ground is usually saturated or very wet so that there is no significant difference from each other. The frozen soil also would be erosion resistant until the surface thawed when much erosion would being to occur. This type of event would be classified as rain on thawing ground.

B. Patterns of Sediment Yields Between Two Seasons.

This section addresses the question as to whether or not there is some timing effect in sediment yield. The main part of this section will concentrate on a pattern search for sediment yield relations between two seasons, winter and spring. The data include the events which were selected from the above three watersheds and additional data from Cow Creek and Little Potlatch Creek. There are a total of 16 station years from 5 watersheds. Each year was divided into two parts, the winter season (November to February) and early spring season (March to April). The reason for choosing these two periods is because the first significant events of the runoff season typically occur in December and frozen ground frequently appears in these months (December to February). March and April are considered the spring months.

From field observations in the winter season, we see that the severity of sediment yield in early spring may be caused by the residual effect of the sediment yield itself during winter. This hypothesis is based on the assumption that an erosion pattern such as rill network and soil clod breakdown etc. becomes established during winter and severe soil erosion will then occur if a threshold value of runoff appears.

The purpose of this study was to determine whether or not any type of timing effect exists between sediment yield in these two seasons. If no such pattern is found in the data, it does not mean that such pattern will never exist but only that it is not found in these limited data.

The analysis procedure is to first find a pattern cluster and then to search for causality among the 6 variables given in Table 5.

In order to find the initial possible clusters, the six variables were reduced to two principal components which were used to plot a two dimensional scatter graph. The approximate clusters are determined from this graph.

The two principal components which accounted for 68 percent of the total variance were selected. The equations are:

$$Y1 = 0.45Ew - 0.09Es + 0.51Sw + 0.10Ss - 0.45Fw - 0.56Fs \quad (27)$$

$$Y2 = 0.24Ew - 0.66Es + 0.15Sw - 0.64Ss + 0.25Fw + 0.12Fs \quad (28)$$

where Y1 and Y2 are the first and second principal components respectively.

The initial clusters were visually determined from a plot of Y1 versus Y2 (Figure 3).

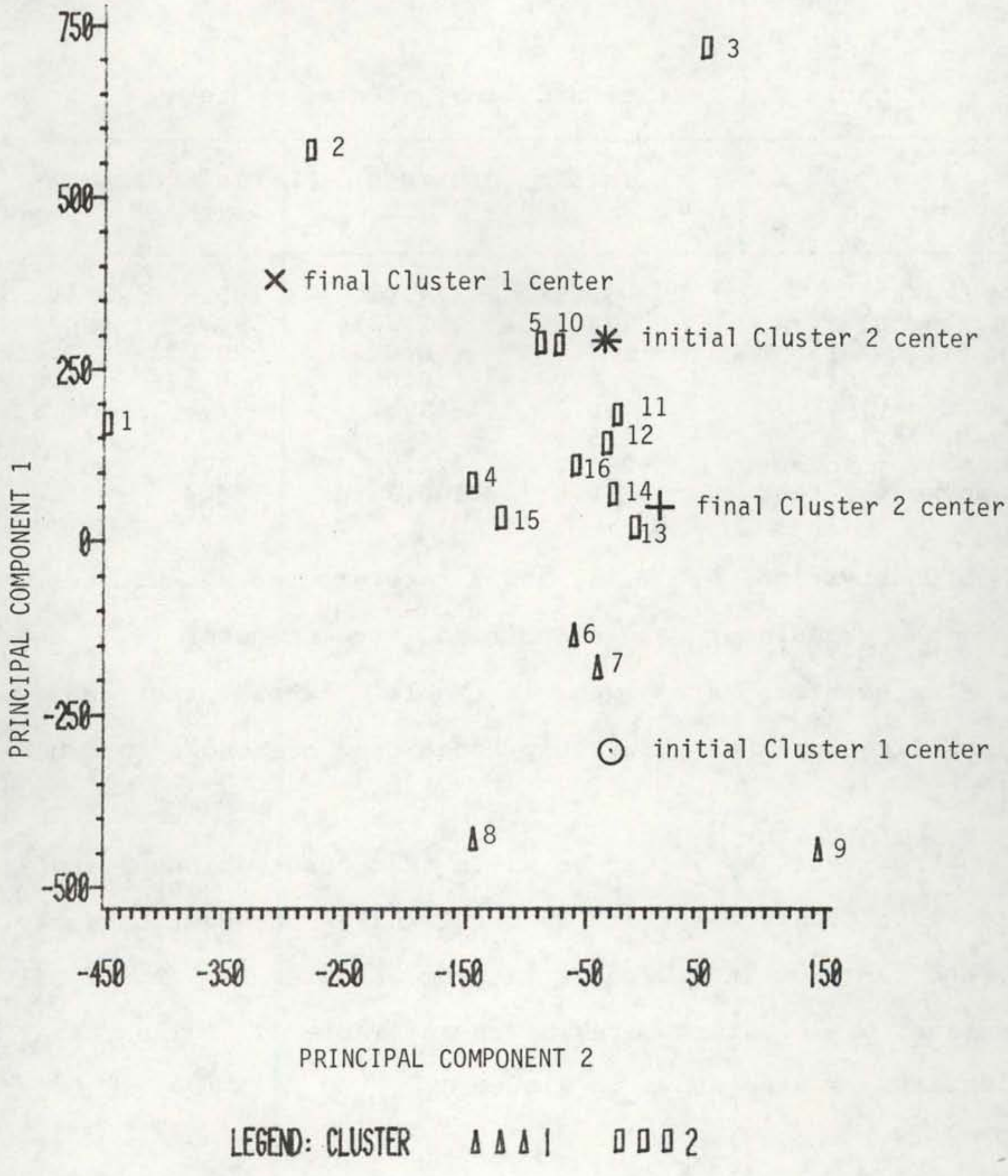

Figure 3. Principal component plots.

Table 7. Initial and final cluster centers.

Variable	INITIAL CLUSTERS 1	2	FINAL CLUSTERS 1	2
Sw (kg/ha)	36.93	174.11	295.9	113.3
Ss (kg/ha)	124.59	162.73	580.6	90.9
Ew (sq cm/hr)	0.014	0.022	0.033	0.018
Es (sq cm/hr)	0.038	0.053	0.126	0.037
Fw (C/day)	326.2	-19.4	-37.6	79.8
Fs (C/day)	325.6	-194.9	-274.3	-40.0
Component 1 Center	-298.2	222.9	363.5	53.4
Component 2 Center	46.4	-106.3	-366.4	-26.0

Observations 6, 7, 8, and 9 are grouped as Cluster 1 and the remainder are classified into Cluster 2. The cluster centers are given in Table 7 while the actual classifications and membership functions are shown in Table 8.

From Table 8, it can be seen that observations 1 and 2 move into Cluster 1 from Cluster 2 while observation 6, 7, 8, and 9 move into Cluster 2 from Cluster 1. The final centers of clusters are given in Table 7. The final clusters are also shown in Figure 3.

Table 8. Membership functions for all 16 observations.

Observation	Initial		Final	
	W1	W2	W1	W2
1	0.30	0.70	0.99	0.0002
2	0.23	0.77	0.98	0.02
3	0.31	0.69	0.05	0.95
4	0.12	0.88	0.05	0.95
5	0.05	0.95	0.01	0.99
6	0.77	0.23	0.02	0.98
7	0.82	0.18	0.02	0.98
8	0.91	0.09	0.04	0.96
9	0.92	0.08	0.04	0.96
10	0.07	0.93	0.02	0.98
11	0.06	0.94	0.01	0.99
12	0.10	0.90	0.01	0.99
13	0.24	0.76	0.01	0.99
14	0.14	0.86	0.01	0.99
15	0.20	0.80	0.05	0.95
16	0.08	0.92	0.01	0.99

Those observations that move from one cluster to the other are used in an adjustment procedure to minimize the covariance distance criterion.

It can be seen from Equations 27 and 28 that the increasing values for Ew, Sw, and Ss and lower values for Es, Fw, and Fs can increase the score of Principal Component 1 while higher values for Ss and Es and the lower values for Sw, Ew, Fw, and Fs can decrease the score of Principal Component 2. Thus, any observation which has high Ss and low freeze indexes (Fs, Fw) tends to be classified into Cluster 1. Therefore, Cluster 1 will tend to have high spring sediment yield and low freeze indices while Cluster 2 will consist of observations with high freeze indices, low runoff energy, and low sediment yield in spring. Cluster 2 can be subjected to further analysis but Cluster 1 cannot because of the lack of observations. All 16 years of data are shown in Table 9.

Table 9. Observation Used for the Cluster Analysis.

Obs.	Ew	Es	Sw	Ss	Fw	Fs	Cluster	Principal Components 1	Principal Components 2
1	0.0012	0.188	4.0	663.3	-38.8	-149.2	1	170.4	-451.6
2	0.0658	0.062	603.0	499.9	-38.7	-353.4	1	570.0	-281.6
3	0.0510	0.007	970.7	68.6	-45.6	-358.7	2	716.8	47.3
4	0.0012	0.256	0.2	201.1	-20.7	-98.3	2	85.3	-145.8
5	0.0284	0.032	115.9	75.6	-72.9	-335.9	2	289.1	-89.5
6	0.0035	0.016	61.0	189.0	77.9	262.8	2	-134.7	-60.8
7	0.000007	0.015	0.2	152.7	95.4	272.8	2	-182.1	-41.1
8	0.0458	0.099	82.9	91.7	566.9	406.7	2	-430.6	-144.2
9	0.0049	0.023	3.6	65.0	564.7	360.1	2	-445.4	143.3
10	0.0440	0.007	102.9	46.0	-76.8	-344.6	2	286.3	-74.5
11	0.0220	0.007	109.4	20.4	-10.0	-216.1	2	184.4	-25.1
12	0.0310	0.007	25.1	14.4	-11.2	-216.1	2	142.1	-34.1
13	0.0123	0.007	50.4	47.3	63.9	-30.9	2	19.4	-10.4
14	0.0052	0.007	28.9	38.3	12.2	-96.5	2	67.9	-28.7
15	0.0007	0.048	4.3	192.8	20.33	-36.2	2	33.1	-122.0
16	0.0032	0.009	74.4	85.2	-14.53	-103.3	2	111.0	-59.4

The structure of the Cluster 2 model is shown in Figure 2. The Equations 23 through 26 are given as Equations 29 through 32 with the path coefficients as shown in Figure 2.

The set of equations is shown below:

$$Sw = 0.60 * Ew \tag{29}$$

$$Ss = -0.08 * Sw + 0.54\ Es \tag{30}$$

$$Ew = 0.02 * Fw \tag{31}$$

$$Es = -0.13 * Ew + 0.08 * Fs \tag{32}$$

The low path coefficient in Equation 30 shows there is no correlation between the sediment yield in winter (Sw) and the sediment yield in early spring (Ss). Therefore, the timing effect of the sediment yield between the two seasons is not significant (Path coefficient = -0.08). The amount of sediment yield in winter is determined by the runoff energy in winter. The sediment yield in spring is affected by runoff energy in early spring.

Because the causual analysis showed only that sediment yield and runoff energy are related regardless of season, another analysis was done to determine at what level is the runoff severe. There must be some threshold amount of runoff to cause significantly high sediment yield from frozen soils otherwise there would be no severe sediment yield problem on frozen ground. The purpose of this section is to give a criterion for discriminating high from low sediment yield caused by runoff on frozen ground.

Thirty-two frozen ground events were selected for the discriminant analysis. The discriminant variables are the volume and the peak of runoff. The median of sediment yield among the 32 events which were collected from Pitzen, Naylor, and Missouri Flat Creek was used to separate the events into two groups - higher than median and lower than or equal to median.

The discriminant analysis classified three storms from Group 1 to Group 2. This rate of misclassification is acceptable. The data necessary to classify new storms using Baysian analysis are given in Table 10.

Table 10. Baysian analysis parameters.

Group	Variable	Mean	Covariance	Matrix
1	Volume of runoff (cm)	0.117	0.0140	0.0003
	Peak of runoff (cm/hr)	0.003	0.0003	0.0001
2	Volume of runoff (cm)	0.831	0.4923	0.0136
	Peak of runoff (cm/hr)	0.041	0.0136	0.0019

The purpose of the above analysis was to discriminate the high and low sediment yield events occurring on frozen ground events by two variables - volume and peak of runoff. The given volume and peak of runoff for a new storm can be identified in its severity by the discriminant criterion mentioned above if sediment yield is unknown before hand.

The severity of sediment yield is determined by runoff energy on frozen ground. Small runoff energy on frozen ground does not necessarily cause severe sediment yield. Therefore, a prediction of the severity of the sediment yield has to consider the frozen ground and sediment yield together. The relationship between sediment yield and runoff energy is shown in Figure 4.

From Figure 4, the minimum runoff energy to cause high sediment yield for a frozen ground event is 12.39 mm^2/hr (0.0192 in^2/hr). The severity of sediment yield is determined by runoff energy and frozen ground events. Small runoff energy on frozen ground will not cause severe erosion as shown in Figure 4.

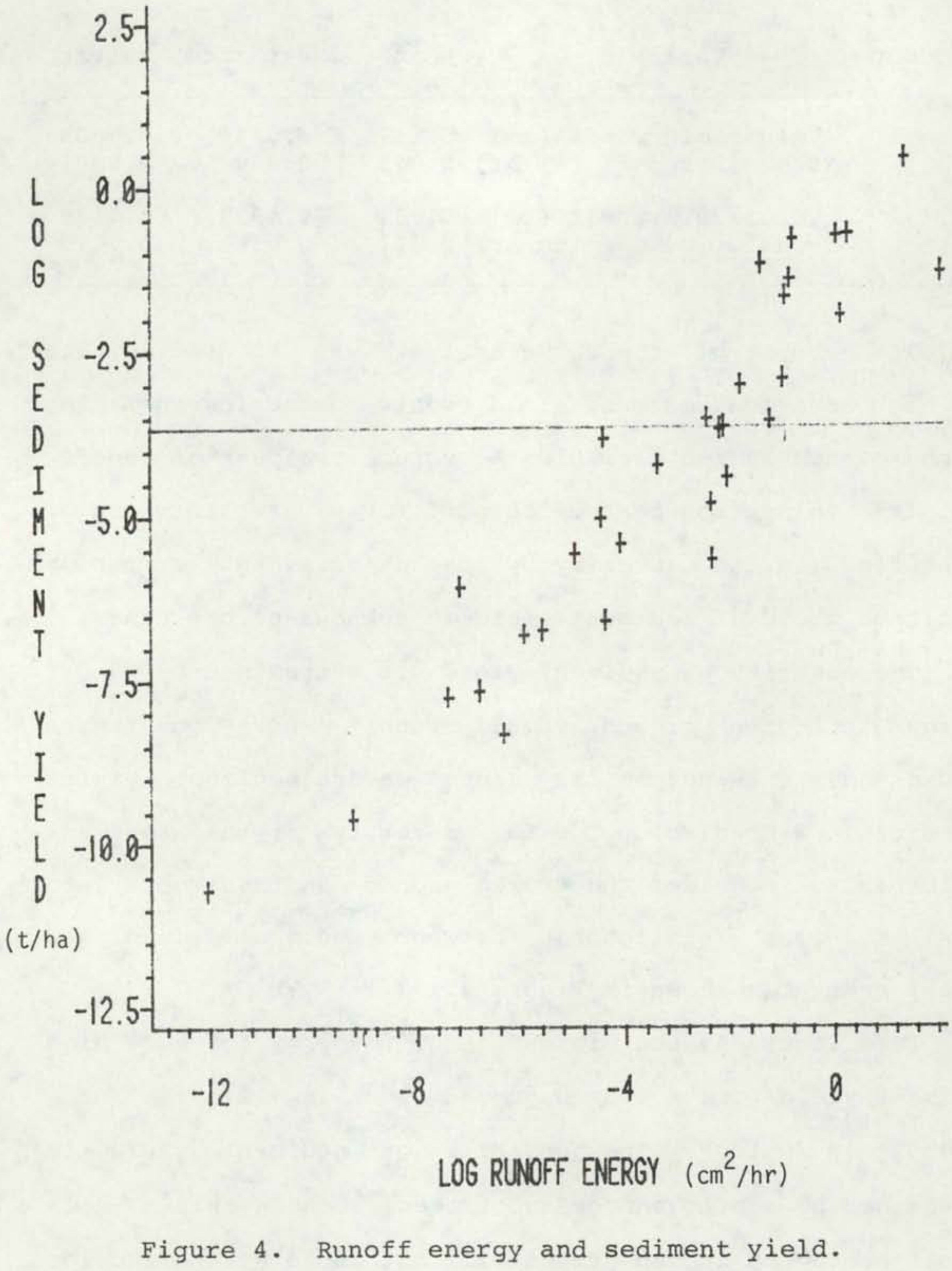

Figure 4. Runoff energy and sediment yield.

C. Surface roughness change and tillage practices.

Tillage creates soil clods on the land surface and changes the surface roughness. An untilled surface has a relatively smooth random roughness, a plow-disked-harrowed surface is intermediate, and a moldboard plowed surface is rough (Burwell and others, 1966). Soil moisture content and crop residue at the time of tillage can affect random roughness. A very wet or dry soil at the time of tillage can produce great random roughness.

The treatments and random roughness along with date of measurement are shown in Table 11. The first measurements of random roughness may be lower than normal because the first measurement was not made immediately after tillage which was done in October. Burwell and others (1966) computed the random roughness of plow-disk-harrow as 2.5 cm and plow as 5.0 cm so the roughness values in Table 11 are lower than those measured in Minnesota.

Table 11. Random roughness (mm) of 4 tillage methods at different times.

Time	Plowed-disked/harrow (East)			Plowed-disked/harrow (South)			Chizel plowed			Moldboard Plowed		
Plot	A	B	C	A	B	C	A	B	C	A	B	C
November 14, 1979	1.13	1.02	1.53	1.05	2.19	1.38	---	---	---	---	---	---
November 15, 1979	---	---	---	---	---	---	1.29	1.26	1.05	1.91	1.98	2.42
February 25, 1980	1.00	1.02	1.44	0.90	1.59	1.33	1.20	1.09	1.03	---	---	---
March 25, 1980	---	---	---	---	---	---	---	---	---	1.38	1.60	1.77
June 2, 1980	0.98	1.01	1.44	0.89	1.45	1.28	1.09	1.01	0.99	1.15	1.35	1.62

Treatments 1, 2, and 3 were measured for the second time on February 25, 1980. Due to inclement weather, treatment 4 was not measured until March 25, 1980. All four plots were measured on one day on June 2, 1980. These 1st measurements may have had some undeterminded effect due to Mt. St. Helens volcanic ash.

The random roughness of the moldboard plowed treatment decreases faster than other treatments (Table 11). For this experiment then, high random roughness decreases faster than low initial roughness.

The maximum frost depth in each treatment is shown in Table 12.

Table 12. Maximum frost depth in each treatment.

Date	Plow-disk-harrow (east) (cm)	Plow-disk-harrow (south) (cm)	Chisel Plow (cm)	Moldboard Plow (cm)
December, 1979	0	0	0	0
January, 1980	26.4	38.2	24.0	31.4
February, 1980	27.8	40.0	25.0	32.6
March, 1980	0	0	0	0

From Tables 11 and 12, it can be seen that the high random roughness seems to have the deeper frost depth. The reason might be that the larger soil clods have more surface exposed to the atmosphere than the small clod.

The freezing index (positive = freeze and negative = thawing) is accumulated from the first below freezing day in November. The freezing index and freeze-thaw cycles up to each rillmeter measurement are given in Table 13.

Table 13. Freezing index and freeze-thaw cycles during rillmeter measurement.

Date	Freeze Index (C-day)	Freeze-Thaw Cycles
November 14-15, 1979	0	0
February 25, 1980	67	50
March 25, 1980	-110	12
June 2, 1980	Mean temp. above freezing	10

Treatment 4 was measured (the second time) on March 25, 1980. The freezing index at this time was -70.0 C-day and the soil was probably thawed. Treatment 1, 2, and 3 are frozen on February 25, 1980.

The random roughness of Treatment 2 decreases faster than Treatment 1 because it faces south and experiences more freeze-thaw cycles than the other treatments. After March, the surface roughness was reduced only by rainfall and runoff. There was no snow on the ground to protect the surface from rainfall (Table 14.)

Freeze-thaw cycles which affect the surface roughness are hard to determine because the time interval which should be used is hourly instead of daily. Also the measured temperature should be soil surface temperature rather than air temperature.

The precipitation and snow depth during rillmeter measurement are shown in Table 14.

Table 14. Monthly precipitation and snow depth from November 1979 to June 1980.

Time	Precipitation (mm)	Snow Depth (cm)
November, 1979	72	5.9
December, 1979	77	2.1
January, 1980	98	15.2
February, 1980	44	4.8
March, 1980	60	0
April, 1980	38	0
May, 1980	122	0
June, 1980	51	0

After the end of February, there was no snow on the ground for any significant period of time. Thus the March measurement of Treatment 4 and all the June measurements were of random roughness reduced only by rainfall impaction and runoff.

Table 15. The mean and standard deviation of random roughness in mm.

Date	Plow-disk-harrow		Plow-disk-harrow		Chisel plow		Moldborad Plow	
	Mean	std dev	Mean	std dev	Mean	std dev	Mean	std dev
November 14, 1979	12.3	2.2	15.4	4.8				
November 15, 1979					12.0	1.1	21.0	2.3
February 25, 1980	11.5	2.0	12.7	2.9	11.1	0.7		
March 25, 1980							15.8	1.6
June 2, 1980	11.4	2.1	12.1	2.3	10.3	0.4	13.7	1.9

The standard deviations of the south facing Treatment 2 are relatively larger than that of the other plots. The south facing plow-disk-harrow plot had a higher standard deviation of its random roughness probably because of the high diural amplitude of the surface temperature.

VII. Conclusions and Summary.

Erosion on upland areas is the source of sediment yield downstream. Sediment yield is the result of erosion of soil and its transport from the land to the stream. Runoff on frozen (or thawing) ground upstream can result in differing amounts of runoff and sediment yield downstream because the same runoff energy may not always cause the same sediment yield depending on whether the ground is frozen or not.

The differences of sediment yield and runoff energy among the 7 different situations found in this study are:

a. The sediment yield and the runoff energy resulting from rain-on-snow on frozen ground are not significantly different from that of rain on thawing ground.

b. There are significant differences in runoff energy and sediment yield from snowmelt on frozen ground and snowmelt on unfrozen ground.

c. The sediment yield and runoff energy caused by rain on thawing ground is not significantly different from that of rain on frozen ground and rain-on-snow on unfrozen ground. The runoff energy is significantly different between rain on thawing ground and snowmelt on frozen soil, but the sediment yield from these two is not significantly different.

d. The sediment yield and the runoff energy from rain-on-snow and snowmelt on unfrozen ground are not significantly different from snowmelt or rain on frozen ground but they are significantly different from rain or snowmelt on unfrozen ground.

e. Sediment yield from snowmelt on frozen ground is significantly different from sediment yield from rainfall or snowmelt on unfrozen ground.

f. The sediment yield and the runoff energy caused by rainfall on frozen ground are not significantly different from rainfall on unfrozen ground.

g. Snowmelt on unfrozen ground has significantly lower sediment yield and runoff energy than rainfall on unfrozen ground.

Using three variables of runoff energy, sediment yield, and freeze index, 16 years of data from 5 watersheds were classified into two homogeneous groups. A principal component analysis followed by a cluster analysis resulted in two clusters. A causal analysis of the clusters showed that there is no statistical relation between the runoff energy, freeze index or sediment in the spring and winter, but that sediment yield in winter is affected by runoff energy and freeze index (thawing ground tends to increase sediment yield) in winter while the sediment yield in spring is determined by runoff energy in spring. This runoff energy is, in turn, affected by the freeze index in the spring.

Random roughness of the moldboard plowed plot is higher than that of other tillage methods. The south facing plot also decreased faster than the east facing, probably because of the increased frequency of freeze-thaw cycles.

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SELECTED WATER RESOURCES ABSTRACT

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15. *Supplementary Notes*

16. *Abstract* An examination of past erosion events shows that erosion and sediment yield affected by frozen soil are usually worse than that occurring on unfrozen soil. The objectives of this project were to determine if the severity of erosion in the early winter had any effect on the severity of erosion in the late winter or spring. The changes in surface roughness of three plots were determined as a function of freeze thaw cycles.

Runoff energy and sediment yield were classified as to whether they occurred on frozen, thawing or unfrozen soil. It was found that there were significant differences in runoff energy and sediment yield from snowmelt or rainfall on frozen or unfrozen soil. Sediment yield from runoff occurring on thawing or unfrozen soils was the same and was significantly different from rain or unfrozen soil.

A principal component and cluster analysis of runoff energy, sediment yield and freeze index showed that there is no statistical relation between the runoff energy, freeze index or sediment yield in the spring and winter but that sediment yield in winter is affected by the runoff energy and freeze index (thawing ground tends to increase sediment yield) in winter with spring sediment yield determined by the spring runoff energy.

Random roughness on south facing plots decreased to a base level faster than other aspect plots but all plots approached the same base level roughness regardless of orientation.

17a. *Descriptors*

Erosion and sedimentation, sediment yield affected by frozen soil

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