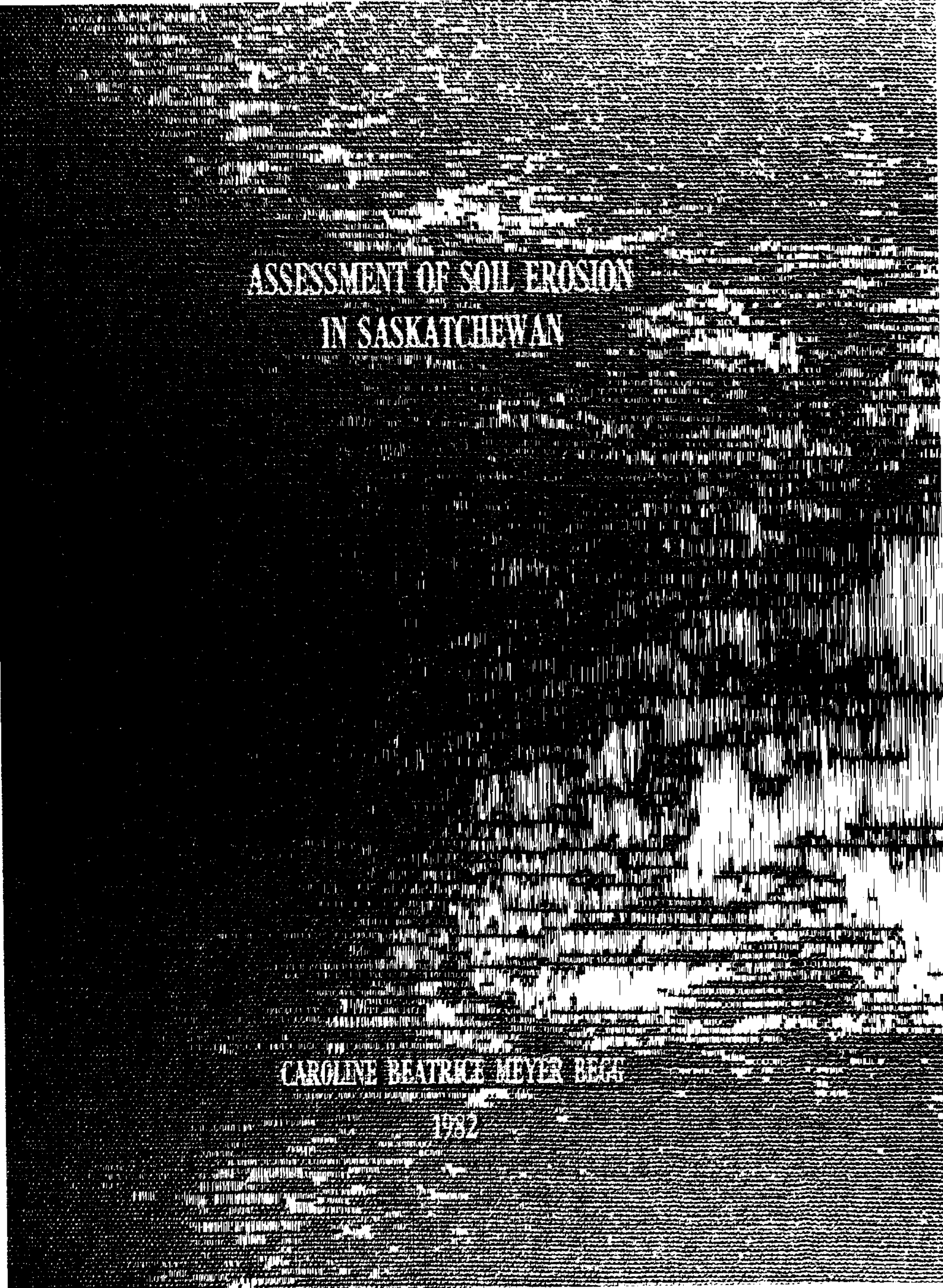

ASSESSMENT OF SOIL EROSION IN SASKATCHEWAN

CAROLINE BEATRICE MEYER BEGG

1982

ASSESSMENT OF SOIL EROSION IN SASKATCHEWAN

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by

Caroline Beatrice Meyer Begg

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UNIVERSITY OF SASKATCHEWAN

College of Graduate Studies

and Research

Saskatoon

CERTIFICATION OF THESIS WORK

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ABSTRACT

The objectives of this study were to determine which soil fractions were removed during the erosion process and to estimate soil loss by the use of a radionuclide tracer, Cesium-137. Soil fractions removed by erosion were collected during the operation of a wind tunnel and a rainfall simulator at four sites. Two pairs of basins, one in the Dark Brown soil zone and one in the Black Soil Zone, were sampled for ^{137}Cs levels. Each pair consisted of a cultivated and uncultivated basin. All soil samples were analyzed for organic carbon, total nitrogen and phosphorus content, particle size distribution, and ^{137}Cs levels.

The suspension of the wind and water erosion was generally enriched in carbon, nitrogen, and clay. Wind erosion selectively removed organic carbon from the soil. At three sites the wind and water erosion suspension was enriched in ^{137}Cs. At the fourth site, the water suspension was lower in ^{137}Cs than the soil, however, the wind suspension was somewhat enriched in ^{137}Cs. Analysis of the combined wind and water erosion samples indicated a strong relationship between ^{137}Cs and organic carbon, and clay.

An inverse relationship between ^{137}Cs and elevation was observed in the cultivated basins. The length-slope factor in the Universal Soil Loss Equation showed no consistent relationship to ^{137}Cs distribution. This was probably due to the loss of soil on the knolls and deposition in the lower areas of cultivated basins. Significant differences were found between ^{137}Cs levels at different slope positions in the cultivated basins, but not in the non-eroded control basins. Estimates of the soil redistribution within the basins were obtained using a 1 to 1 relationship between ^{137}Cs levels and soil movement.

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1. INTRODUCTION

Traditional cultivation practices in Saskatchewan have increased soil and nutrient loss by erosion. Both wind and water erosion occur on the knoll and depression landscape typical of most of Saskatchewan. The redistribution of soil by erosion from the knolls to the depressions affects the overall soil productivity and grain yields. The process of erosion destroys the soil structure which is important for plant growth. Increasing fertilizer applications do not adequately compensate for the depletion of the A horizon, and increased fertilizer costs have made the loss of nutrients an important economic concern.

Estimates of soil loss due to wind or water erosion in Saskatchewan are difficult to obtain. The wind and water soil loss equations developed in the United States estimate soil loss under specified conditions but they do not take into account soil deposition in the landscape depressions. Erosion selectively removes those soil fractions and associated nutrients most easily transported.

The objectives of this study were twofold. Firstly, to determine the extent to which particular soil fractions are removed selectively during wind and water erosion, and to relate the properties of these fractions to their ^{137}Cs (a fallout radionuclide) content. Secondly, to use ^{137}Cs distribution in the landscape to estimate soil erosion, and to evaluate the applicability of the Universal Soil Loss Equation under Saskatchewan conditions.

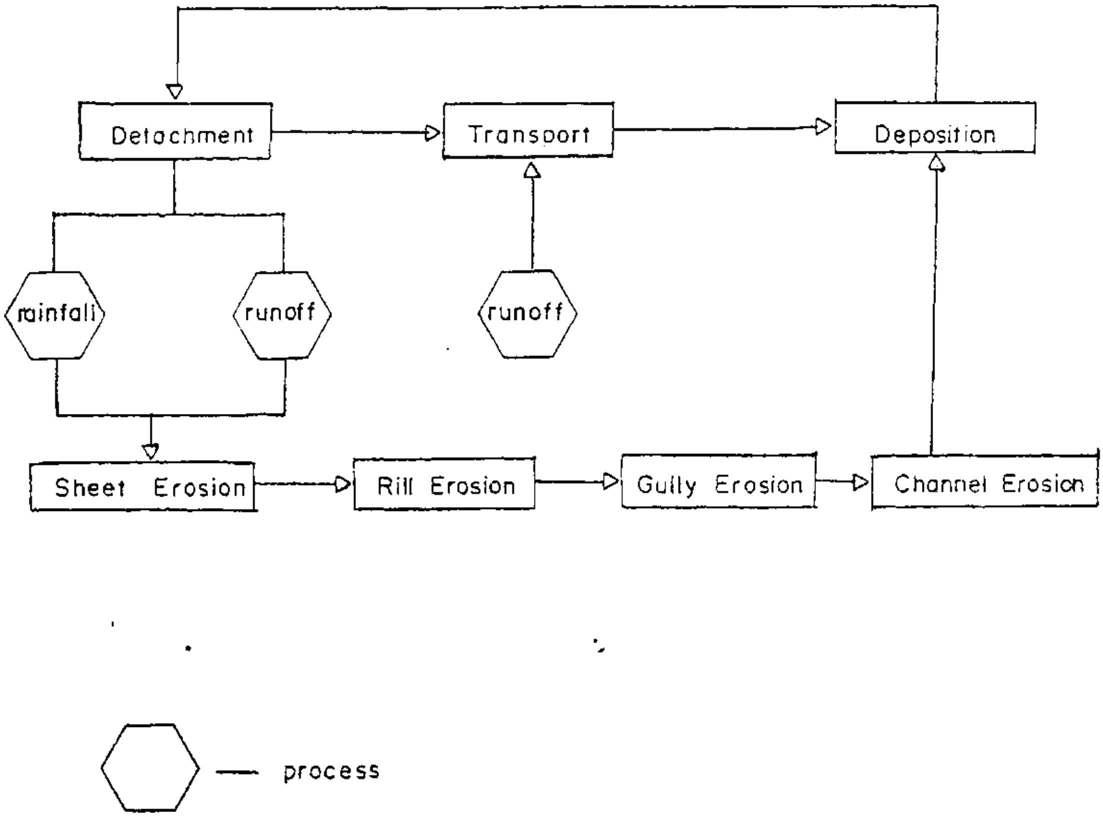
2. LITERATURE REVIEW

Soil erosion decreases soil productivity. Grain yields on severely eroded soils in Minnesota were 2/3 of the yields on slightly eroded soils (National Soil Environment Research Planning Committee 1981). Data from eroded soils in Saskatchewan indicate that crop yields will be seriously affected by the loss of organic matter and nitrogen (Doughty 1943). There are two major types of erosion: geological and accelerated. Geological or natural erosion includes both soil forming and soil eroding processes. Accelerated erosion is the deterioration and loss of soil as a result of man's activities. There is a direct loss of soil and nutrients from the eroded areas and indirect damage associated with the deposition of sediment material (Dickinson and Wall 1979). Wind and water are the main eroding agents and will be discussed separately in subsequent sections.

2.1 Water Erosion

Water erosion involves the detachment, entrainment and transport of soil by water (Dickinson and Wall 1979). Figure 1 shows the relationship between water erosion processes and types of soil erosion. Ellison (1947) separated water erosion into two components: 1) detachment and 2) transport. Detachment requires energy which is provided by falling raindrops (Wischmeier and Smith 1958). Soil aggregates are broken down by the impact of raindrops and primary particles are detached from the soil mass. Ellison (1944) found a 10 to 40% increase in small aggregates in the eroded soil and in the sediment compared to the source soil indicating a substantial destruction of aggregates. Much of the raindrop energy may be expended in puddling and sealing of the land surface thus increasing

Figure I The Process of Soil Erosion



Dickinson and Wall (1979)

overland flow. The reduction of either soil erosion component, detachment or transport, has been found to limit erosion even when erosion due to the other component increases.

The capacity of rainfall to transport soil by splashing is a function of slope steepness and rain intensity (Meyer and Wischmeier 1969; Quansah 1981). On a sloping surface the drop impact is no longer perpendicular to the surface and the drop force possesses a downslope directional component. The effect of gravity changes the symmetric splash pattern to asymmetric, thus there is a net transport of material downslope. On a six percent slope 75% of the material from raindrop splash moved downslope (Ellison 1947). However, Alberts et al. (1980) do not consider direct splash downslope a major form of transport. A relatively small depth of water will protect the soil from further raindrop detachment (Wischmeier and Smith 1958; Palmer 1965).

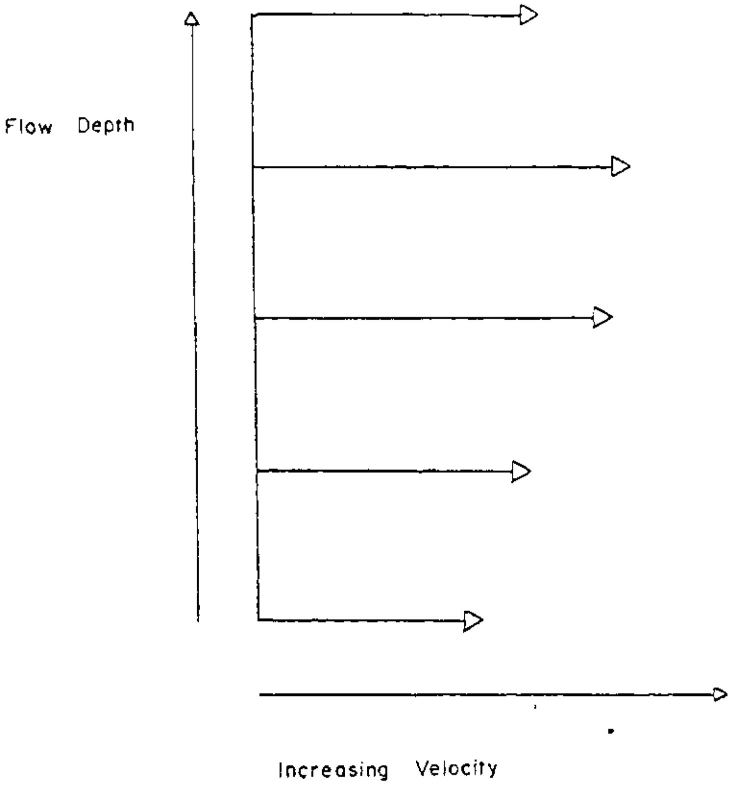
When the rainfall intensity exceeds the infiltration rate plus surface detention, excess water moves downslope as runoff and provides transportation for soil particles (Ellison 1947; Wischmeier and Smith 1958). The ability of runoff to move soil particles (the tractive force) is related to the depth and turbulent characteristics of the flowing water; all of which are related to rainfall intensity and volume, and land topography (Gray 1970). The flowing water exerts several forces on the soil particles:

1) the velocity of flow exerts a dynamic pressure on the particles
2) the difference in mean downstream velocity between the top and bottom of the particle produces an aerodynamic lift in accordance with Bernoulli's principle
3) in turbulent flows the vertical currents and eddies will lift some particles from the surface into the flow (Carson and Kirby 1972).

There are three types of soil movement: suspension, saltation and bed load. Particle movement by saltation occurs when particles skip or bounce along the soil surface. The height of the bounce is directly proportional to the ratio of particle density to fluid density (Schwab et al. 1966). The abrasive action of saltation causes soil detachment when a particle strikes another with enough force to lift it into the flow. Suspended particles are those which remain in suspension in the runoff for a considerable length of time. The turbulence created by raindrops in runoff promotes soil transport by maintaining particles in suspension (Walker et al. 1977; Alberts et al. 1980). Bed load is sediment that is rolled or pushed along the soil surface by the force of the runoff.

The resistance of the soil to particle detachment depends upon its cohesive strength. In non-cohesive soils the resistance to movement by raindrop impact increases with particle size. In fine-grained cohesive soils, there is an initial 'dust' layer on the surface which is easily removed after which soil resistance to detachment is very high. The critical tractive force for cohesive soils is correlated with the plasticity index, dispersion ratio, particle size, and clay content (Schwab et al. 1966). Within the runoff, flow velocity varies with distance above the soil surface (Fig. 2). The distance between the point of greatest velocity and the soil surface will depend on the depth of flow. When the point of greatest flow velocity strikes just above the particle centre the highest amount of kinetic energy is expended (Lutz and Hargrave 1944). The tractive force of the flow will be insufficient to cause particle movement if the greatest velocity strikes below the particle centre (i.e., large sand particles and aggregates). If the depth of flow is sufficiently greater than the average particle diameter (i.e.,

Figure 2 Velocity Distribution in Water Flow



Schwab et al (1966)

dispersed clays and silts) detachment will be difficult. Small particles are hard to detach but more easily transported than large particles. The mean flow velocity (V) of the runoff is related to many aspects of erosion (Ayers 1936; Laursen 1958; Meyer and Monke 1965):

1) the tractive force of the runoff increases as V^2,
2) the quantity of sediment that runoff can transport increases as V^5,
3) the size of particles that runoff can move increases as V^5.

For a relatively non-cohesive soil (high silt or sand) erosion is seldom limited by the available detached soil but by the transport capacity of the flow (Meyer and Wischmeier 1969).

According to Wischmeier (1966) water runoff amounts are not proportional to the corresponding soil loss. The hydro- and sedigraphs of a field experiment on soil, water and nutrient losses from soybeans did not show any relationship (Römkens et al 1979). However, in a lab experiment by Walker et al. (1978) total solids discharged varied as the water discharge varied.

Sheet erosion is a more or less uniform soil movement that results from raindrop splash and runoff. It is dependent on rainfall characteristics and the magnitude of sheet erosion varies with soil conditions, slope, cover and management practices. The depth of sheet flow is only a few millimetres (Lutz and Hargrove 1944; Wischmeier and Smith 1958) and soil movement occurs by saltation and rolling (Meyer and Monke 1965). Rill erosion results when surface runoff concentrates in depressions and develops small well defined channels. Rainfall tends to level the surface, reducing the depth of rill channels. The broader, shallower channels decrease the flow velocity and this in turn decreases the detaching and carrying capacity of the runoff. Suspension, saltation and bed load transport all occur in rill channels. Gullies form after extensive rill channelling and are the final stage of water erosion.

2.2 Water Erosion Equations

Soil loss equations were developed in the 1940's as empirical relationships. Zingg (1940) related soil loss to slope length and steepness. Soil conditions, management, slope characteristics and a rainfall factor were combined by Musgrave (1947) in an equation to predict annual soil loss. The Universal Soil Loss Equation (USLE) was developed in 1954 in the USA based on extensive measurements of precipitation, runoff and soil loss at 49 stations east of the Rocky Mountains. The qualification of factors affecting water erosion (rainfall, soil erodibility, slope factors, vegetation and conservation measures) is based on 10,000 plot-years of field data (Wischmeier and Smith 1978). After the 1960's, rainfall simulators were used in States west of the Rocky Mountains to provide further information.

The erosion at a given site is determined by the particular way in which numerous physical and management variables are combined at that site (Wischmeier and Smith 1978). The USLE predicts long-term average soil loss from specific field areas in specified cropping and management systems. It is widely used to develop conservation plans for cropland where maintaining the productivity is the main objective. The predicted soil loss is a product of six major factors:

$$A = R\,K\,L\,S\,C\,P$$

where A = soil loss
R = rainfall and runoff factor
K = soil erodibility factor
L = slope length factor
S = slope steepness factor
C = cover and management factor
P = support practice factor

The predicted soil loss per unit area (A) is expressed in the units selected for K and time period selected for R. Generally A is computed as the average annual soil loss in tonnes/ha/yr. Soil loss tolerance limits (4.5 to 11.2 tonnes/ha/yr) for USA soils were derived based on soil depth, soil characteristics affecting root development, gully prevention, sediment production, organic matter reduction and plant nutrient losses (Wischmeier and Smith 1978).

The rainfall and runoff factor (R) combines the number of rainfall erosion index (EI) units with a factor for runoff from snowmelt where significant. The erosive power of intense rainfalls is greater because of the larger drop size. Mean raindrop size is related to rain intensity (Laws and Parson 1943). The drop size distribution and their terminal velocity (measured as rainfall intensity) determine the kinetic energy of rainstorms. The erosion index (EI) formulated by Wischmeier and Smith (1958) combines particle detachment and transport capacity of a rainstorm. The erosion index (EI) of a rain is calculated as the product of the maximum 30 minute intensity and of the total storm energy. The EI index has the highest correlation with soil loss and explained 72 to 97% of the variation in individual storm losses (Wischmeier 1959). The product of energy and the maximum 15 minute intensity, which may be more appropriate to prairie climatic conditions (Toogood 1963), was also highly correlated with soil loss (Wischmeier and Smith 1958).

Local values of the EI index may be obtained from isoerodent maps, which show areas of equal rainfall erosivity. Values from the maps for Montana and North Dakota (climatic conditions similar to the prairie provinces) range from 11.5 to 20.2 metric $EI_{(m)}$ units (tonne-metres/ha/yr). The isoerodent lines for the North Central

States were approximated but are compatible with the few known point values, i.e., $EI_{(m)}$ units observed over 22 years ranged from 1.7 to 58.2 at Miles City, Montana (Wischmeier and Smith 1978).

The original soil loss equation (USLE) did not include soil losses due to snowmelt. Subsequent investigations recognized the importance of this factor in areas of high snowfalls and short springs. A factor to account for early spring runoff from snowmelt (Rs) was added to the rainfall and runoff erosion factor (Wischmeier and Smith 1978). The modified R-factor (R_T) is:

$$R_T = R + R_s$$

where R_T = rainfall and runoff erosion factor,

R = rainfall and runoff factor for late spring, summer and fall months, and

R_s = runoff erosion factor for early spring and winter months.

An estimate of the subfactor (R_s) for thaw and snowmelt may be obtained by taking 1.5 times the local December-through-March precipitation (expressed in cm of water)(Wischmeier and Smith 1978). In southern Ontario a better approximation of R_s was found using a factor of 1 (van Vliet and Wall 1979). The R factor is increased by approximately 10% when the snow runoff factor for Southern Ontario is included (van Vliet and Wall 1979). There was no significant difference between observed and predicted (USLE) soil loss when the R_s value for southern Ontario was incorporated (Wall and Dickinson 1979).

The erodibility factor (K) is the soil loss rate per erosion index unit for a specified soil on a unit plot of clean tilled fallow, 22 metres in length with a 9% slope. The soil's inherent erodibility is a complex property dependent on infiltration capacity and the property to resist detachment and transport by rainfall and runoff (Wischmeier and Mannering 1969). The erodibility value is based on fifteen soil parameters such as particle size distribution, organic matter and pH. The inherent erodibility (K) is evaluated independently of all other variables in the USL equation. Wischmeier et al. (1971) developed a soil erodibility nomograph based on five soil parameters: % silt and fine sand, % organic matter, structure and permeability. The nomograph allows a quicker and less tedious evaluation of the erodibility factor (K). Soil erodibility in Montana can be more accurately predicted with an expression which takes into consideration the degree of soil aggregation and type of clay (Young and Mutchler 1977). Soils in the upper Midwest have a higher degree of aggregation because of the clay type and climatic conditions.

The slope-length and steepness factor (LS) is the ratio of soil loss from a field with a given slope length and steepness to that from a standard plot with a 9% slope and 22 metres in length. The interaction between slope length and steepness has the form (Wischmeier and Smith 1978):

$$LS = \left(\frac{L}{22.1}\right)^m (65.41 \sin^2 \theta + 4.56 \sin \theta + .065)$$

where L = slope length, metres

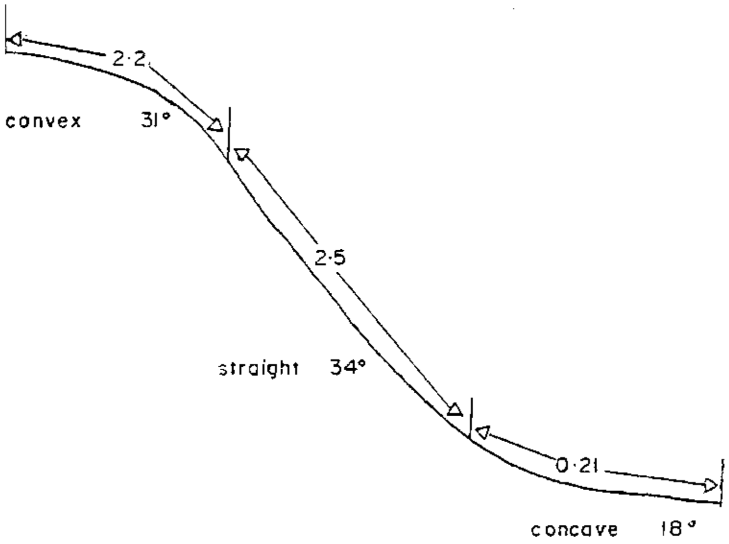
θ = angle of the slope, degrees

m = proportionality factor which depends on the slope to steepness ratio (usually assumed equal to 0.5)

Mutchler and Greer (1980) determined the exponential power (m) to be 0.15 for slopes <5% rather than the commonly used value of 0.5. Soil loss on slopes ranging from 0.1 to 3% is overestimated by the USLE when using m = 0.5 (Murphree and Mutchler 1981). Doubling the slope length increases soil loss by about 1.5 times while doubling the slope steepness increases erosion by approximately 2.5 times (Dickinson and Wall 1979).

Soil movement is a dynamic process which occurs at all locations along a slope. The slope shape affects the rate of erosion at different locations along its entire length as portrayed in Fig. 3.

Figure 3 Rates of Erosion from Different Slope Shapes

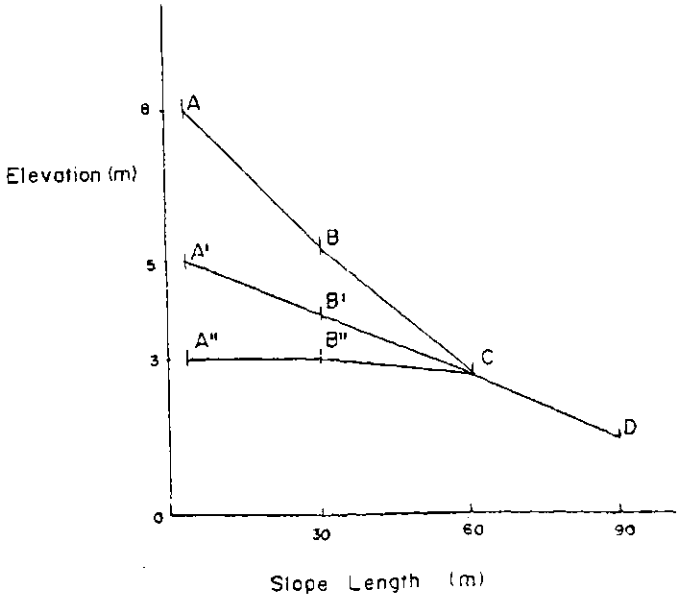


Carson and Kirkby (1972)

Numbers above the profile show rates of erosion at measurement stakes in mm/yr and those below the profile show slope gradient in degrees. There are four slope types: concave, convex, uniform and complex. The effect of raindrop impact on soil detachment dominates on the knolls while the detachment ability of runoff dominates erosion beyond a critical point downslope (Meyer and Wischmeier 1969). The gradient and sediment load are low on the upper portions of a convex slope. As slope steepness and length increases the sediment load also increases (Meyer and Kramer 1969). Alternatively concave slopes have the greatest steepness at the upper portion of the entire length where the least runoff occurs. On uniform slopes sediment load increases as the length increases. Deposition on concave and complex slopes occurs along the lower one-third of the slope with little soil movement beyond the base, while the sediment load beyond the base of uniform and convex slopes is high (Meyer and Kramer 1969). Young and Mutchler (1969) reported that concave slopes eroded less than uniform and convex slopes. Due to runoff quantity and velocity, the maximum soil displacement on concave slopes occurred on the upper third of the slope while maximum displacement on convex and uniform slope took place at about three-quarters of the distance from the knoll (Young and Mutchler 1969).

The effect of irregularities in slope shape on sediment loads is only approximated by the average overall steepness. Successive segments of a complex slope cannot be treated as independent shapes as surface runoff flows from one segment to the next (Foster and Wischmeier 1974). The sediment load at a particular slope position is limited by one of two factors: 1) transport capacity of the runoff and rainfall, 2) the amount of detached soil material available for transport. The USL equation applies when detachment limits the sediment load and detachment is determined by the distance from the particular point to the top of the slope and values of S, K, C and P at the location. Detachment rate rather than sediment load is determined by the particular conditions at a location. Figure 4 shows the dependence of sediment load on upslope conditions. According to previous concepts the sediment load at point D would be the same regardless of whether the slope shape is ABCD, A'B'CD or A"B"CD. Although detachment on each segment is independent of upslope conditions the total sediment at point D is the sum of all soil detached on all segments of the slope and thus dependent on upslope conditions.

Figure 4 Slope Shapes and Sediment Load



Foster and Wischmeier (1974)

The irregular slope is divided into a series of n segments such that the slope steepness and soil type within each segment can be treated as uniform (Foster and Wischmeier 1974). The total soil loss is the sum of losses from the n segments. The USL equation can be rewritten, with the bracketed expression replacing the LS factor, as (Foster and Wischmeier 1974):

$$A = R\,K\,C\,P \sum_{j=1}^{n} \frac{S_j \lambda_j^{1.5} - S_j \lambda_{j-1}^{1.5}}{\lambda_e \,(22.1)^{0.5}}$$

where A, R, K, C, P were defined previously

λ_j = the distance from the top of the slope to the lower end of any segment j, metres

λ_{j-1} = the slope length above segment j, metres

λ_e = overall slope length, metres

S_j = the slope gradient for segment j, 5.

The cover and management factor (C) is the ratio of soil loss from an area of specified cover and management to that from continuous fallow. The influence of crop cover and management practices on soil erosion has been evaluated for different crops and practices (Wischmeier 1960). Values for the C factor are found in tables given in Wischmeier and Smith (1978).

The erosion control practice factor (P) is the ratio of soil loss with a control practice (e.g., contouring) to straight row farming up and down the slope. Soil loss for each conservation practice can be predicted (if all other factors are constant) and thus used to select adequate control methods. The P factor values are dependent on slope length and steepness (Wischmeier and Smith 1978).

The application of the Universal Soil Loss Equation is site specific rather than regional. Soil losses computed by the equation are estimates rather than absolute values. The equation will predict soil loss only from sheet and rill erosion on a particular slope. It does not predict field sediment yield as deposition is possible within the field. Erosion can create rills and gullies on a field without substantial loss of soil from the particular field. As the USLE was developed for conservationists working in the field, certain refinements were sacrificed in the interests of utility (Wischmeier 1976). Each factor from the USLE has to be considered of uniform value over the entire area in question. The equation computes long term average annual soil losses for a specific site and does not predict soil losses from a specific storm event.

According to Dickinson and Wall (1979) the principal obstacles to the use of USLE in Canada are: 1) lack of information on the rainfall (R), cropping (C) and erodibility (K) factors, and 2) the high percentage of snow rather than rain in the northern temperate climates. Results from southern Ontario displayed in Table 1 show no significant difference between observed and predicted (using the USLE) soil loss values (van Vliet and Wall 1979). Voroney et al. (1981) using the USLE estimated soil loss to be 1.7 tonnes/ha/yr from a cultivated site in Saskatchewan.

Runoff from snowmelt accounts for 85% of the total runoff from agricultural watersheds in Western Canada (Nicholaichuk 1967). Snowmelt accounted for much of the annual water and soluble nutrient losses in Minnesota (Burwell et al. 1975). Nutrient transport of nitrogen (N) and phoshorus (P) in surface runoff from snow exceeded

Table 1. Measured and predicted (Universal Soil Loss Equation) soil losses from runoff plots (Van Vliet and Wall 1979).

Location	Treatment	Soil loss: Predicted (Universal soil loss equation) (tonnes/ha)	Soil loss: Measured[*] (tonnes/ha)
Elora Research Station	2% slope, spring plowed	2.5	1.8[**]
	6% slope, spring plowed	10.3	9.9[**]
University of Guelph	Stover left on surface, manure added, fall plowed	35	35[†]
	Stover left on surface, manure added, not plowed	6	2[†]
	Stover removed, manure added, fall plowed	47	54[†]
	Stover removed, manure added, not plowed	37	35[†]
	Stover removed, no manure added, not plowed	39	30[†]

[*] Mean of two replicates

[**] Four year average values

[†] Six year average values

Saskatchewan water quality limits, but the 2.8 kg N/ha/yr and the 1.6 kg P/ha/yr were agronomically insignificant (Nicholaichuk and Read 1978). Nutrients were found to be primarily removed in the sediment (Römkens et al. 1973), however, the average loss in nutrients by sediment transport was less than 0.1 kg/ha/yr in Saskatchewan studies (Nicholaichuk and Read 1978). Toogood and Newton (1950) in Alberta observed considerable soil loss from rapid runoff of melting snow. In a 10-year soil erosion study in Alberta a maximum soil loss of 4.5 tonnes/ha/yr was observed and considered to be insignificant (Toogood 1963). However only precipitation events from May to August (no snowmelt) were used and the experimental soil was a recently cultivated Chernozem.

Particle detachment and transport are important factors in water erosion. If fine particles are selectively eroded a major loss of nutrients can occur. Most sediment erodes as aggregates (Swanson et al. 1965; Alberts et al. 1980; Meyer et al. 1980). The cohesiveness of the soil significantly influences the material in suspension (Gabriels and Moldenhauser 1978). Swanson et al. (1965) found an enrichment of silt and clay particles in the eroded sediment. Runoff sediments can be enriched by clay (Rhoton et al. 1979). However, other studies have found no significant enrichment of fines in the sediment (Gabriels and Moldenhauser 1978; Meyer et al. 1980).

2.3 Wind Erosion

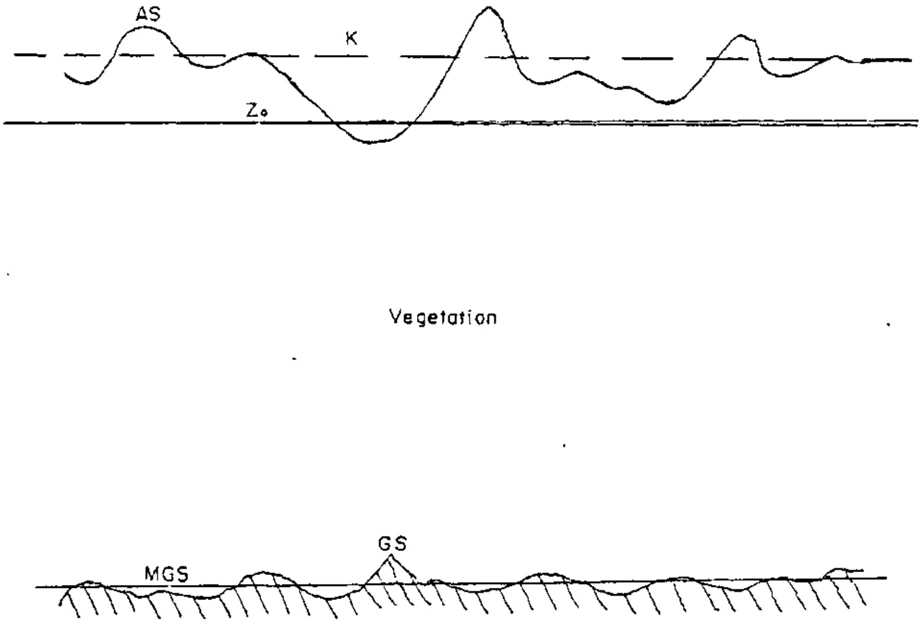
When the prairies were originally cultivated the natural vegetation cover was removed and the soil was laid bare to wind erosion. Wind erosion reduces soil productivity by the removal of fine particles and nutrients. Chepil (1949) reports one prairie field lost virtually all its silt and clay in less than 60 years. Bare summerfallow degrades the soil and compounds the erosion hazard (Johnson 1977). Approximately 20 to 35% of the improved farmland in Manitoba and Saskatchewan is in summerfallow (Johnson 1977). At the tolerable level of wind erosion, defined as a soil loss of 11.2 tonnes/ha/yr, there is no visible soil movement or damage to plants

(Chepil et al. 1962). Lindstrum et al. (1979) report that only 56% of the cultivated Great Plains can produce enough residue (greater than 0.5 tonnes/ha) to hold soil loss by wind erosion to 11.2 tonnes/ha/yr. Lands damaged by wind erosion in which soil movement is readily observable by the eyes, lose soil at a rate of over 34 tonnes/ha/yr (Kamberlin et al. 1977).

There are three types of particle movement in wind erosion, suspension, saltation and soil creep. Soil particles move in response to forces generated by the wind. A turbulent wind is necessary to move soil particles (Zingg and Chepil 1950; Chepil and Woodruff 1963; Lyles 1977). The relative positions of air, vegetative and ground components at the soil surface are portrayed in Fig. 5. The aerodynamic surface (Z_0) is estimated by plotting the wind velocity above the ground projections against the height above the average ground surface and determining the y intercept as shown in the left-side of Fig. 6. At a certain height (K) above the aerodynamic surface the average forward wind velocity is zero in the zone of turbulent air flow. Above the mean aerodynamic surface (Z_0) the turbulent air flow is unrestricted and fast-moving (Chepil and Woodruff 1963). Particle movement is dependent on the turbulent boundary layer above the soil surface. Wind speed near the ground depends entirely on the type of surface cover (Chepil and Milne 1941) as shown in the right side of Fig. 6. Wind velocity is greater over a smooth surface than over a rough surface, but a rough surface causes greater air turbulence and is subject to a greater wind force. Wind velocity near the surface is restricted by eroding particles in the air.

The threshold velocity of the wind is defined as the velocity

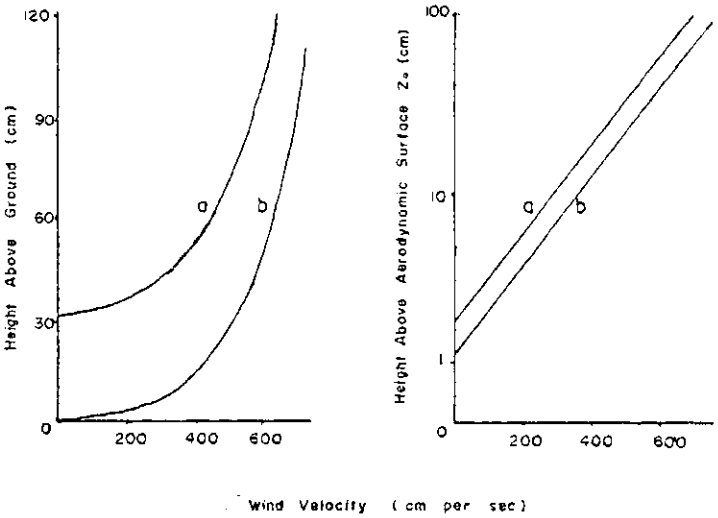
Figure 5 Air, Ground and Vegetative Components in Air Streams



Z_o	mean aerodynamic surface
K	the height above the aerodynamic surface where the wind velocity is zero
AS	aerodynamic surface
MGS	mean ground surface
GS	ground surface

Chepil and Woodruff (1963)

Figure 6 Wind Velocity Distribution



Wind velocity distribution determined for the same wind above;

a : sorghum stubble; maximum height 53 cm

b : growing wheat; maximum height 5 cm

Chepil and Woodruff (1963)

necessary to initiate soil movement (Chepil and Woodruff 1963; Lyles 1977). The required velocity varies directly with the average size of soil particles (Chepil 1945). Fluctuations in wind velocity and pressure are important in determining threshold values that initiate particle movement (Lyles et al. 1971). The amount of soil erosion is determined by the wind distribution in and above the vegetative and soil elements at the surface. If the surface roughness is increased the turbulence of the wind stream is also increased, and the threshold velocity is lowered (Lyles et al. 1974).

The most readily eroded particles range from 0.05-0.15 mm in diameter and require a wind speed of 13 to 14 km/h at a 15 cm height to initiate and continue soil movement (Chepil 1941). On either side of this range as particle size increases or decreases, the threshold velocity increases (Chepil 1949). Fine particles are highly resistant to erosion because they are too small to project above a viscous air layer close to the soil surface, i.e. they are below the mean aerodynamic surface (Chepil 1945). The presence of dispersed fine particles in the soil increases the threshold velocity. Woodruff and Siddoway (1965) consider the erodible fraction of the soil to be those particles less than 0.84 mm.

Erosion rates vary directly as the cube of the wind speed (Chepil 1945; Bondy et al. 1980). Before the soil will erode forces generated by the wind have to overcome the forces of gravity and cohesion acting on soil particles. The initiation of soil movement can be caused by impulsive forces generated by differences in wind velocity (Bisal and Nielsen 1962). The differences in velocity pressure from top to bottom on a soil particle cause a lift force to act on the particle (Bernoulli's Law of fluid transport). The lift is caused by a steep velocity gradient near the surface but the force is effective only to 2.5 cm in height (Chepil and Woodruff 1963). The lift force and drag velocity, defined by Chepil and Woodruff (1963) as the rate of velocity increase with the log of height, act together on the particle to initiate movement. The drag velocity continues to act on the particle as it moves into the air stream (Chepil and Woodruff 1963). Bisal and Nielsen (1962) and Lyles (1977) observed particles vibrating in the wind stream and then suddenly leaving the surface once they had obtained enough energy.

Saltation is a prerequisite to the other forms of particle movement. Once the particle is dislodged from the surface it is carried down wind. When it strikes the surface it may either rebound or lose most of its energy by striking other particles and initiating their movement. Saltation is essentially a surface phenomenon and accounts for the bulk (50 to 80%) of the total transport (Lyles 1977). Particles moved by saltation range from 0.1 to 0.5 mm in diameter (Chepil 1949). The abrasive action of saltation breaks down large aggregates and surface crusts, and damages seedlings.

The actual measurement of soil lost in suspension is difficult. Particles less than .01 mm are resistant to wind erosion unless mixed with coarse particles capable of saltation. Saltating particles dislodge fine particles into the turbulent air stream where they are easily transported (Gillette and Walker 1977). Particles in suspension can be carried to high altitudes depending on their size, shape and density (Lyles 1977) and account for 3 to 35% of the total soil movement (Chepil 1945). Smith et al. (1970) report strong positive correlations between dust deposition rates and rainfall parameters, indicating considerable suspended dust is carried down by rainfall.

Particles from 0.1 to 0.5 mm in diameter move by surface creep and are driven by the impacts of saltating particles. Surface creep accounts for 7 to 25% of the total movement (Chepil 1945). Non-erodible elements reduce the wind drag on the erodible fraction of the soil. As the erodible material is removed the surface roughness is increased, which increases the friction velocity or drag force. The friction velocity is divided between the non-erodible elements (where it is ineffective) and the erodible soil. Erosion ceases when enough erodible soil is removed allowing all the friction velocity to be absorbed by the non-erodible fraction. If there is considerable abrasion the soil surface may never stabilize.

2.4 Wind Erosion Equations

Zingg and Whitfield (1957) observed soil loss to be related to the percent of particles <0.42 mm and the weight of wheat residue on the soil surface. Soil loss by wind erosion depends on several factors: the erodible particle size distribution, proportion and size of the non-erodible fraction, field roughness, vegetation and soil moisture content. Soil moisture creates a cohesive force between aggregates. Little wind erosion occurs on a soil with a moisture content larger than the 15 atmospheres water content (permanent wilting point). The soil becomes more erosive at a moisture content only slightly less than the permanent wilting point (Chepil 1956). Woodruff and Siddoway (1965) developed a Wind Erosion Equation (WEE) that predicts the amount of soil loss in tonnes/ha/year as a function of five variables. The equation is based on climatic conditions at Garden City, Kansas, U.S.A. The equation has the form (Woodruff and Siddoway 1965):

$$E = f\,(I', K', C', L', V')$$

where E = soil loss in tonnes/ha/yr

I' = soil erodibility index

K' = soil roughness

C' = climatic factor

L' = equivalent field length

V' = equivalent vegetative cover

The complexity of the relationships between the variables restricts the derivation of a single equation expressing soil loss (E) as a function of five dependent variables. The equation is solved by mathematical or graphical solutions where each step evaluates the effect of an additional variable.

The soil erodibility index (I') is the potential soil loss (tonnes/ha/yr) from a wide, unsheltered, isolated field with a bare smooth, non-crusted surface. The erodibility index was developed from wind tunnel and field measurements of erodibility. It is related to soil cloddiness and its value increases as the percentage of soil fractions greater than 0.84 mm in diameter decreases. A factor for knolls or slopes can be incorporated into the index.

The soil roughness (K') is a measure of the surface soil unevenness in the form of ridges or small undulations. The K' factor is expressed in terms of standard soil ridge heights (Zingg and Woodruff 1957). A value of 1.0 indicates a completely smooth surface which is highly erodible. Clods and vegetation are not included in this measure.

The climatic factor (C') combines the wind velocity and surface soil moisture. The C' factor evaluates the effect of wind velocity, quantity and frequency of rainfall and the rate of surface drying (Chepil et al. 1962):

$$C' = \frac{100}{2.9} \cdot \frac{V^3}{(P-E)^2}$$

where C' = combined wind erosion climatic factor expressed as a percent of that at Garden City, Kansas, U.S.A.

V = corrected mean annual wind velocity at a height of 10 metres (km/h)

$P\text{-}E$ = moisture index developed by Thornthwaite (1931)

2.9 = the approximate average value at Garden City, where $V = 18.5$ km/h and $P\text{-}E = 29$ units

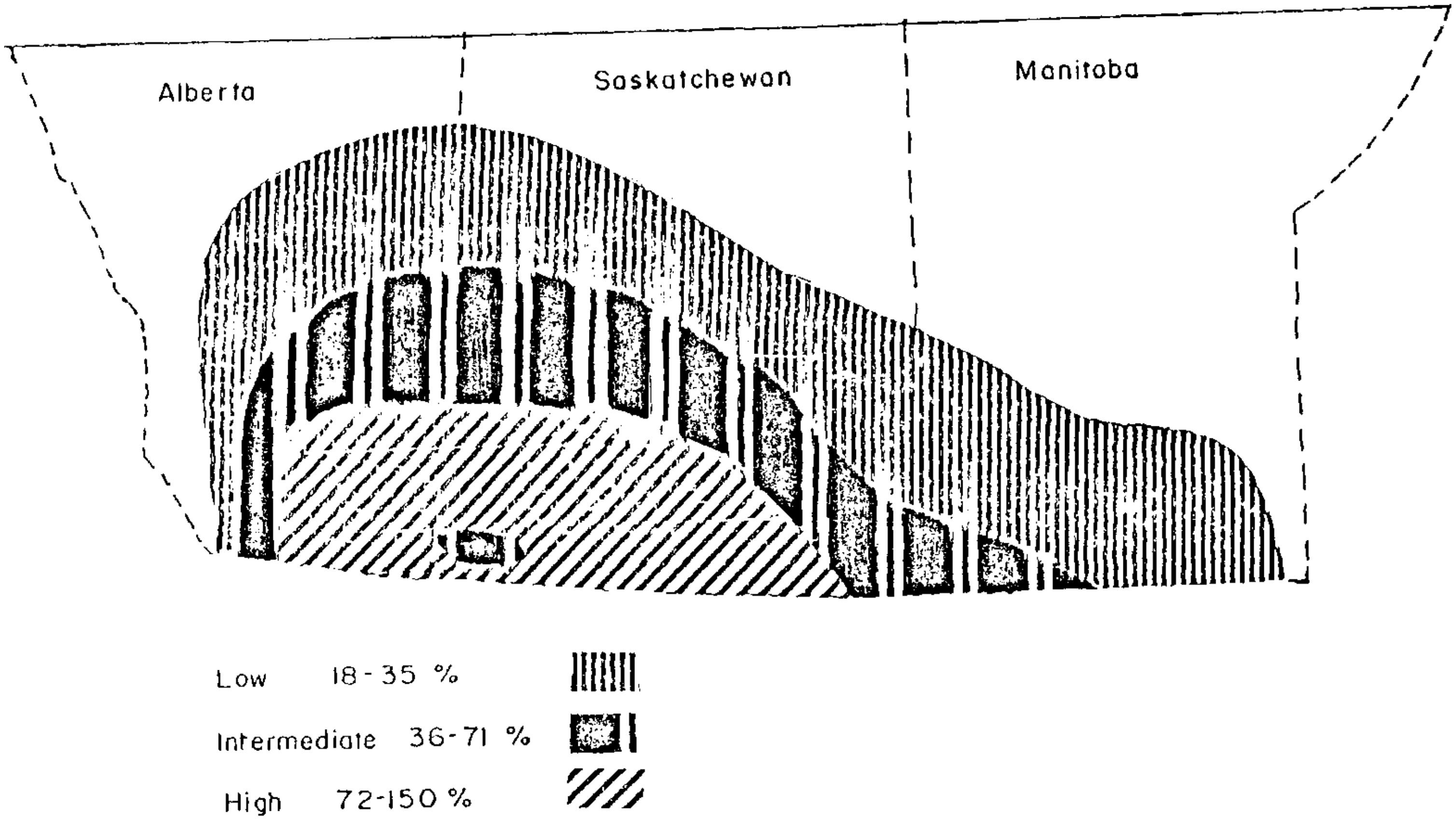
The rate of soil movement varies inversely as the square of surface soil moisture content. The climatic factor converts the standardized soil loss for Garden City, Kansas, to the local potential soil loss. Figure 7 shows the distribution of the wind erosion climatic factor (C') in western North America.

The equivalent field length (L') is the difference between the total distance (measured along the prevailing wind direction) and the sheltered length. Soil movement is zero on the windward edge and increases with distance to the leeward side. The equivalent vegetative cover (V') is an interaction of factors representing the quantity, kind and orientation of vegetative cover. The greater the surface area of the vegetative material, the larger the decrease in wind erosion. The height and erectness of vegetative cover also decrease the soil loss.

Bondy et al. (1980) developed a method of computing wind erosion based on wind-energy distributions. The procedure is similar to that used in the Universal Soil Loss Equation. It allows the individual factors in the WEE to be determined for each crop stage.

Soil productivity (crop yield) is linearly related to soil thickness according to Lyles (1975). Wind erosion damages the soil by

Figure 7 Wind Erosion Climatic Factor C'



Chepil et al (1962)

removing fine particles (Daniel 1936; Chepil 1946; Lyles 1975; Gillette and Walker 1977; Kimbelin 1977). Drifting is most severe on clay and sand soils and due to a sorting action the drifts contain less fine particles than adjacent virgin soils (Moss 1935; Daniel 1936). Measurements of aersol, collected at 3.5 m, show it to have up to 20 times the organic carbon content compared to the source soil. Some low density vegetative material was also present in the aersol (Delany and Zenchelsky 1976).

The susceptibility of the Brown soils of Saskatchewan and Alberta to wind erosion is increased over the winter months (Johnson 1977). Warm winds melt the snow cover and dry the surface aggregates. Freezing and thawing cycles will increase the percent of non-erodible aggregates (Anderson and Wenhardt 1966), but the loss of water by sublimation causes the disintegration of aggregates and increases the soil erodibility (Anderson and Bisal 1969).

2.5 Methods of Studying Soil Erosion

An actual measurement of water erosion, including runoff and sediment loss can be obtained with permanent field plots (Toogood 1963; Nicholaichuk and Read 1978). Such plots must be observed over a long period as it may take 10 to 20 years before a comprehensive coverage of natural rainfall and soil conditions is obtained (Meyer 1965). Most studies have been conducted over a shorter time period. For example, Nicholaichuk and Read (1978) measured nutrient runoff from natural rain and snowfall on dyked plots over a 6 year study, and Römkens et al. (1979) reported on a 2 year study measuring runoff composition from soybean management systems. Chepil (1960) measured soil loss by wind erosion on field plots (January through April) by estimating the depth to which wheat crowns and roots were exposed. The quantity of material in suspension was determined from a relationship between visibility and dust concentration (Chepil and Woodruff 1957). Maintenance of erosion plots is time consuming and costly and other techniques to study soil erosion have been developed. The use of simulators and tracers in erosion research is recognized as viable means of measuring soil and water loss (Meyer 1965; I.A.E.A. 1973; Fryrear and Lyles 1977).

Rainfall simulators were first used in the 1930's (Meyer and McCune 1958). Since then several studies have used simulators to determine the soil erodibility factor K (Dangler and El Swaify 1976; Barber et al. 1979) or the slope-length factor LS (Mutchler and Greer 1980). Research into the effect of soil management practices on erosion frequently uses simulators (Bairisas et al. 1978; Laflen et al. 1978; Römken et al. 1979). Laboratory rainfall simulators are used in soil detachment and transport studies (Lyles et al. 1974; Hagen et al. 1975; Walker et al. 1978). Field simulators are expensive, complicated and problems often affect the overall performance of the simulator. The small plot size and short slope length used in simulation are opposite to the conditions under which water erosion occurs naturally. Mech (1965) observed that it is a simple matter to measure soil loss and runoff from plots subject to simulated rain but it is difficult to extrapolate these measurements to field conditions and natural rain.

Rainfall simulators can shorten the length of time necessary for a comprehensive study of water erosion. The storm intensity and duration, along with soil conditions, can be controlled and replicated at different sites. The rainfall characteristics which influence soil erosion are intensity, drop size distribution and drop velocity (Meyer and McCune 1958; Meyer 1965). The relationship between raindrop impact - size distribution, and rainfall intensity - energy form the basis of the rainfall simulator design.

Spray nozzles can produce a drop size distribution similar to natural rainfall and drops have an initial velocity dependent on water pressure (Mutchler and Hermsmeier 1965). Almost all recent simulators use a single nozzle or a group of oscillating nozzles to produce artificial rain. The area covered by portable rainfall simulators is variable. Simulators developed by Meyer and McCure (1958) and Swanson (1965) are effective on plot sizes ranging from 25 to 130 m^2. Meyer and Harmon (1979) and Bertrand and Parr (1961) constructed simulators to measure erosion on an area less than 2 m^2 between crop rows.

Barnett and Dooley (1972) compared erosion losses from simulated and natural rainfall. The rainfall Erosion Index (EI) is used to indicate the erosive power of each rainfall event. The EI index was similar for both natural and simulated rain and there was no significant difference between soil loss from natural and simulated rain. Young and Burwell (1972) found that soil losses from simulated rain averaged 77% of the total soil loss from natural rainstorms with similar EI indexes.

Measurement of wind erosion in the field is difficult due to the lack of control over the variables involved. Development of field sampling equipment is a major research need (Fryrear and Lyles 1977). Natural winds can be sampled for soil suspension by dust traps. Suspended particles are removed from natural winds in traps either containing a liquid medium (Smith et al. 1970) or a filter (Delany and Zenchelsky 1976; Gillette and Walker 1977). Dust traps sample large soil areas and are subject to variable wind and soil conditions. Particles moved by saltation can be sampled from soil drifts (Moss 1935; Daniel and Langham 1936).

Laboratory wind tunnels were developed to study soil movement in air streams. Field wind tunnels can reduce the variability in erosion studies by controlling wind speed. The apparatus should be portable, produce a steady air stream of uniform characteristics and it should be large enough to allow free movement of soil particles (Zingg 1951). The wind tunnel developed by Zingg (1951) had a cross-section of 1 m^2 and was 9 m in length, and allowed the free movement of particles. The soil suspension was collected using modified vacuum cleaners. A comparative study of soil·drifting in the field and in a wind tunnel showed little difference in soil movement and in the characteristics of suspension, saltation and creep (Chepil and Milne 1939). Wind tunnels have been used to evaluate the effect of crops on soil movement (Lyles and Allison 1975).

Tracers provide an effective indirect method of measuring soil movement (Carson and Kirkby 1972). Tracers can be artifically applied to certain components of the soil system, for example, ^{14}C and ^{15}N are used to monitor the movement of organic compounds (I.A.E.A. 1973). Frissel et al. (1973) traced soil water movement with ^{36}Cl, ^{60}Co and ^{3}H. Wooldridge (1965) studied soil particle movement with ^{59}Fe.

Extensive atmospheric tests of nuclear weapons occurred during the 1950's and 1960's. About 20 megacuries (MCi) of ^{90}Sr and 30 MCi of ^{137}Cesium were released into the environment (Lippmann and

Schlesinger 1979). For health reasons the fallout of ^{90}Sr is monitored worldwide. It is possible to infer the flux of ^{137}Cs from reported ^{90}Sr fluxes as the ratio of ^{90}Sr to ^{137}Cs in fission is relatively constant (Squire and Middleton 1966; Edington and Robbins 1976). Both ^{90}Sr and ^{137}Cs are removed from the atmosphere by precipitation. The amount of fallout depends on meteorological conditions and the quantity of radioactive debris present in the atmosphere. The relationship of ^{137}Cs to rainfall varies spatially and in time but the overall pattern of fallout from year to year is similar throughout the world (McCallum et al. 1980).

The radioisotope ^{137}Cs is strongly sorbed by soil particles especially the clay fraction (Jacobs and Tamura 1960; Walton 1963). The transport of adsorbed ^{137}Cs is with soil particles and thus it is a good tracer for soil movement. Cesium-137 is a strong gamma emitter and concentrations present in the soil can be measured using gamma ray spectroscopy.

If ^{137}Cs was distributed uniformly over land areas, the soils and sediments should receive equal amounts of fallout. Each subsequent sampling of the soil or sediment should contain the same ^{137}Cs concentration if there were no disturbances. Erosion will cause an enrichment of ^{137}Cs in the deposition areas and a reduction in the eroded areas. The particle movement can be caused by both wind and water erosion. Sedimentation rates in water bodies in North America and England have been determined using ^{137}Cs as a tracer (Pennington et al. 1973; Delaune et al. 1978). A technique developed by Ritchie et al. (1974) and Ritchie and McHenry (1978) uses the levels of ^{137}Cs in the soil profile to estimate soil erosion. There is a logarithmic relationship between measured soil loss and ^{137}Cs loss from soils (Ritchie et al. 1974). The relationship has the form:

$$Y = 1.6\ X^{0.68}$$

where Y = radionuclide loss expressed as a percent of radionuclide input,

X = predicted soil erosion using the USLE, in tonnes/ha.

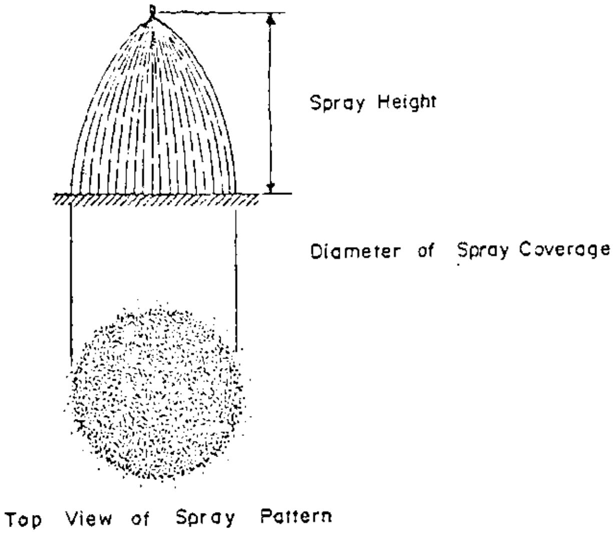
3. MATERIALS AND METHODS

Three experiments were initiated to study soil erosion near Saskatoon. A rainfall simulator and a wind tunnel were used to obtain soil fractions representative of water and wind erosion respectively. No attempt was made to determine actual total soil loss per area during the wind erosion study. Measurements of the quantity and distribution of ^{137}Cs in the landscape were used to estimate areas of soil loss based on a method developed by Ritchie and McHenry (1974).

3.1 Rainfall Simulator Experiments

The rainfall simulator was built according to specifications by Bertrand and Parr (1961). The nozzle used was a Full Jet (type $\frac{1}{8}$ GS, distributed by John Brooks Canada Ltd.) with a full cone spray pattern (Fig. 8) and a uniform drop size distribution. At the nozzle height of 3.36 m the spray pattern encompassed the experimental plot of 1 m^2, tilled and graded to a 7% slope. A canvas-covering over a metal structure of 3.66 m^2 which surrounded the simulator and plot was used to reduce wind effects on the spray pattern. The amount and intensity of the simulated rainfall depend on the water pressure, the latter was controlled by a valve and measured by a pressure gauge. The storm intensity for various pressures was determined by measuring the quantity of water sprayed in one hour. The kinetic energy (KE) per storm intensity was calculated from the height of raindrop fall. The assumption was made that the raindrops had reached their terminal velocity upon ground impact. The return period, which describes the frequency of occurrence of a certain storm intensity, was calculated from Figs. 9 and 10 (Gray 1970). The return period of the storm intensities used in the simulator can be calculated from the equation

Figure 8 Spray Pattern of 1/8 GF Fulljet Nozzle



John Brooks Canada LTD Data Sheet

(Fig. 10):

$$P_{tr} = \bar{P}_{24} (1 + KCv)$$

where P_{tr} = precipitation (inches) with return period tr (years),

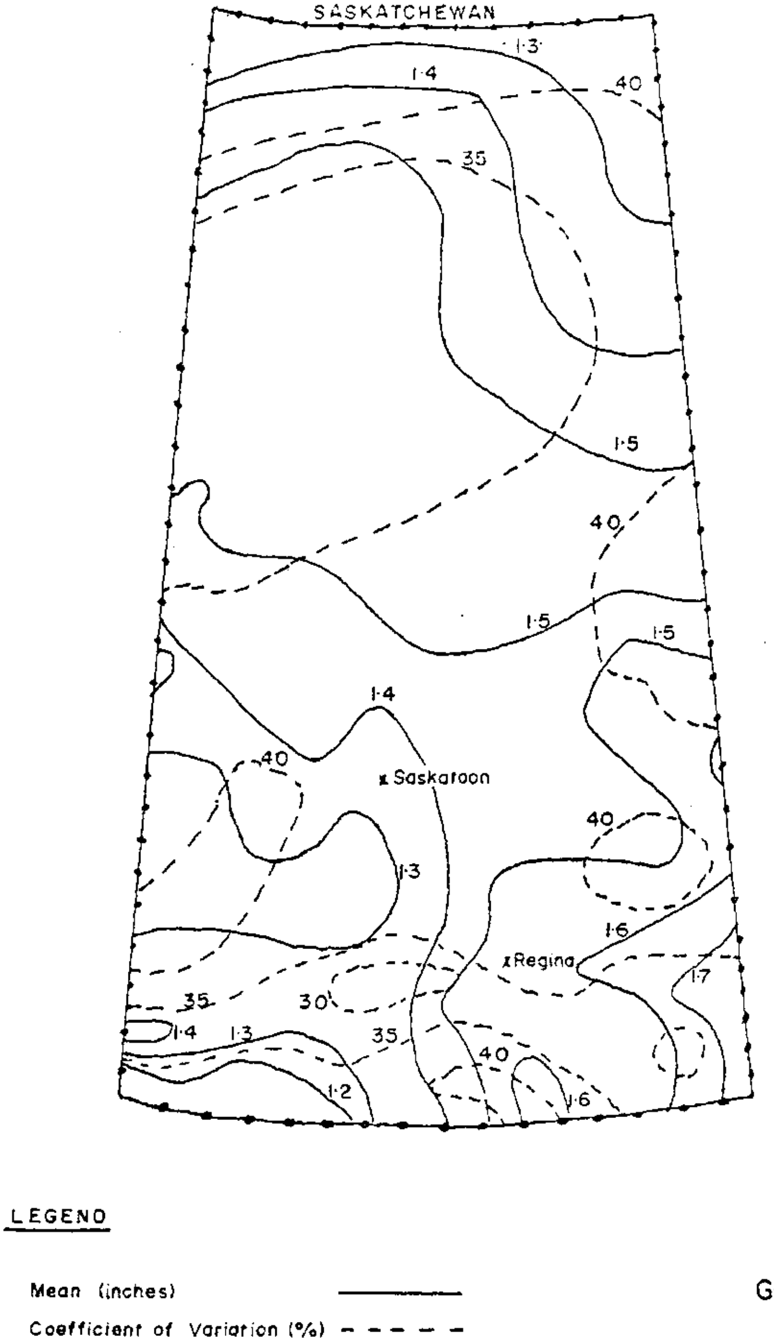
$\bar{P}_{24}$ = mean annual 24-hr precipitation extreme (inches) (Fig. 9),

Cv = coefficient of variation (Fig. 9),

K = frequency factor or the number of standard deviations by which the considered extreme exceeds the sample mean.

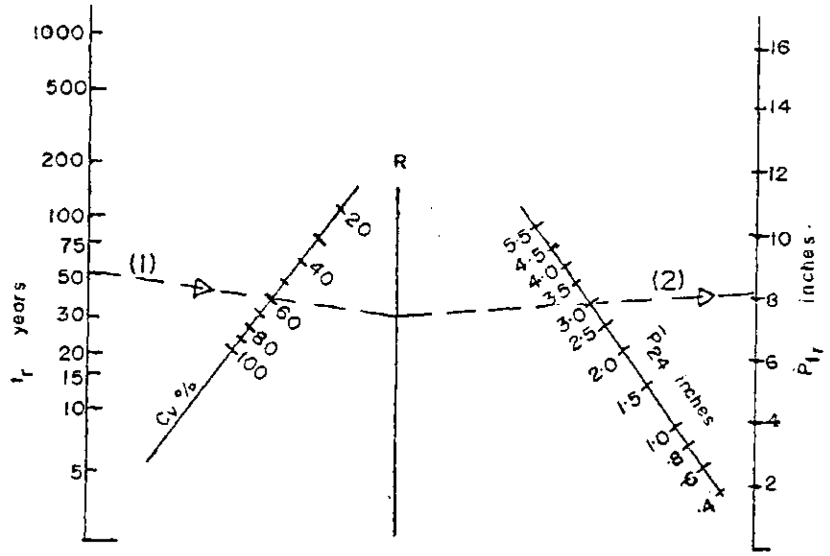
If the precipitation P_{tr} is known (from the simulator) the nomographic

Figure 9 Means and Coefficients of Variation of Annual 24-Hour Precipitation Extremes



Gray (1970)

Figure 10 Nomographic Solution of $P_{t_r} = \overline{P}_{24}(1 + KC_v)$



Example

Given years, $C_v = 60\%$, $\overline{P}_{24} = 3.0$ inches, $t_r = 50$ years

Proceed from $t_r = 50$ along line (1) through $C_v = 60$ to line R

From point of intersection on line R proceed along line (2)

Through $\overline{P}_{24} = 3.0$ to scale P_{t_r} read answer $P_{t_r} = 8.2$ inches

Gray (1970)

solution can be worked backwards to calculate the corresponding return period in years.

A diagram of the rainfall simulator is shown in Fig. 11 and Table 2 lists the sites where tests were made. The flume carried water and sediment outside of the covered structure to the collecting jars (.946 litre glass jars with sealed screw-top lids). The runoff was collected at 5-minute intervals throughout the 60 minute storm. The two storm intensities, approximately 2.7 cm/h and 4.6 cm/h, were triplicated at the Kernen and St. Denis sites. Only the 2.7 cm/h intensity was triplicated at the Lanigan site. Beakers, placed at each corner of the metre square plot, served as rain gauges. Rainfall intensity was calculated for each storm from the volume of water and area of the beakers. All samples were stored for several months in a coldroom at $4^{\circ}C$ until analyzed. A sample of the water used at each site also was collected. The runoff volume per 5 minute intervals was measured and hydrographs constructed. The runoff-suspension mixture for each interval was decanted and the remaining water and suspension was centrifuged at 2,000 rpm for 20 minutes to remove the fine clays from suspension. The soil fraction obtained was dried and weighed for each time interval. The triplicated soil fractions were bulked according to the time interval. Further compositing was necessary to obtain enough soil for ^{137}Cs measurements.

Before each simulator-run a soil sample of the 0-5 cm depth was collected and the moisture and bulk density determined. A second bulk soil sample of the 0-5 cm depth was collected after the run. All soil samples (including suspension, source and eroded soils) were analyzed for organic carbon, total nitrogen, particle size distribution and

Figure II Rainfall Simulator

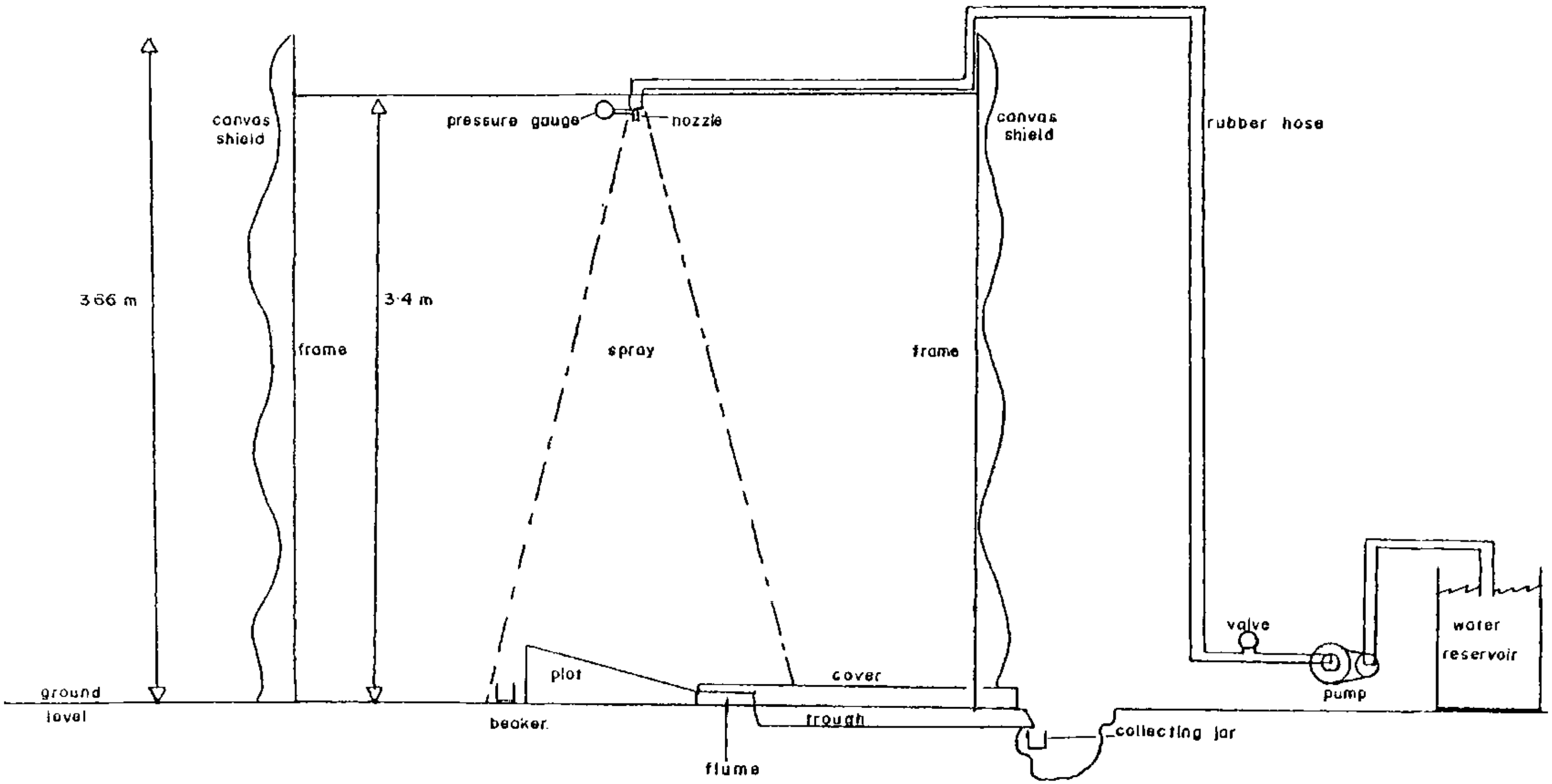


Table 2. Soils at the sites used for wind and water erosion tests.

Site	Soil association	Classification	Texture
Kernen farm (edge of cultivated field)	Sutherland	Dark Brown Chernozem	Silty clay loam
St. Denis (fallow)	Weyburn-Biggar	Dark Brown Chernozem	Sandy loam
Lanigan Farm (fallow, broken 3 yrs previously)	Oxbow	Black Chernozem	Loam
Goodale Farm (fallow, stubble crop)	Bradwell	Dark Brown Chernozem	Fine sandy loam

^{137}Cs activity. The runoff was analyzed for soluble Ca, Mg, K and Na by the flame spectrometer and for dissolved NH_4^+, NO_3^- and HPO_4^{-2} on a Technicon AutoAnalyzer. All analyses followed standard soil test procedures.

The erosion index (EI) was calculated for each rainfall intensity (Table 3). The kinetic energy of 1 cm of rain falling on one hectare is calculated from its potential energy by:

$$KE = mgh$$

where KE = kinetic energy, tonne-metres/ha/cm of rain,

m = mass, tonnes/ha, of one cm of rain on one hectare,

g = accelation due to gravity, metres/second squared,

h = height of fall, metres.

Table 3. Rainfall intensities used during the simulation and soil properties at the start of the rain.

Site	Rep.	Pressure (kPa)	Intensity (cm/h)	EI (tonne-m/ha/h)	Return period (yrs)	Time to runoff (min)	Antecedent moisture (% by wt.)	Bulk density (g/cm^3)
Kernen	1	69	2.8	3.1	10-15	12	11.8	0.93
	2	69	2.5	2.6	10-15	10	10.4	1.02
	3	69	2.5	2.6	10-15	18	10.4	1.04
	4	138	4.8	9.3	>100	14	8.6	1.17
	5	138	4.3	7.5	>100	18	11.8	0.93
	6	138	4.6	8.4	>100	16	11.8	0.92
St. Denis	1	69	2.5	2.6	10-15	3	12.7	1.30
	2	69	2.8	3.1	10-15	4	15.8	1.26
	3	69	2.8	3.1	10-15	8	15.8	1.38
	4	138	4.6	8.4	>100	3	13.7	1.33
	5	138	4.6	8.4	>100	4	13.7	1.41
	6	138	4.8	9.3	>100	3	13.7	1.28
Lanigan	1	69	2.5	2.6	10-15	15	21.9	0.85
	2	69	3.5	4.4	10-15	21	20.4	0.90
	3	69	2.5	3.1	10-15	15	9.4	0.83
Goodale	1	138	4.5	-	>100	*	-	-

*An attempt to obtain runoff from the rainfall simulator failed at the Goodale site. After 2 hrs of rainfall at 4.5 cm/h there was still no runoff and the experiment was discontinued to estimate what proportion of the air stream was sampled, thus an accurate measure of soil loss by suspension could not be obtained. Therefore the wind tunnel experiment was not used to estimate actual soil losses by wind erosion, but rather to collect samples typical of materials lost by saltation and suspension. The soil under the tunnel was sampled before and after the erosion to depth of 5 cm. Each sample of the source material, eroded soil, saltation and suspensions was analyzed for organic carbon, total nitrogen and phosphorus, particle size distribution and ^{137}Cs activity. A description of the four test sites is given in Table 2. The replicates at the Kernen and St. Denis sites were bulked to obtain sufficient soil for analysis.

3.3 ^{137}Cs Distribution in Small Watersheds

An estimate of soil erosion can be obtained using ^{137}Cs fallout from atmospheric tests of thermonuclear devices. During the summer of 1980 four well-defined basins were selected for a ^{137}Cs tracer study. The basins are paired, cultivated and native (or in pasture for over 30 yrs). Each pair has the same soil association (Table 4) and was subject to the same climatic factors. The basins are enclosed, i.e., all water drains from the knoll position into the centre depression,

Table 4. Location, land use and soils used for ^{137}Cs sampling.

Site	Land use	Soil association	Classification	Texture
Lanigan Farm	1) Fallow 2) Crested wheat grass, 35 yrs	Oxbow	Black Chernozem	Loam
St. Denis	1) Fallow 2) Native prairie	Weyburn-Biggar	Dark Brown Chernozem	Sandy loam

and there are no secondary deposition sites. The basins were surveyed to define the drainage pattern (contour maps were drawn by R. Kachanoski). Surface water flow patterns within the basin were drawn according to a method by Speicht (1968). Different length-slope combinations were sampled at the foot, the midslope and the knoll positions. One sample was taken at the lowest point in the depression.

The soil was sampled to the C horizon. The sampling interval was generally 10 cm for all positions other than the depression and the knoll positions. The centre of the depression was sampled by 5 cm intervals until a minimum depth of 30 cm. A single sample to a 15 cm depth was taken on the knoll positions when the C horizon was reached at that depth. A hydraulic corer (11.4 cm diameter) was used to take two or more cores at each landscape position to obtain at least 1000 grams of material for each depth increment. Each sample was analyzed for organic carbon, total nitrogen and phosphorus, particle size distribution, Middleton's dispersion index and ^{137}Cs activity. Bulk densities were calculated for each sampling depth.

3.4 Analysis

Soil samples for ^{137}Cs analysis were air-dried, ground and passed through a 2 mm sieve. Samples collected from the enclosed basins were counted for ^{137}Cs in 1 litre Marinelli beakers. The wind and water erosion samples were counted in 150 ml plastic containers. The soil samples were counted with a high purity germanium detector (APTEC PHYGE Series 1011) coupled to a Canberra Series 80 multichannel analyzer. A calibration curve relating counting efficiency to soil volume was drawn from data gathered by Villar (1981). Counting efficiency is related to the sample height above the detector. Preliminary studies showed that bulk density had a small but consistent effect on efficiency (de Jong et al. 1982). A computer program was developed that takes into account the effect of mass absorption of gamma radiation at different sample volumes and densities. The program calculates ^{137}Cs as pCi/g and converts this to an area basis using the field bulk density.

Organic carbon was determined using a dry combustion technique (Tiessen et al. 1981). Soil samples were analyzed for total nitrogen and phosphorus on the Technicon AutoAnalyzer using an acid digest and pretreatment for NO_3 (Thomas et al. 1967). Particle size distribution in the soil sample was determined by the pipette method (Am. Soc. for Testing and Materials 1959); in some cases, the sand fraction was subdivided with sieves. Middleton's dispersion ratio, which is a measure of the degree of aggregation, was calculated from the amount of <50 µm particles present in a dispersed and an undispersed suspension. The difference in concentrations between the two suspensions gives the amount of silt and clay aggregates in particles >50 µm. Middleton's dispersion ratio was calculated as: the percentage of particles smaller than 50 µm in the aggregated sample divided by the percentage of particles of the same size in the dispersed sample. The aggregation index is defined as: 100 minus Middleton's dispersion ratio.

4. RESULTS

4.1 Water Erosion

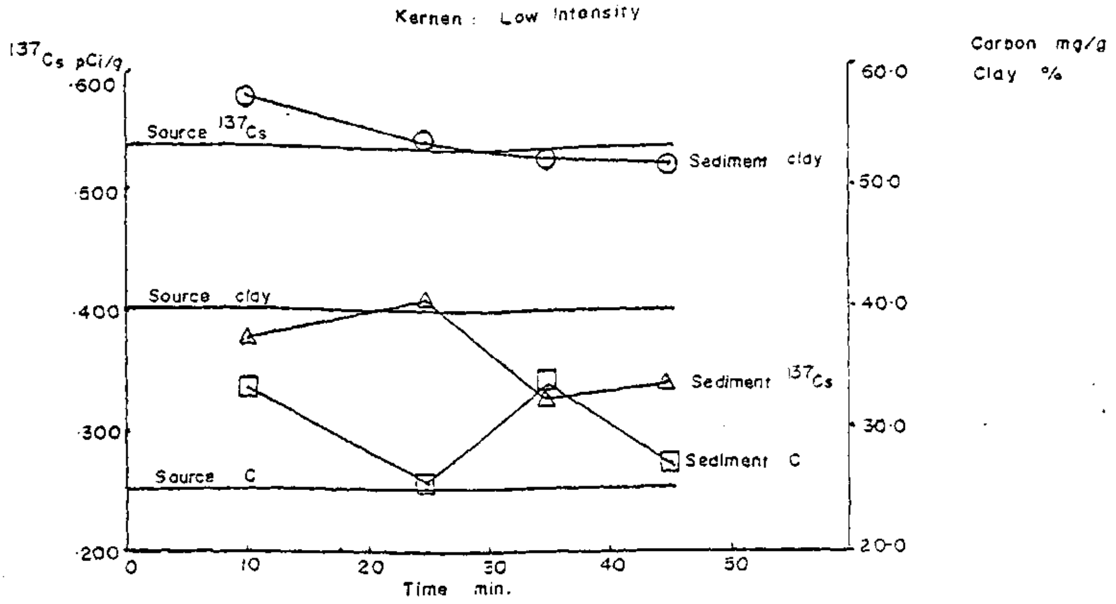
The sediment referred to in the analysis was the soil material carried in the runoff as suspension. The average discharge and sediment load for five-minute intervals for each storm intensity at the three sites are displayed in Figures A.1 to A.10 in Appendix I. The Goodale site had no runoff after a two hour simulated storm of 4.5 cm/h, presumably due to its light texture. Both discharge and sediment load showed high standard deviations when plotted against time at all three sites. Bertrand and Parr (1961) recommended that three replicates be run for each rainfall intensity to reduce the variability resulting from the soil and from the operation of the rainfall simulator. The infiltration rate is reduced when aggregates break down under raindrop impact and cause surface sealing. The dispersed fine particles fill the pores and further reduce the infiltration rate. Middleton's dispersion ratio measures the degree of dispersion of the silt and clay fraction of the soil. The Kernen site had a high aggregation index ranging from 60 to 78%. The low discharge rate (Figs. 1 and 3, Appendix I) compared to the St. Denis site, which had an aggregation index of 20 to 49%, reflects this difference in aggregation. The recently broken Lanigan site had the lowest discharge volume. The site has a high organic carbon content and was a Black Chernozem with an aggregation index of 27 to 46%. Organic matter aids in the cohesion and water stability of large aggregates thus increasing the infiltration capacity of a particular soil. Middleton's dispersion index was not determined for the Goodale site.

The runoff rate at all sites increased as time progressed and infiltration rate decreased. The sediment discharge tended to increase as the storm progressed however it varied independently of the runoff rate which agrees with the results of Wischmeier (1961). The runoff water was analyzed for ammonium (NH_4^+), nitrate (NO_3^-) and inorganic phosphate ($HPO_4^=$). The average values of NH_4^+, NO_3^- and $HPO_4^=$ in the runoff for all sites (Table A.11 in Appendix I) were not agronomically significant and are less than those found by Nicholaichuk and Read (1978).

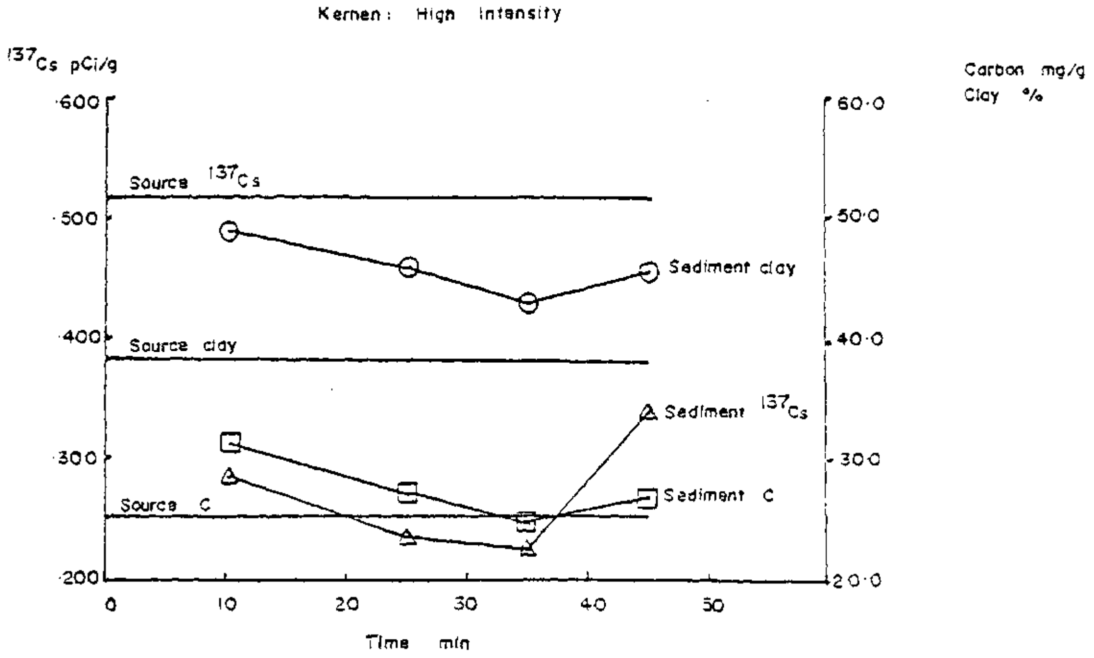
Differences in properties between the source and sediment material were determined using t-tests and are given in Table 5. The Lanigan site had little soil removed during runoff and the entire storm interval was combined and only a single value for each parameter was determined (Table A.4 in Appendix I).

At the Kernen site, ^{137}Cs activity, organic carbon and clay content of the sediment tended to decrease as time progressed (Fig. 12). The ^{137}Cs activity in the sediment was significantly less ($P < .01$) than that of the source. The sediment showed a trend to have a higher carbon content although it was not significantly different from the source. The sediment was significantly ($P < .05$) enriched in nitrogen (Table 5). The sorting effect of the runoff was limited at the Kernen site by its high aggregation index. However, the suspension was significantly ($P < .01$) enriched with clay and significantly ($P < .01$) depleted in sand (Table 5). The preferential movement of clay agrees with the results of Rhoton et al. (1979). The decreased ^{137}Cs activity of the sediment relative to the source material appears to be in direct opposition to the observed increases in clay and to a lesser degree organic carbon. There is no apparent explanation for

Figure 12 Water Erosion Sediment and Source Values of Cesium-137, Carbon and Clay



Kernen : Low Intensity



Kernen: High Intensity

Table 5. Comparison of soil properties at Kernen and St. Denis sites.

Site: Intensity	Comparison: Source and Sediment	$\bar{X}$ difference	Standard deviation	Significance
		Kernen site		
2.5 cm/h	^{137}Cs	0.1720	0.0307	**
	Carbon	-4.68	4.28	-
	Nitrogen	-0.7995	1.46	**
	Sand	13.11	3.45	**
	Silt	0.310	1.71	-
	Clay	-13.42	2.69	**
4.6 cm/h	^{137}Cs	0.2185	0.0551	**
	Carbon	-1.708	2.24	-
	Nitrogen	-0.2655	0.139	*
	Sand	4.38	2.99	-
	Silt	3.35	0.424	**
	Clay	-7.53	2.62	*
		St. Denis site		
2.8 cm/h	^{137}Cs	-0.1104	0.097	-
	Carbon	-11.29	6.44	*
	Nitrogen	-1.260	0.523	**
	Sand	13.370	7.18	*
	Silt	-5.92	3.27	*
	Clay	-7.10	4.40	*
4.6 cm/h	^{137}Cs	-0.4016	0.137	*
	Carbon	-19.21	11.3	-
	Nitrogen	2.0793	0.967	-
	Sand	27.30	21.5	-
	Silt	-7.9867	7.38	-
	Clay	-19.38	14.1	-

*P <.05

**P <.01

this contradiction.

At the Kernen site, the low intensity rain (Fig. 12) showed an increase in ^{137}Cs activity, organic carbon and clay content in the sediment collected during the last time interval. This increase may have been caused by the addition of the wash from the flume. The high initial loss of carbon and clay at the Kernen site may have been caused by particulate organic matter and dispersed aggregates. The breakdown of aggregates by raindrop impact is the highest during the initial stages of the storm when there is no water flow to protect the soil surface (Ellison 1947; Wischmeier and Smith 1958). The ^{137}Cs activity did not show a correlation with either carbon or clay but there was a strong correlation between carbon and clay (Table 6) at the Kernen site. Excluding the source samples, there is a positive correlation between ^{137}Cs and clay content, but not between ^{137}Cs and organic carbon of the sediment samples.

At the St. Denis site, ^{137}Cs, clay and organic carbon content of the sediment decreased with time (Fig. 13), and the same was true for nitrogen and silt (Table A.2 in Appendix I). The St. Denis site had the highest discharge volume of all sites which indicated a low infiltration capacity due to a low aggregate stability. The high initial losses of silt and clay (Table A.2 in Appendix I) also indicated a poor aggregate stability. As the storm progressed the material in suspension became coarser and lower in organic carbon as the erodible soil fractions were removed. Consequently, ^{137}Cs which is strongly correlated with both carbon and clay (Table 6) also decreased with time. As time progressed the ^{137}Cs, organic carbon and clay content of the sediment decreased and approached or dropped below

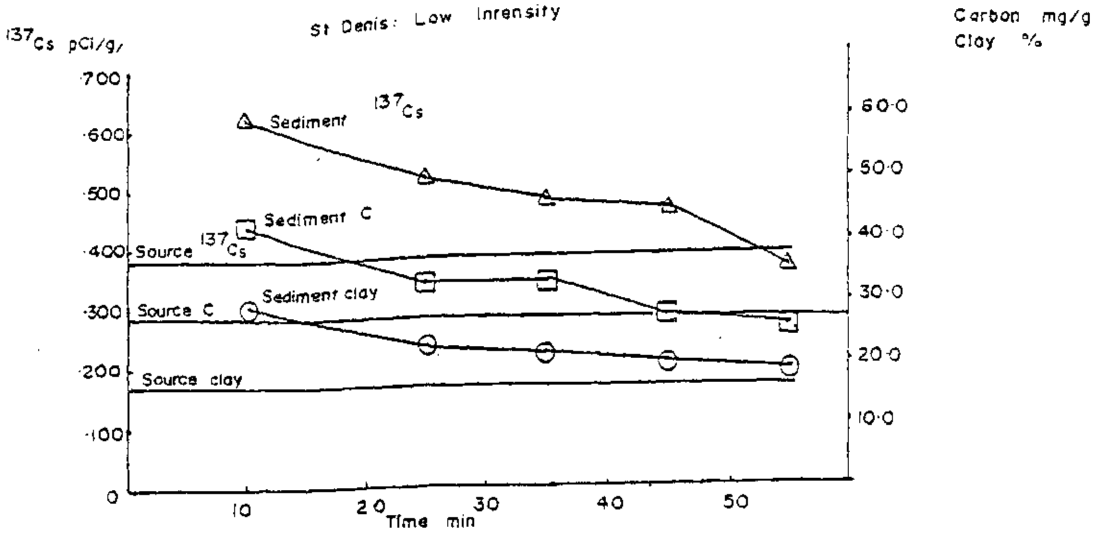
Table 6. Correlation coefficients between properties of water erosion samples.

	^{137}Cs	Carbon	Nitrogen	% sand	% silt	% clay	Degrees freedom
				Kernen			
^{137}Cs	1.0	-0.250	-0.572	0.270	0.473	0.362	8
Carbon (mg/g)		1.0	0.699*	-0.726	-0.146	0.719*	
Nitrogen (mg/g)			1.0	-0.896**	-0.151	0.881**	
				St. Denis			
^{137}Cs	1.0	0.920**	0.972**	-0.870**	0.872**	0.845**	8
Carbon (mg/g)		1.0	0.980**	-0.973**	0.962**	0.944**	
Nitrogen (mg/g)			1.0	-0.947**	0.939**	0.932**	

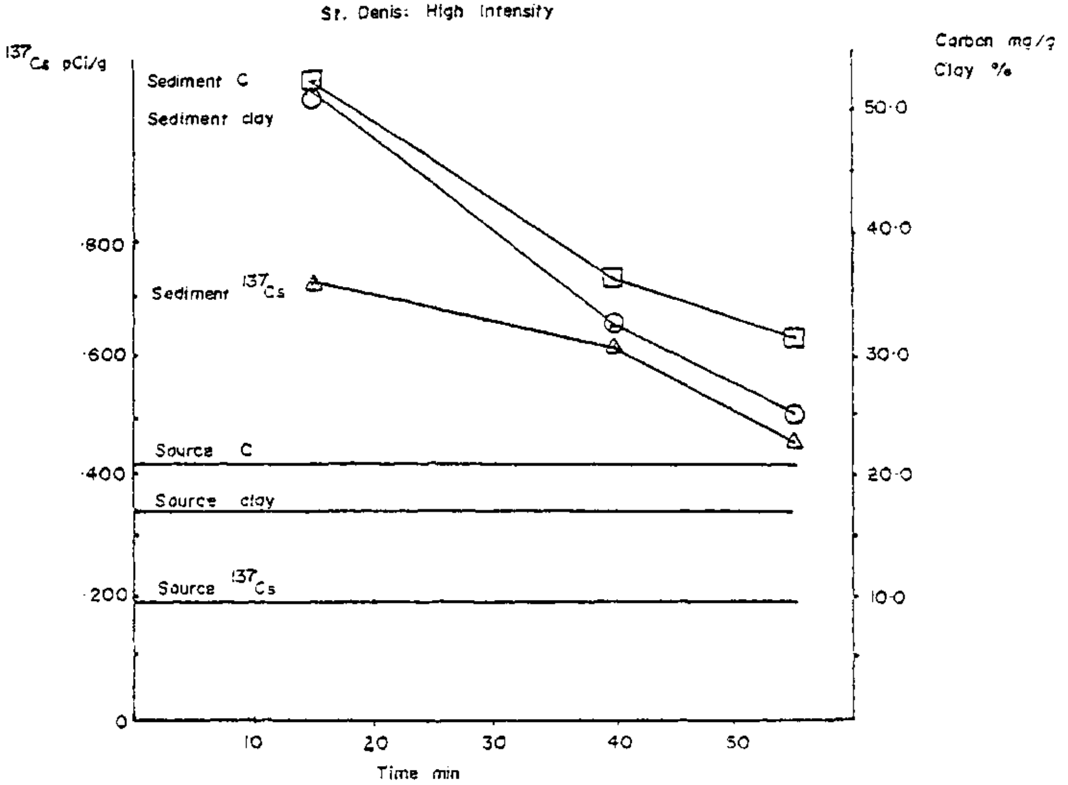
*P <.05

**P <.01

Figure 13 Water-Erosion Sediment and Source Values of Cesium-137, Carbon and Clay



St Denis: Low Intensity



St. Denis: High Intensity

the levels in the source material at the St. Denis site (Fig. 13). The initial ^{137}Cs activity in the sediment was extremely high (Table A.2 in Appendix I) compared to the source material. Once the easily detached and transported material was removed further erosion, due to raindrop impact, at the St. Denis site was low. The sediment at the 2.8 cm/h intensity was significantly ($P <.05$) enriched in organic carbon, total nitrogen, silt and clay (Table 5). At the high intensity rain the differences in C, N, silt and clay between the source and sediment were reduced as the initial high losses were followed by the erosion of the coarser soil fraction (for example, the sediment had an initial sand content of 6% which increased to 47% in the final interval). The ^{137}Cs activity was significantly ($P <.05$) enriched in the sediment (Table 5).

Only one intensity of rain (2.8 cm/h) was run at the Lanigan site. There was a low discharge rate (Fig. A.9 in Appendix I) and little material carried in suspension (Fig. A.10 in Appendix I). The sediment was enriched in ^{137}Cs, organic carbon and nitrogen, clay and silt as compared to the source. As there was only one sample it was impossible to perform any statistical analysis. The total soil obtained over the entire 45 minute storm was 17.91 grams (Table A.4 in Appendix I), much lower than the soil loss for comparable simulated storms at the Kernen and St. Denis sites.

4.2 <u>Wind Erosion</u>

The wind tunnel experiment was twice replicated at each of the four sites. Soil samples were collected from: (1) the source material before erosion, (2) the eroded soil after erosion had ceased, (3) the soil moved by saltation, and (4) the soil moved in suspension.

The ^{137}Cs activity of the source material and corresponding eroded soil sample did not differ. This is to be expected as only a small portion of the topsoil was eroded during the test. Therefore, the source and eroded samples were combined and subsequently analyzed as representative of the source material. At the Kernen and St. Denis sites the replicates were combined to obtain sufficient suspension soil material for analysis. Each replicate of the Goodale and Lanigan sites was analyzed separately.

The levels of ^{137}Cs activity, organic carbon, total nitrogen and phosphorus, and the particle size distribution of the source, saltation and suspension samples are portrayed in Figures 14 to 18. For the Goodale and Lanigan sites, the replicates were averaged before being included in the figures. Significant differences in the various parameters were determined using t-tests (assuming equal variances and a normal distribution) and are given in Table 7.

In all wind tunnel experiments the suspension was significantly enriched with ^{137}Cs (Table 7 and Fig. 14), while there was no signficant difference in any soil property between the source and saltation samples. The general trend, except for the Kernen site, shows a lowering of total nitrogen and phosphorus in the saltation material (Table A.1 in Appendix I). The saltation sample is only partially representative of the extreme sorting that has helped form the drifts on field edges. There was a lowering of ^{137}Cs, organic carbon, total nitrogen and phosphorus, silt and clay in the saltation sample compared to the suspension at all sites.

Soil moved by saltation consists of aggregates and primary sand particles (Chepil and Woodruff 1963) and drifts tend to have a higher

Figure 14 Cesium-137 and Carbon in Wind Erosion Samples

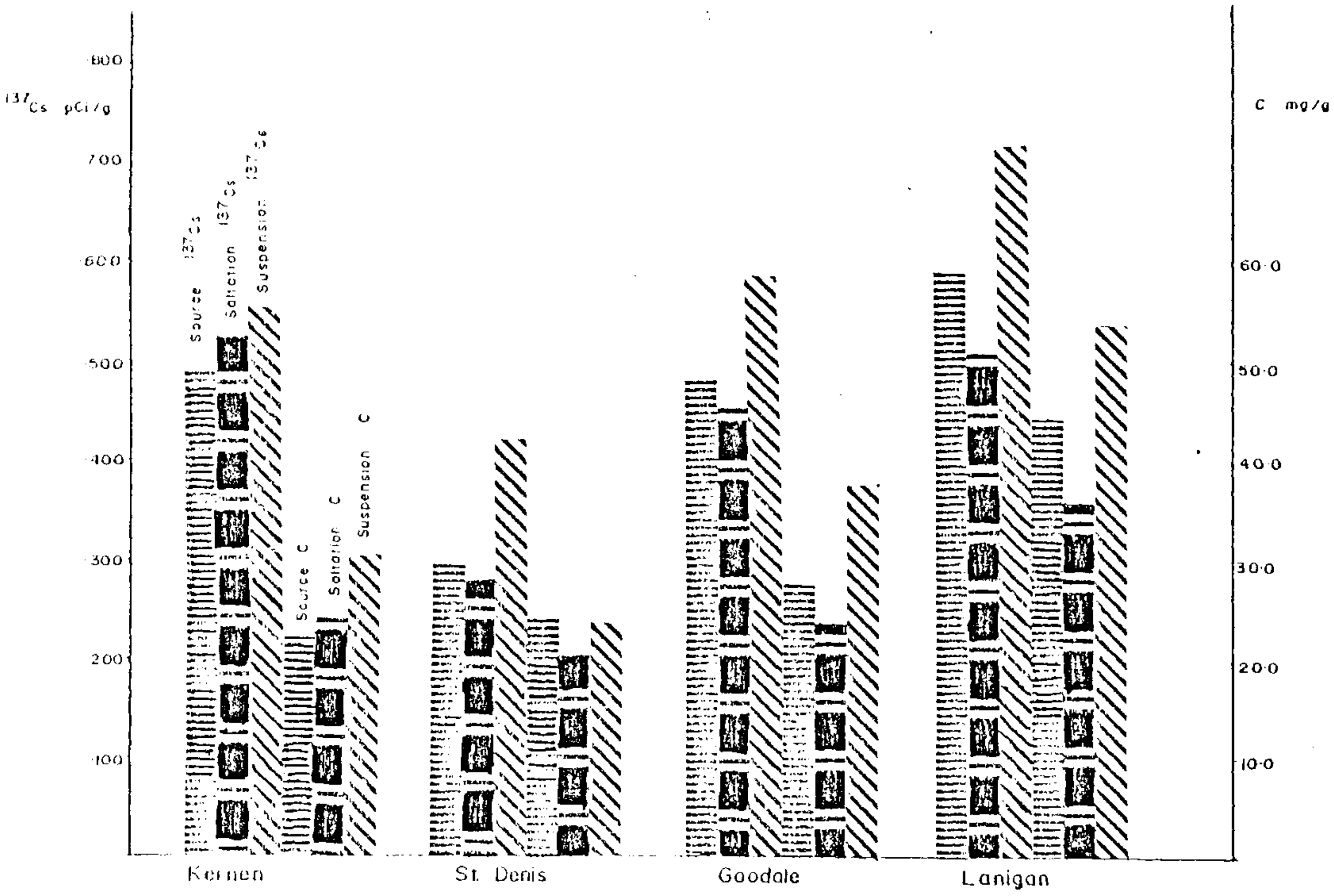


Figure 15 Nitrogen and Phosphorus Levels in Wind Erosion Samples

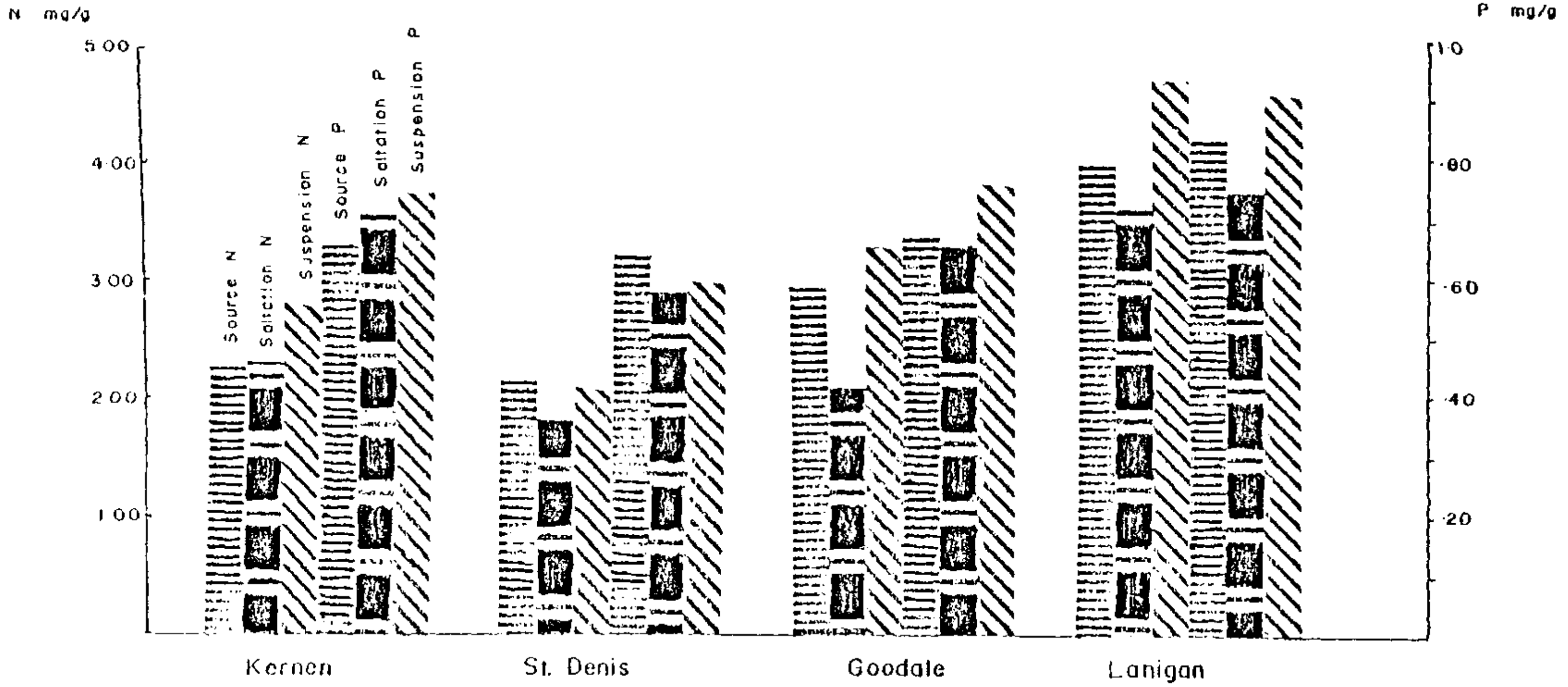


Figure 16 Sand % in Wind Erosion Samples

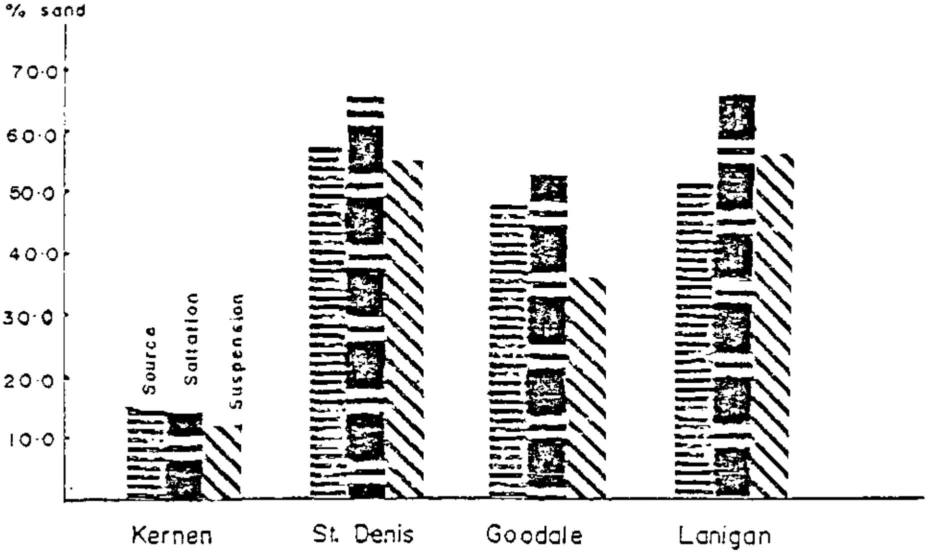


Figure 17 Silt % in Wind Erosion Samples

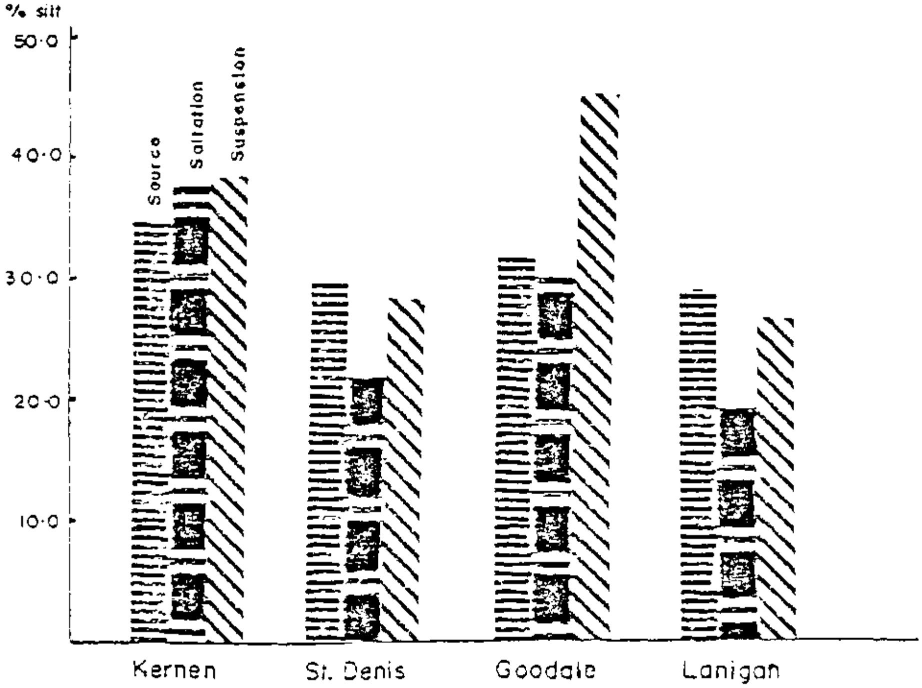
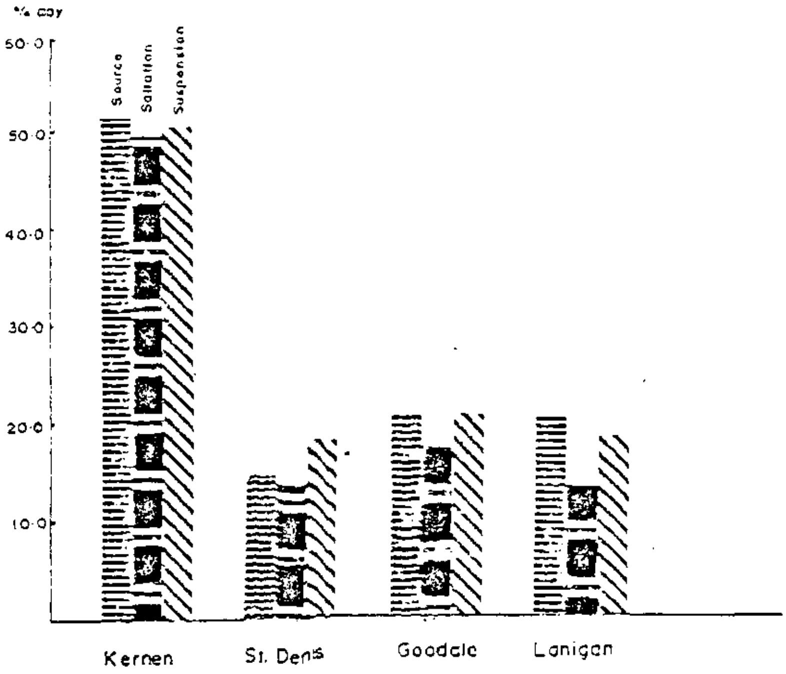


Figure 18 Clay % in Wind Erosion Samples



percentage of sand and are generally less fertile than the original soil (Moss 1935; Daniel and Langham 1936). The saltation samples of the St. Denis and Lanigan sites were enriched in sand compared to the source (Fig. 16). There was little difference in sand content between the saltation and source samples at the Kernen site. The Kernen site was a well-aggregated clay loam and compared to the other sites it has a low sand content (Fig. 16). Generally sand particles move in saltation and breakdown aggregates by abrasion. Possibly at the Kernen site the percent sand was insufficient to initiate aggregate break down and cause the sorting effect found in the suspension and

Table 7. Differences in soil properties between source, saltation and suspension collected in the wind tunnel experiment[1].

Soil property	Comparison	X difference	Standard deviation	Significance
^{137}Cs	Source and Saltation	0.0172	0.0486	-
	Source and Suspension	-0.1084	0.0311	**
	Saltation and Suspension	-0.1256	0.0755	*
Carbon	Source and Saltation	3.3400	4.64	-
	Source and Suspension	-6.6625	4.75	-
	Saltation and Suspension	-10.0020	6.80	-
Nitrogen	Source and Saltation	0.2700	0.247	-
	Source and Suspension	-0.5000	0.364	-
	Saltation and Suspension	-0.7700	0.439	*
Phosphorus	Source and Saltation	0.0202	0.0569	-
	Source and Suspension	-0.0515	0.0684	-
	Saltation and Suspension	-0.0718	0.0640	-
Sand	Source and Saltation	-7.45	7.36	-
	Source and Suspension	3.20	7.24	-
	Saltation and Suspension	10.65	6.42	*
Silt	Source and Saltation	4.0750	5.64	-
	Source and Suspension	-3.400	6.97	-
	Saltation and Suspension	-7.475	5.44	-
Clay	Source and Saltation	3.3375	2.90	-
	Source and Suspension	0.1875	2.34	-
	Saltation and Suspension	-3.1500	1.63	*

[1] Paired t-test on means for each of the 4 test sites

*P <0.01

**P <0.05

saltation samples of the other sites.

Clay particles will remain in aggregates unless the latter are broken down by the abrasive action of saltation. At the Kernen site, the suspension is not enriched in clay (Fig. 18). This may be due to the lack of abrasive action by sand at the Kernen site which could affect the amount and type of material moved into suspension. Only the St. Denis site, which had the highest sand content, showed a significant enrichment of clay in the suspension (Table A.1 in Appendix I) supporting the results of Gillette and Walker (1977). At this site the suspension was not enriched in organic carbon, which contrasts with the observations at the remaining three sites. The enrichment of carbon in the material moved in suspension agrees with the findings of Delany and Zenchelsky (1976). The variability in the amount of aggregation and organic matter found in the soil are expected to affect the percent clay and organic carbon found in suspension. In Table 8 correlations between the measured soil properties for the different samples (source, saltation and suspension) are given. The data for the Kernen and St. Denis site must be treated with extreme caution because of the low sample numbers. At all sites there is a strong positive correlation between specific activity of ^{137}Cs and carbon, but the correlation between percent clay and ^{137}Cs ranged from -0.642 to 1.00. The generally poor correlation between ^{137}Cs and clay is not in agreement with the literature (Miller and Reitemeier 1963; Tamura 1964) which states that ^{137}Cs is strongly sorbed to the clay fraction of the soil. Some variability in the

Table 8. Correlation coefficients between properties of the wind erosion samples.

	^{137}Cs	Carbon	Nitrogen	Phosphorus	% sand	% silt	% clay	Degrees freedom
				Kernen				
^{137}Cs (pCi/g)	1.0	0.948	0.863	1.00**	-0.921	1.00**	-0.642	1
Carbon (mg/g)		1.0	0.979	0.945	-0.997*	0.938	-0.364	
Nitrogen (mg/g)			1.0	0.858	-0.992	0.848	-0.167	
Phosphorus (mg/g)				1.0	-0.917	1.00**	-0.649	
				St. Denis				
^{137}Cs (pCi/g)	1.0	0.507	0.494	-0.286	-0.720	0.471	1.00**	1
Carbon (mg/g)		1.0	1.00**	0.681	-0.963	0.999**	0.525	
Nitrogen (mg/g)			1.0	0.692	-0.959	1.00	0.512	
Phosphorus (mg/g)				1.0	-0.459	0.711	-0.266	
				Goodale				
^{137}Cs (pCi/g)	1.0	0.849*	0.794	0.904*	-0.936**	0.915*	0.194	4
Carbon (mg/g)		1.0	0.991**	0.973**	-0.928**	0.831*	0.493	
Nitrogen (mg/g)			1.0	0.952**	-0.881*	0.758	0.589	
Phosphorus (mg/g)				1.0	-0.921**	0.854*	0.369	
				Lanigan				
^{137}Cs (pCi/g)	1.0	0.936**	0.838*	0.547	-0.535	0.571	0.490	4
Carbon (mg/g)		1.0	0.944**	0.788	-0.663	0.706	0.599	
Nitrogen (mg/g)			1.0	0.887*	-0.571	0.615	0.504	
Phosphorus (mg/g)				1.0	-0.593	0.624	0.536	

*P <.05

**P <.01

^{137}Cs-clay correlation may be due to the small sample sized used in the statistical analysis. Carbon and clay were not significantly correlated at any of the sites (Table 8) which contrasts with the results of the water erosion experiment (Table 6). The high correlation between organic carbon and nitrogen was expected and the correlation between ^{137}Cs and total nitrogen is a reflection of the near constant C/N ratio. Organic carbon and total phosphorus are also positively correlated but the relationship is not as significant as the one between organic carbon and total nitrogen. There is a strong negative correlation at all sites between ^{137}Cs and sand. This was expected as sand particles have few adsorption sites for any nutrients, organic molecules or radionuclides.

The suspended material in the runoff of the rainfall simulator tests varied significantly with time (see Section 4.2). A similar variation with time is expected in the wind suspended material, however, the data cannot show this as only a single suspension sample was collected. This sample represents an average of the soil material that could be lost during one wind erosion event. Similarly, the saltation sample represents an average for the particular wind-erosion run.

4.3 Basin Studies

Each sample site within the basin was assessed as to its relative position in the landscape, i.e., footslope, midslope, and knoll. Slope positions were defined in terms of possible overland water flow, e.g., knoll positions represent the uppermost position from which water could flow to the footslope and depression sites, and elevation alone does not define slope positions.

As part of the experiment each basin was surveyed and contour maps drawn (Figs. 19-22). Water flow lines were drawn according to a method by Speight (1968) (Figs. A.11-A.14 in Appendix I). This procedure gives an approximate picture of overland water movement within the basins. Because of the grid system used each flow line represents an area of 5 x 5 square metres. The water flow patterns help to distinguish deposition areas, gullies and ridges within the basin. The total area that contributed to flow at a sample point was calculated by counting the incoming flow lines. The effective length of all slopes contributing to surface flow at a given sample site was determined by counting the number of flow lines crossing a line of 2.5 metres drawn on either side of the sampling points parallel to the contour lines and multiplying this number by 5. The slopes within the basin were rarely of uniform length and gradient. The equation for water erosion on irregular slopes developed by Foster and Wischmeier (1974) (described in Section 2.2 of Literature Review) was used to relate slope length combinations to soil properties. The equation on Page 11 was used to calculate two values for LS based on L values representing:

(1) The effective slope length (based on the total contributing area to the sample point),

(2) The simple slope length (the distance from the sample point to the highest point on that slope).

The slope for a particular sample point was determined from the distance between the contours and the height of the contour interval. In both slope-length parameters, the slope percent for a sample point was the same.

The basin samples were analyzed for ^{137}Cs activity, organic

Figure 19. Topographic map of Lanigan cultivated basin.

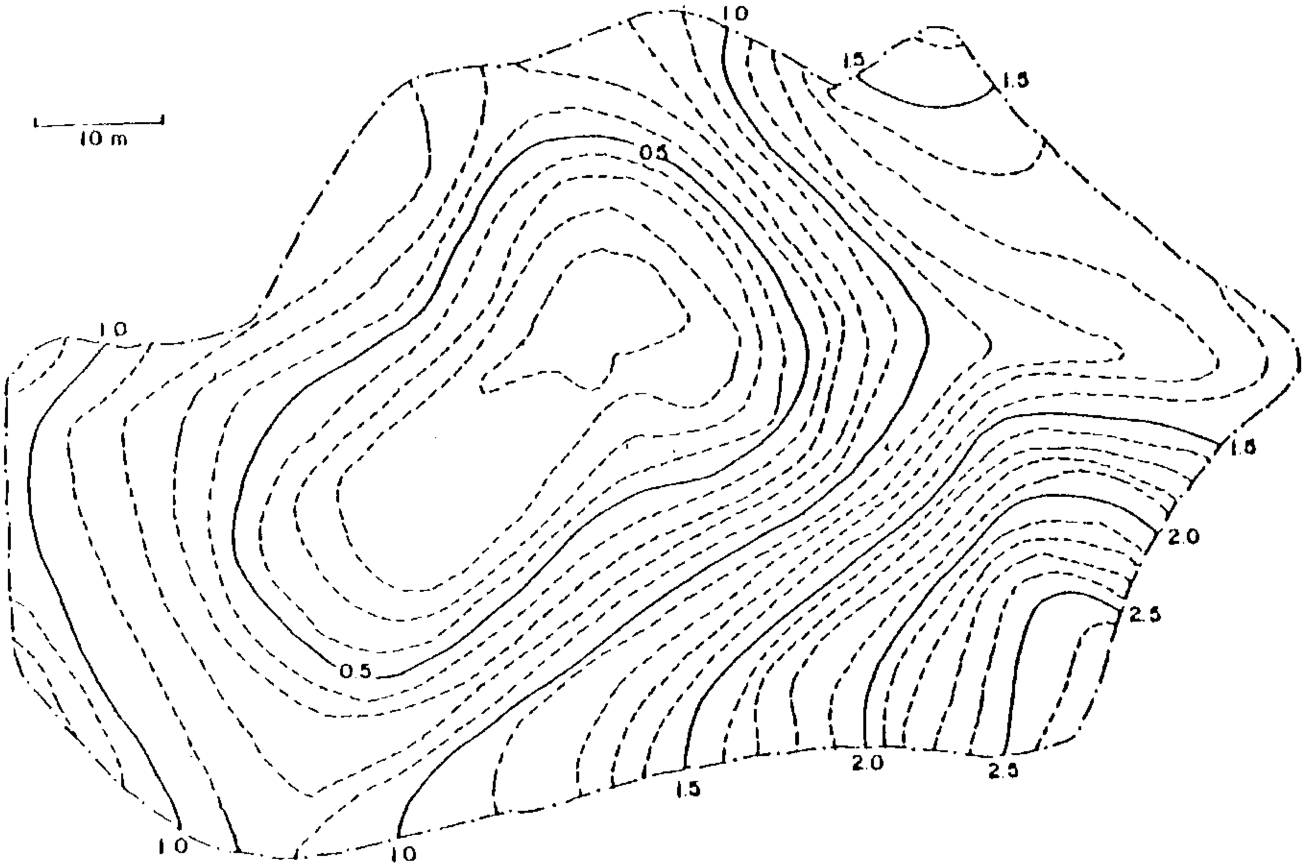


Figure 20. Topographic map of Lanigan control basin.

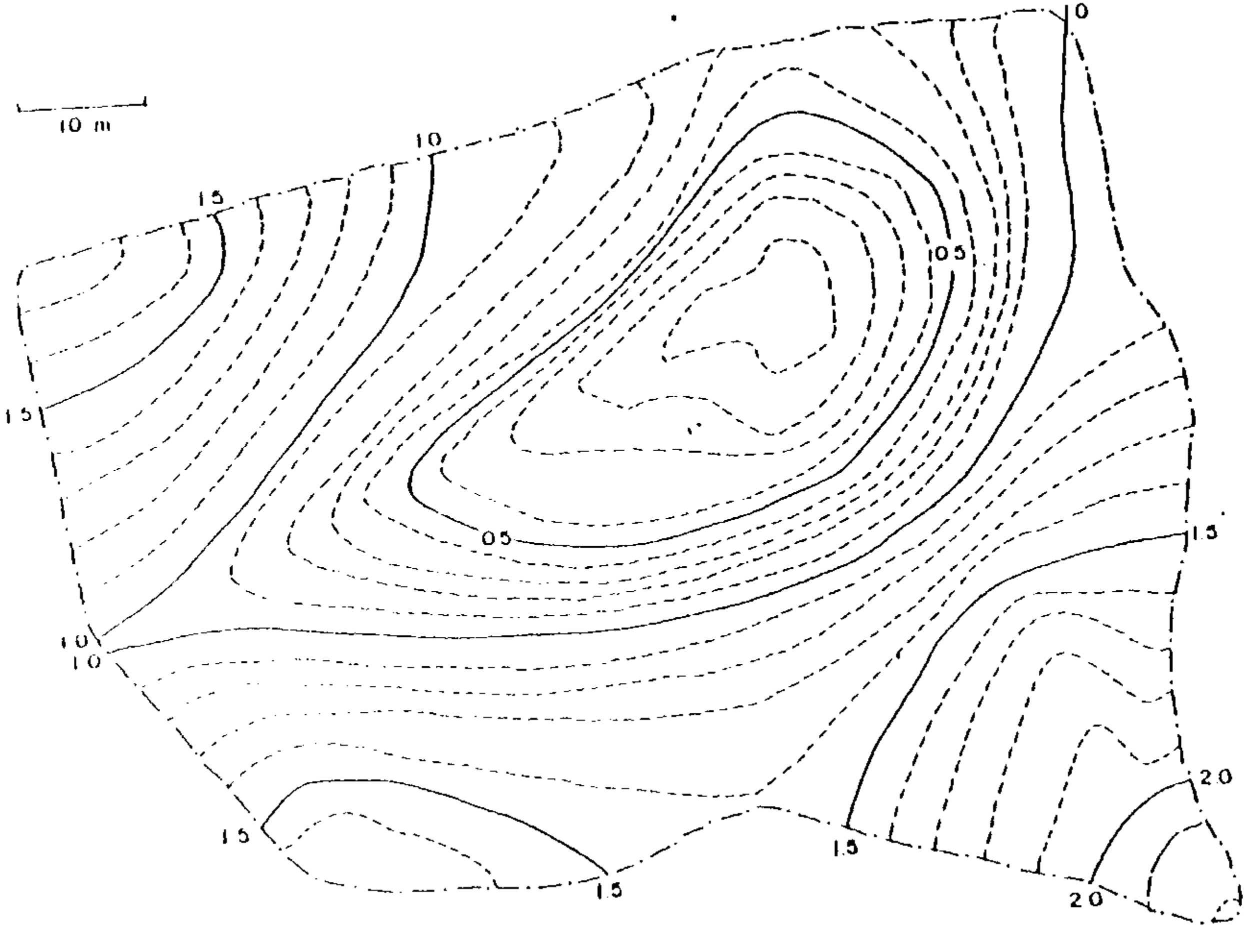
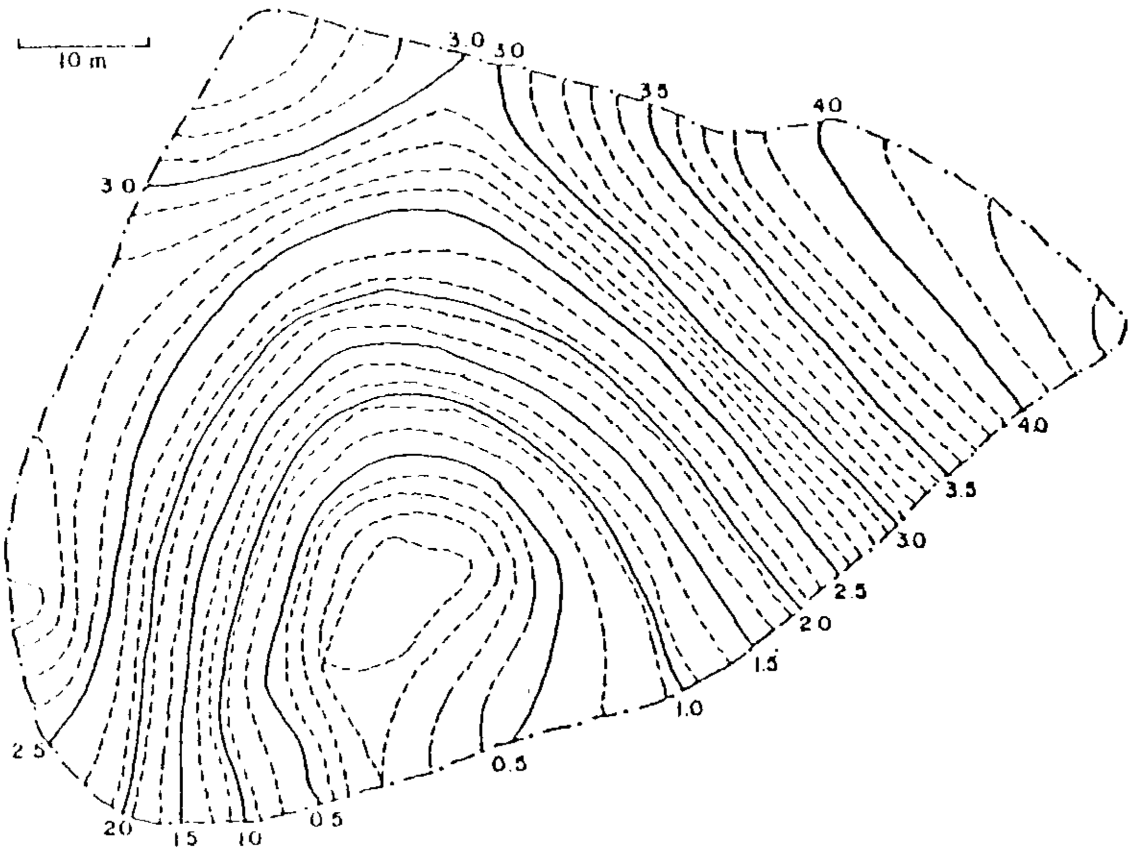


Figure 21. Topographic map of St. Denis cultivated basin.



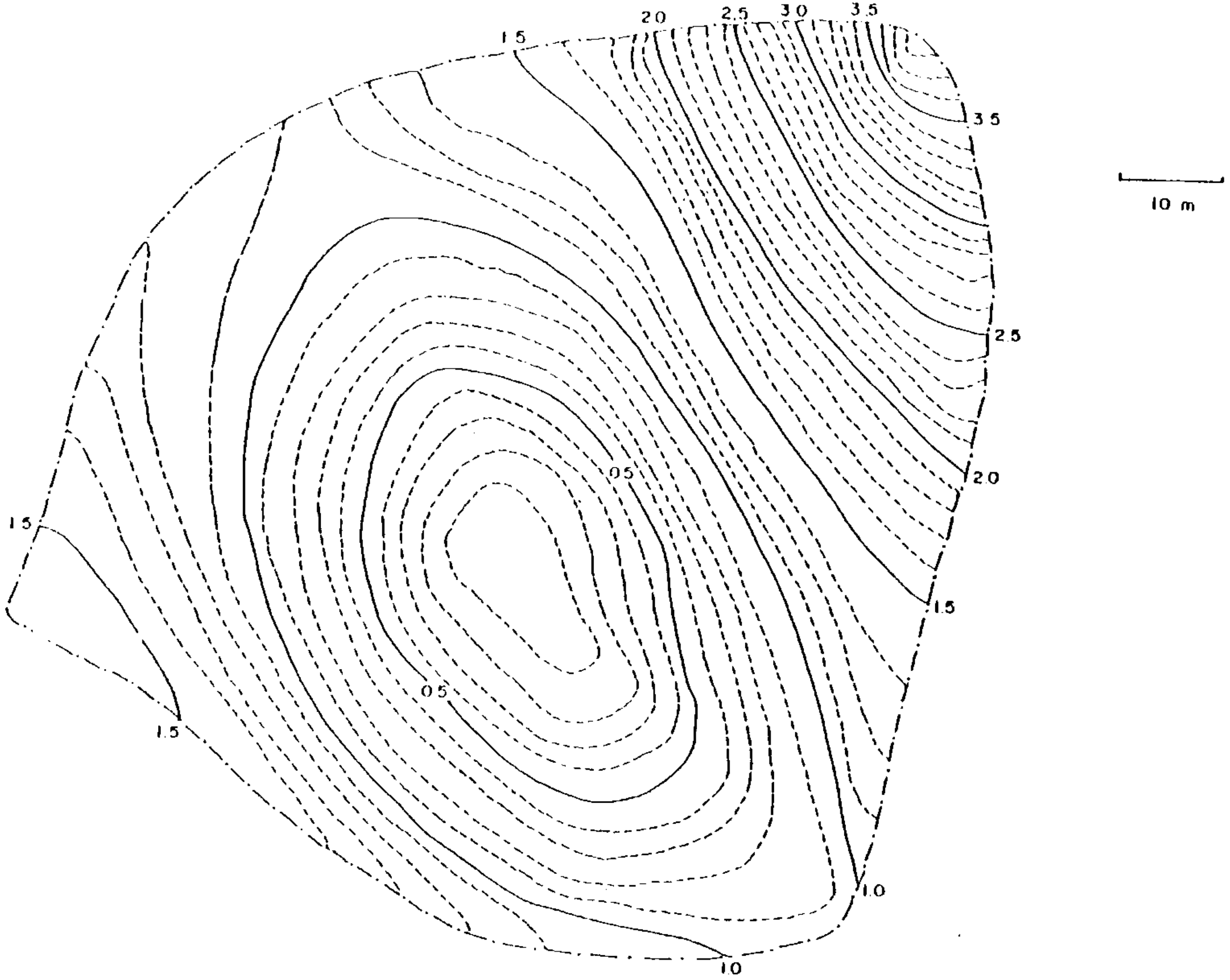


Figure 22. Topographic map of St. Denis control basin.

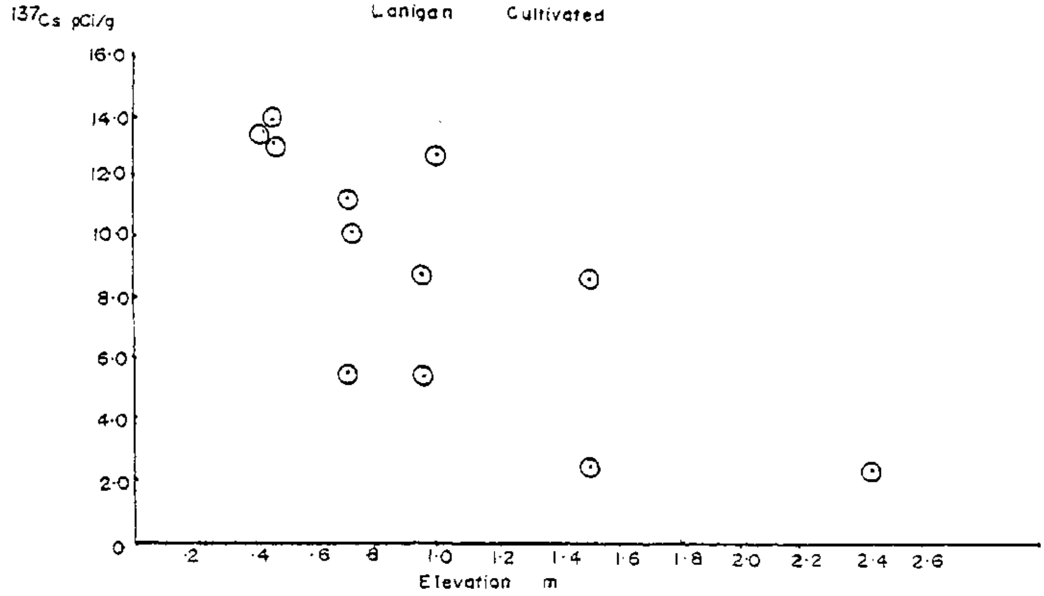
carbon, total nitrogen, total phosphorus and particle size distribution. Soil property values were separated according to their landscape position (Tables A.6-A.9 in Appendix I). The depression values were not included in the statistical analysis. Differences between means for slope positions were determined using t-tests. Correlation coefficients between soil properties to the depth to which ^{137}Cs is found, are given in Table 9. The relationship between ^{137}Cs activity and elevation for each site are graphed in Figures 23 and 24. Figures 25 and 26 portray the relationship between ^{137}Cs activity and simple slope length.

Negative correlations occur between ^{137}Cs activity and elevation (Table 9, Figs. 23 and 24) at the cultivated sites. The relationship of decreasing ^{137}Cs with increasing elevation is due to the combined effect of wind and water erosion. The St. Denis control site also shows this negative correlation, which may be due to deposition of wind eroded material within the basin. In the centre of the native site there were shrubs standing over 5 metres high. During the winter months the shrubs acted as snow traps. In the early spring of 1982 the snow varied from a 15 cm depth on the knolls to a 45 cm depth in the depression. Wind blown soil was visible in the snow of the depression. The Lanigan control shows no correlation between ^{137}Cs activity and elevation which suggests that no significant erosion or soil deposition occurred at this site.

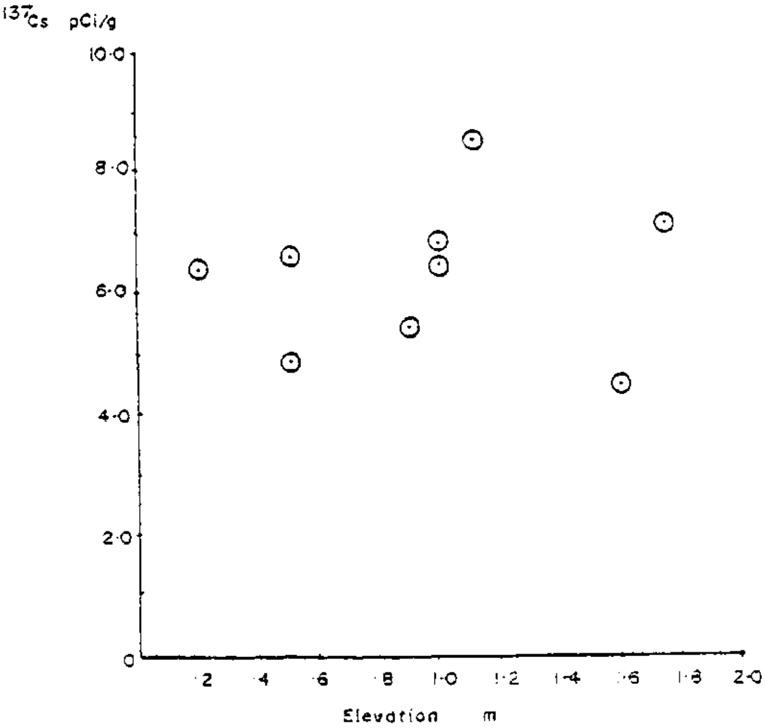
Both cultivated sites showed positive correlations ($P < .05$) (Table 9, Figs. 25 and 26) between ^{137}Cs activity and the simple slope length. The runoff from the longer slope erodes over a larger area thus a greater amount of ^{137}Cs may be removed and deposited in the

Figure 23 The Effect of Elevation[1] on Cesium-137 Levels : Lanigan

Lanigan Cultivated



Lanigan Control



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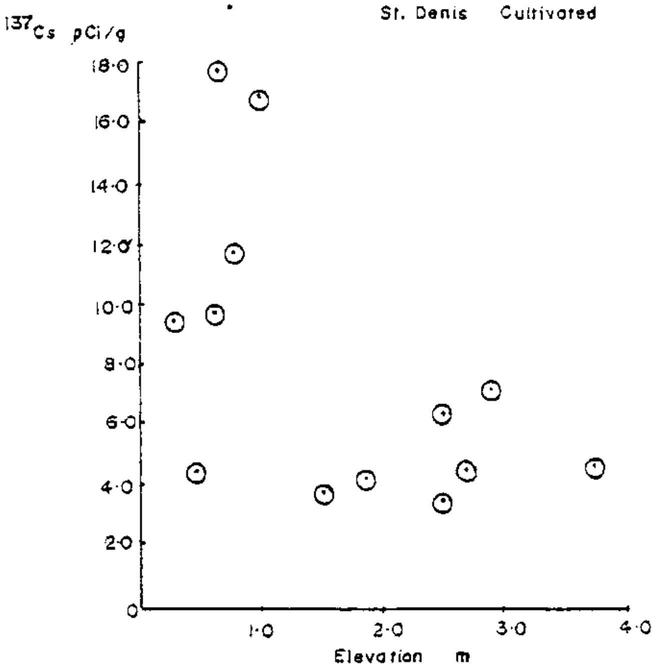
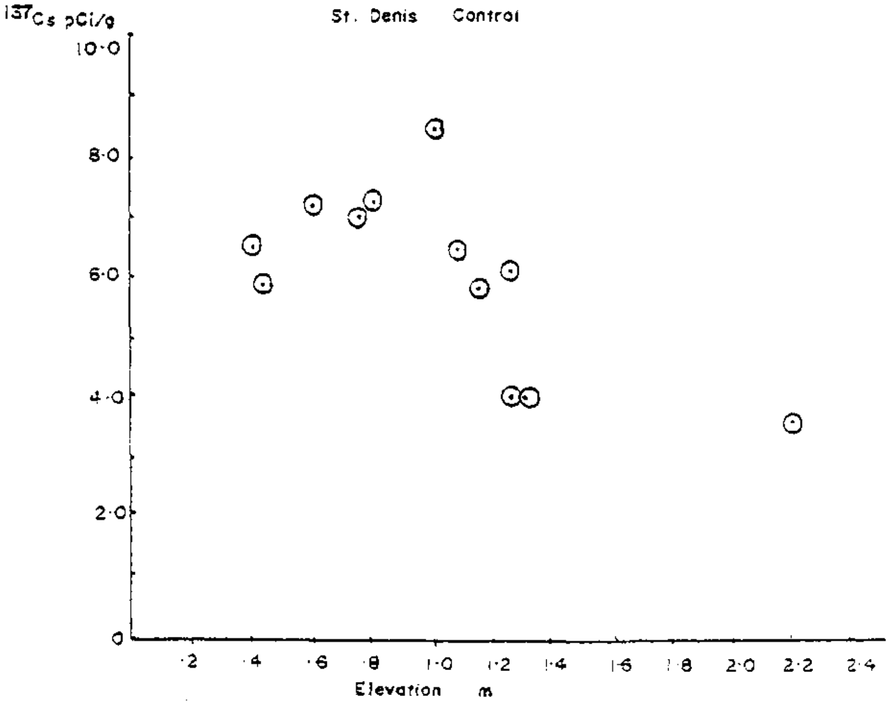
[1] Relative to the central depression sampling point.

Figure 24 The Effect of Elevation[1] on Cesium-137 Levels: St. Denis





[1] the central depression sampling point.

Table 9. Correlation coefficients between soil properties[1].

	^{137}Cs	Carbon	Nitrogen	Phosphorus[2]	Length[3]	Elevation	Degrees of Freedom
			Lanigan				
Treatment:							
^{137}Cs (pCi/cm^2)	1.0	0.385	0.537*	0.518	0.538*	-0.804**	12
Carbon (mg/cm^2)		1.0	0.912**	0.637*			
Nitrogen (mg/cm^2)			1.0	0.852**			
Control:							
^{137}Cs (pCi/cm^2)	1.0	0.148	0.130	0.001	-0.135	0.119	9
Carbon (mg/cm^2)		1.0	0.791**	0.248			
Nitrogen (mg/cm^2)			1.0	0.768**			
			St. Denis				
Treatment:							
^{137}Cs (pCi/cm^2)	1.0	0.602*	0.567*	0.513	0.680*	-0.535	11
Carbon (mg/cm^2)		1.0	0.970**	0.670*			
Nitrogen (mg/cm^2)			1.0	0.625*			
Control:							
^{137}Cs (pCi/cm^2)	1.0	0.301	0.089	-0.165	0.266	-0.589*	11
Carbon (mg/cm^2)		1.0	0.900**	0.754**			
Nitrogen (mg/cm^2)			1.0	0.848**			

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[1] C,N,P present in the depth of soil in which ^{137}Cs was present

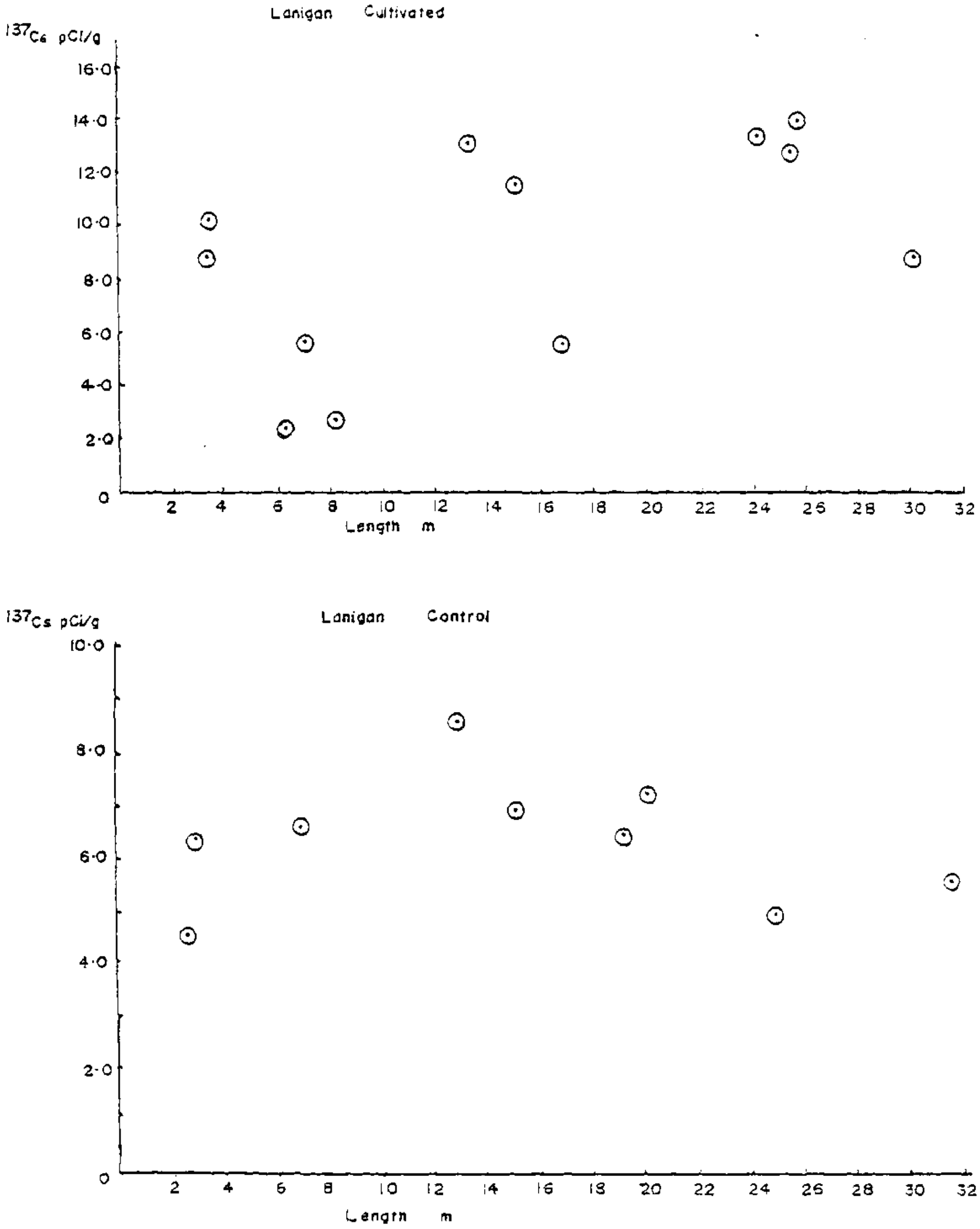
[2] Phosphorus in mg/cm^2

[3] Simple slope length

*P <.05

**

Figure 25. The effect of simple slope[1] length on ^{137}Cs levels: Lanigan



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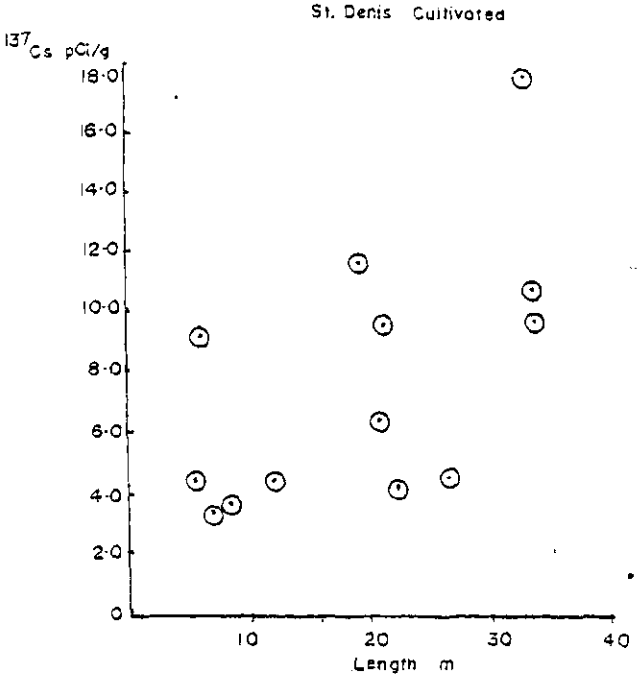
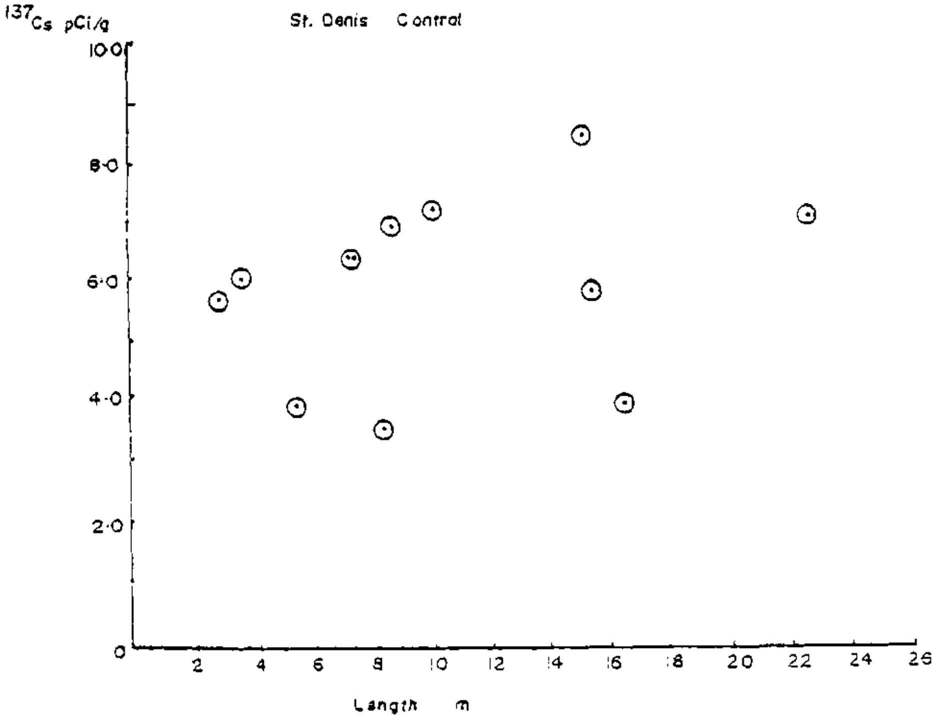
[1] Simple slope length defined as distance from sample point to highest

Figure 26. The effect of simple slope[1] length on ^{137}Cs levels: St. Denis





ngth defined as distance from sample point to highest footslope areas. The controls showed no significant correlation with length which was expected if there was little water erosion (Table 9). The St. Denis cultivated site showed the only significant relationship between ^{137}Cs activity and the slope-length combinations. Generally the best correlations occurred in the cultivated sites. The relationship between slope length and ^{137}Cs is opposite to that predicted by classical erosion equations. Classical erosion equations predict that knoll positions, with the least runoff, should have a higher ^{137}Cs activity than mid- and lower slope positions where runoff and erosion should occur. The Universal Soil Loss Equation does not predict what happens to the eroded material and does not predict where deposition of sediment will occur. Depressions and footslope positions are areas of deposition and, as expected, have the highest ^{137}Cs activity at both cultivated sites (Table 10). Figures 23 and 24 and Table 10 showed the lowest ^{137}Cs activity on the knolls of the cultivated sites presumably because of wind and water erosion. Footslope positions and sample sites in gully channels showed ^{137}Cs accumulation representing sedimentation of soil moved by runoff. Brown et al. (1981) were also unsuccessful at accounting for variations in ^{137}Cs activity through the slope-length factor used in the Universal Soil Loss Equation.

The slope shape, i.e., concave, convex or uniform, affects the erosive capacity of the runoff. As the slopes were only slightly concave or convex, it was difficult to perceive differences in ^{137}Cs accumulation as a result of slope shape. Slope shape will affect the capacity of water but not wind erosion.

Both cultivated sites showed highly significant ($P < .01$) differences in ^{137}Cs activity between knoll and footslope positions

Table 10. Average ^{137}Cs values according to site positions.

Site	Position	^{137}Cs (pCi/cm^2)	% of total (based on control values minus 5%)
Lanigan control	Footslope	6.0 ± 2.6	—
	Midslope	7.1 ± 1.1	—
	Knoll	5.6 ± 0.9	—
	Average[1]	6.9 ± 2.6	—
Lanigan cultivated	Footslope	13.6 ± 0.4	+106
	Midslope	9.1 ± 3.0	+38
	Knoll	4.6 ± 2.6	-30
St. Denis control	Footslope	6.6 ± 0.6	—
	Midslope	5.9 ± 2.1	—
	Knoll	5.2 ± 1.2	—
	Average[1]	5.9 ± 1.5	—
St. Denis cultivated	Footslope	11.9 ± 3.5	+112
	Midslope	5.0 ± 1.2	-11
	Knoll	4.8 ± 1.5	-14

[1] Includes depression value of ^{137}Cs

(Tables A.6 and A.8 in Appendix I). Clearly the footslope zones, at both sites, were areas of deposition (Table 10). The central depression sample site was not included with the footslope samples of the cultivated sites as it was not necessarily a zone of deposition. The slopes entering the depression often had a low gradient (Figs. 19 and 21). Both control sites showed no difference in ^{137}Cs activity due to landscape position (Tables A.7 and A.9 in Appendix I).

The fine to coarse particle size ratio is defined as the sum of particles <50 μm divided by the amount of particles >50 μm in dispersed samples. The differences in the ratio along a slope reflect the selective loss or deposition of fine particles if the ratio decreases or increases, respectively. The St. Denis control showed a significant ($P <.05$) loss of fine particles from the knoll positions and a deposition in the footslope zones. The accumulation in the footslope area was probably a result of wind blown soil during the winter months. The cultivated sites did not show selective erosion of fine particles on their slopes. The Lanigan control also showed no differences in the fine to coarse ratio.

The Middleton dispersion ratio (calculated from % silt, % clay and % undispersed in the Data Sheets, Appendix II) gives an indication of aggregate stability. The dispersion ratio is used as an indicator of the soils' susceptibility to erosion. Both the Lanigan and St. Denis cultivated sites had similar aggregation values of particles <50 µm, at each landscape position. Aggregation indexes for soils on the knolls at the Lanigan and St. Denis cultivated sites (40 and 44%, respectively) are higher than the footslope and midslope positions (32 and 31%, 31 and 32%, respectively). The lower slope positions generally had greater percent silt values than the knoll positions. This increase in the dispersed silt would lower Middleton's ratio. Middleton's ratio is an indication of water stable aggregates not wind-stable aggregates. The index was possibly too water erosion specific to be used in knoll and depression topography as an indicator of the soil's capacity to resist erosion, where both wind and water erosion occur.

The control sites represent the average amount of ^{137}Cs deposited by precipitation during the peak fallout years (1961-1963). According to de Jong et al. (1982) most of the fallout on the prairies occurred with rain during the spring to fall months. A possible 5% loss of ^{137}Cs due to crop uptake and snow redistribution can occur on cultivated fields (de Jong et al., 1982). If the ^{137}Cs loss of 5% occurred on the cultivated sites then average values of ^{137}Cs, 6.6 ± 2.6 pCi/cm^2 and 5.6 ± 1.5 pCi/cm^2, should be found at the cultivated Lanigan and St. Denis sites, respectively. An average value greater than the fallout on the control site indicates areas of deposition and a value less than the fallout, areas of depletion or some loss (Table 10). Thus the footslope and midslope positions of the cultivated Lanigan site were areas of ^{137}Cs accumulation while the St. Denis cultivated site showed a loss of ^{137}Cs at both the knoll and midslope positions. Figures 27 and 28 delineate areas of footslope, midslope and knoll positions within the Lanigan and St. Denis cultivated basins.

Assuming that the cultivated sites received the same fallout as the corresponding control, the Lanigan cultivated site should have a total of 0.23 ± 0.09 mCi ^{137}Cs and the St. Denis cultivated site a total of 0.18 ± 0.05 mCi ^{137}Cs (Table 11). The total amount of ^{137}Cs calculated from the landscape positions agrees within error with the fallout total for each site (Table 11).

Figure 27 Lanigan cultivated: Delineated upslope, midslope and footslope zones

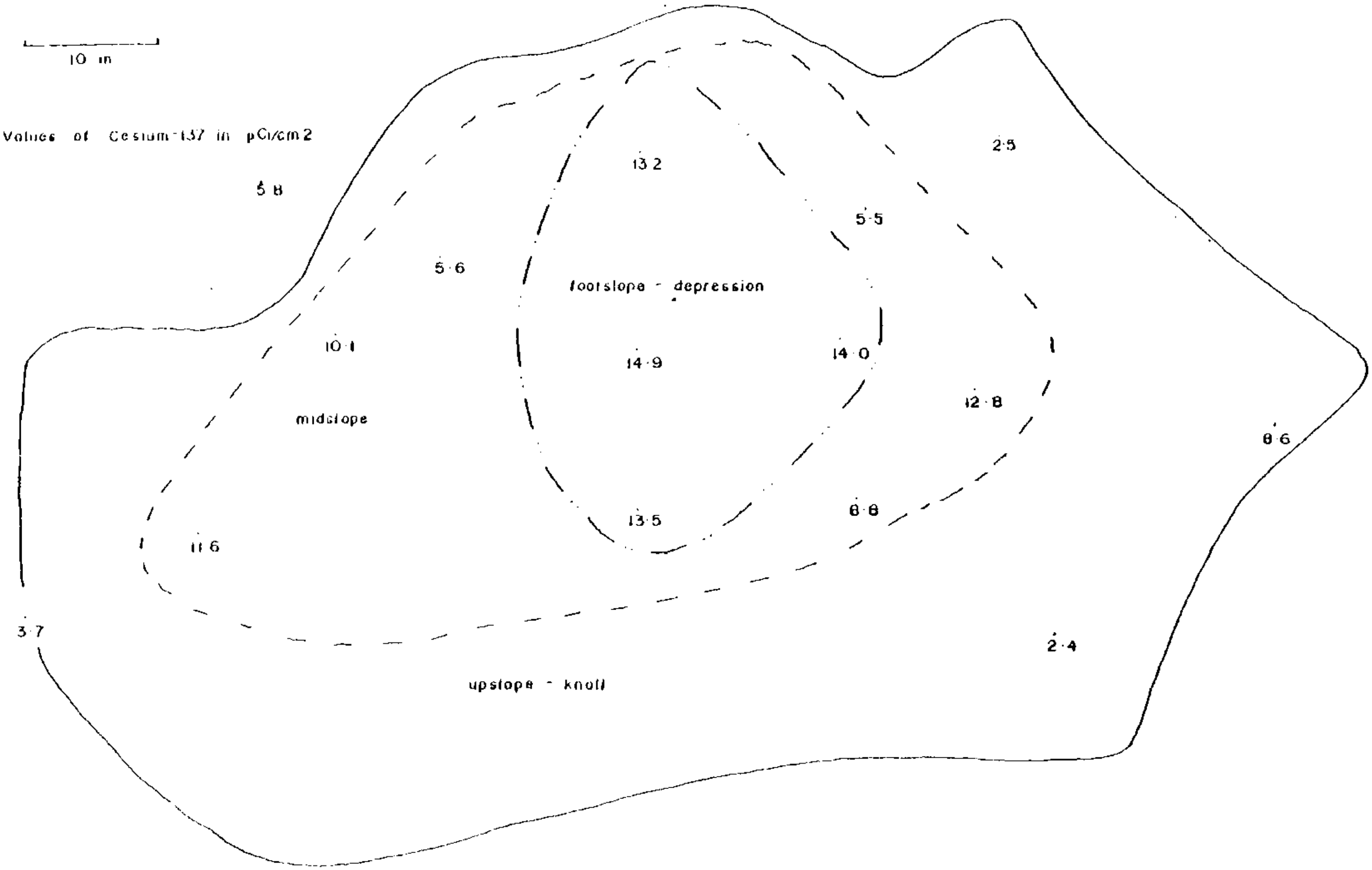


Figure 28 St. Denis cultivated: Delineated upslope, midslope and footslope zones

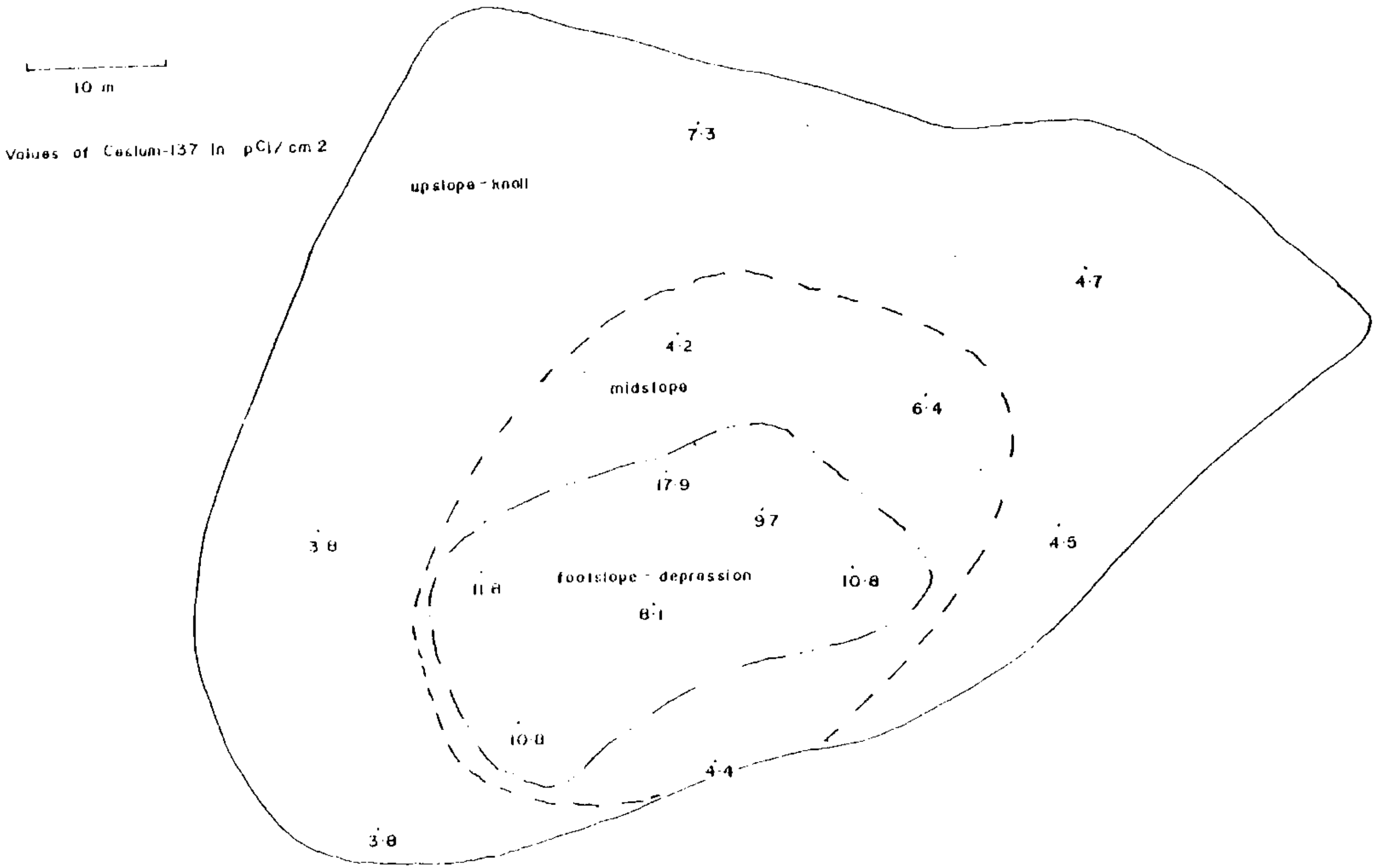


Table 11. Basin totals of ^{137}Cs.

Cultivated area (m^2)			Total ^{137}Cs mCi
		Lanigan site	
Input based on control:			
Total[1]	3360		0.23 ± 0.09
Total[2]	3360		0.22 ± 0.09
Actually present:			
Footslope	475		0.06
Midslope	1025		0.09
Knoll	1860		0.08
		Total	0.23
		St. Denis site	
Input based on control:			
Total	3075		0.18 ± 0.05
Total[1]	3075		0.17 ± 0.05
Actually present:			
Footslope	500		0.06
Midslope	550		0.03
Knoll	2025		0.10
		Total	0.19

[1] Includes depression value

[2] Corrected for snowblowing and crop uptake

5. DISCUSSION

The rainfall simulator was effective at reproducing storms that could occur in Saskatchewan at least once every ten years. Due to problems in the simulator design the wind caused some dispersal of the raindrop pattern. The rainfall intensity was effectively maintained by the pressure gauge. The experimental plot was not sufficiently large (1 square metre) to obtain a good estimate of total soil loss. The simulator requires at least two people to operate it effectively. As a practical tool in the field the simulator would require some modifications to improve its versatility and its operating capacity in various wind speeds.

The wind tunnel allowed effective sampling of the representative types of soil moved by wind erosion. Total amounts of soil lost were impossible to determine due to the sampling method and lack of calibration. Calibration of the wind tunnel would have been a lengthy process. The emphasis of the study was placed on the soil components lost during wind erosion and not on measuring total soil loss. The tunnel was cumbersome to transport but could be operated by a single individual. The quantity of suspension sampled could have been increased by increasing the number of vacuum cleaners used to sample the airstream.

Both the wind suspension and runoff suspension at all sites (Tables A.1-A.4 in Appendix I) nearly always showed an enrichment of carbon and nitrogen. Both suspension types can be transported great distances away from the original source with the resulting loss of nutrients. Water erosion selectively removed the fines at both experimental sites. Definite sorting occurred between the saltation and suspension samples of wind erosion. Thus soil drifts generally are depleted in fine particles and nutrients. One of the major effects of erosion on the soil is aggregate destruction. As the aggregates break down under raindrop impact, the infiltration capacity decreases and this reduces the soils capacity to supply moisture to crops throughout the growing season. Wind erosion destroys aggregates by the abrasive action of sand particles. In all cases a soil left bare without trash cover or stubble is subject to the destructive forces of the elements. The knoll and depression topography of the landscape does not allow distinct separation of the two erosive agents, wind and water. Water erosion is severest on the steep slopes of bare fallow associated with some basins. As the surface soil moisture frequently decreases below the permanent wilting point on the upslope on knoll positions in the landscape, wind erosion can be especially severe at these local points.

An attempt was made to use the soil fractions from the simulated water and wind erosion experiments to elucidate the relationship between ^{137}Cs, clay and organic carbon. At any given site wind and water erosion have resulted in sorting of the original soil and regression analysis was run between ^{137}Cs, clay, sand and organic carbon present in these fractions and the original soil. The Kernen site was not included in this analysis because of the unusual ^{137}Cs levels found in the sediment of the water erosion tests. Table 12 gives the r^2 values of equations which explain ^{137}Cs variability as a function of clay, organic carbon, or sand. For the St. Denis and Lanigan sites high r^2 values (0.845 and 0.893, respectively) were obtained between ^{137}Cs and organic carbon. Similar curves (Figs. 29

Table 12. Linear regression equations between properties of the wind and water erosion samples ($Y = A + Bx$)[1].

Site	Equation	r^2	df
Lanigan	Cs = 0.164 + 0.0103 carbon	0.893^{**}	6
	Cs = 0.311 + 0.0185 clay	0.742^{**}	6
	Cs = 1.22 - 0.0102 sand	0.768^{**}	6
	Carbon = 12.5 + 1.88 clay	0.916^{**}	6
St. Denis	Cs = 0.0062 + 0.0145 carbon	0.845^{**}	11
	Cs = 0.150 + 0.0125 clay	0.751^{**}	11
	Cs = 0.857 - 0.0088 sand	0.786^{**}	11
	Carbon = 9.77 + 0.870 clay	0.905^{**}	11

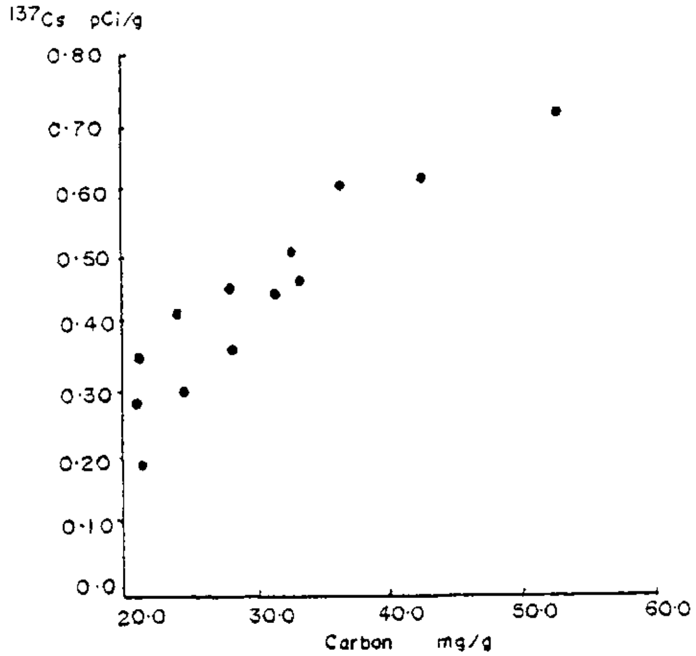
[1] Cs in pCi/g; carbon in organic C mg/g of soil; sand and clay is in % of mineral fraction

and 30) between ^{137}Cs and organic carbon were obtained at these two sites.

The multiple regression of ^{137}Cs as a function of clay and organic carbon showed a negligible contribution of clay in explaining the ^{137}Cs variability at the St. Denis and Lanigan sites , this is not surprising in view of the strong correlation between organic carbon and clay (Table 12). Jacobs and Tamura (1960) and Walton (1963) found a strong adsorption of ^{137}Cs on clay, but they used pure clay minerals. The results from the simulated erosion studies were based on unaltered soil, where clay and organic matter are present in complexes (Greenland 1965), and cannot be easily separated.

The Kernen site was a fine textured silty-clay-loam soil. The relationships between ^{137}Cs, and organic carbon and/or clay, observed

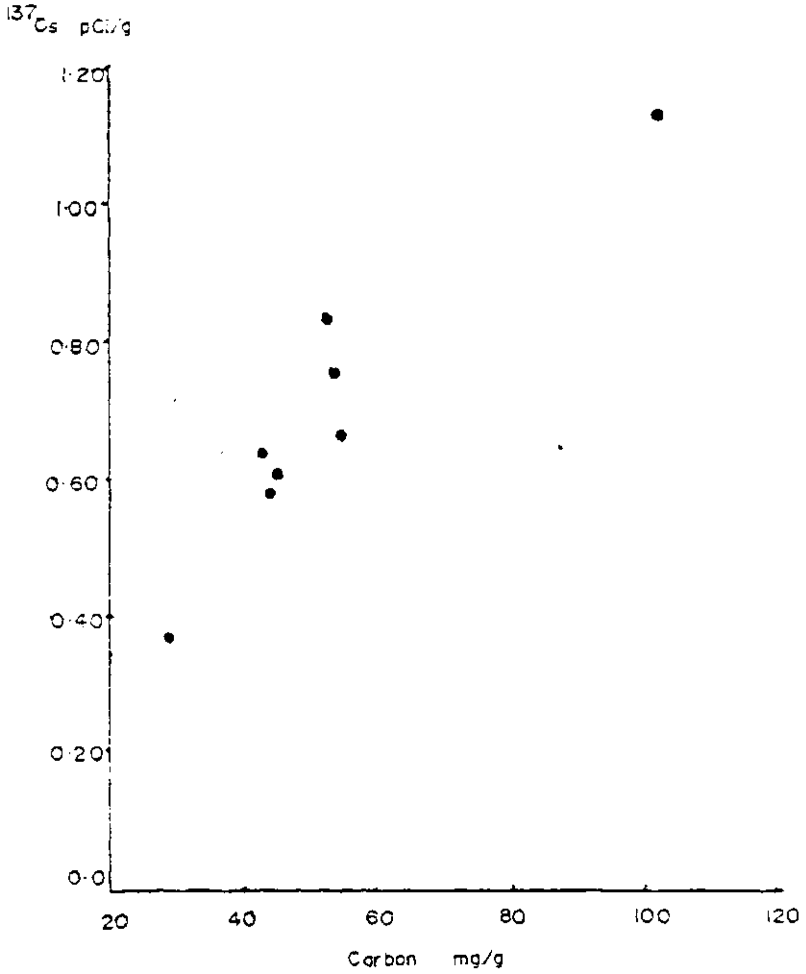
Figure 29 St. Denis Wind and Water Erosion Samples: ^{137}Cs versus Carbon



at the other sites were not found at the Kernen site. There was a significant (P <.01) enrichment of clay in the suspension material of the Kernen runoff. The suspension was lower in ^{137}Cs compared to the source and slightly enriched in organic carbon. At the Kernen site fine particles were not displaced into the turbulent wind layer and carried as suspension (Fig. 18) presumably since there was little abrasive action by the sand fraction during wind erosion. These results agree with those of Moss (1935) and Daniels (1936) which showed that no significant loss of clay or carbon occurred during wind erosion on on fine-textured soils.

At the Kernen site the suspension was actually depleted in ^{137}Cs during water erosion (0.6 of the source) and in wind erosion it

Figure 30 Lanigan Wind and Water Erosion Samples : ^{137}Cs versus Carbon



was slightly enriched (1.1 of the source) (Tables A.1 and A.3 in Appendix I). At the St. Denis site both suspensions were enriched (1.8 and 1.4 of the source, during water and wind erosion, respectively) and the same was true at the Lanigan site for the wind and water suspended soil (1.2 and 1.4 of the source, respectively) (Tables A.1, A.2 and A.4 in Appendix I). At the two medium-coarse textured sites (Lanigan and St. Denis), ^{137}Cs was associated strongly with carbon and clay (Table 12). The redistribution of ^{137}Cs in the landscape reflects the movement of carbon and clay but is not necessarily a direct indicator of soil loss. Even if it is assumed that the ^{137}Cs is uniformly mixed into the Ap horizon, ^{137}Cs appears to move preferentially with the soil colloidal fraction.

At the Lanigan control site, of the basin studies, ^{137}Cs was only found in the upper 10 cm of the soil cores and landscape position did not affect ^{137}Cs distribution. The St. Denis control contained ^{137}Cs generally in the surface 15 cm, except for the depression and two sites in a gully where ^{137}Cs was found to 20 cm in depth. Again there was no difference in ^{137}Cs activity due to landscape position. These control sites are unlikely to have had erosion and thus their ^{137}Cs content is representative of the total ^{137}Cs fallout for their particular area. The ^{137}Cs activity at each sample site was summed and the average value (minus 5% due to snowblowing and crop uptake) used as the total radionuclide input on cultivated fields (Table 10). The St. Denis cultivated site showed deposition zones occurring in the footslope areas where ^{137}Cs was found down to 20 cm. The depression contained ^{137}Cs only in the surface 10 cm. The depression and footslope zones of the cultivated Lanigan site showed ^{137}Cs activity down to 20 cm in depth. There was a definite difference in the depth to which ^{137}Cs was found between the control and corresponding cultivated site. Both cultivated sites exhibited differences in ^{137}Cs activity due to landscape position. These landscape differences reflect ^{137}Cs movement, thus they also reflect soil movement.

The Universal Soil Loss Equation predicts that soil loss by water erosion increases as slope length increases. In fact the classical studies of Horten (1938, 1945) indicate that no erosion will occur within a critical distance from the knoll as the eroding force of the runoff is too small. The observed ^{137}Cs distribution (Tables A.7-A.10 in Appendix I) on the cultivated fields are not in agreement with the USLE predictions. One of the reasons for the disagreement is that USLE does not account for deposition of sediment in the footslope or depression areas. The use of the equation is only justified along slope sections which are eroding. The slope lengths within the basins were possibly too short to give an accurate picture of an eroding slope. The lower sampling points were often in deposition zones which cannot be explained by the USLE. The topography of the basins precludes the use of classical water erosion equations. To compound the problem, wind erosion often occurs on the knolls. The knolls are the driest areas of the basins, thus subject to the greatest loss of soil by wind erosion. The wind erosion equation estimates soil loss on flat fields where the only topographic factor used is the length of the field, however, an emperical factor for knolls can be included. The literature does not contain any reference to soil loss from knolls. The WEE is also a soil loss equation with no reference to deposition areas.

Assuming ^{137}Cs is evenly mixed throughout the plow layer, it can be used as a tracer of soil loss. At a first approximation, de Jong et al. (1982) assumed that a 10% loss of ^{137}Cs corresponded to a 10% loss of soil over the approximately 20 years since the initial deposition. The total soil loss or gain for 20 years, according to landscape position at each site, calculated using this approximation is given in Table 13. The total ^{137}Cs input (obtained from the control sites) is needed to estimate the soil loss by the method of Ritchie et al. (1974). The equation used by Ritchie et al. (1974) is based on a relationship between the percentage of radionuclide input still present and predicted soil loss by the USLE. Table 13 also gives soil loss per year calculated from this method. If there is an enrichment of ^{137}Cs in eroded fractions the approximate method of de Jong et al. (1982) would overestimate soil loss. As a comparison, an enrichment value of 15% was assumed and new losses calculated (Table 13). The method of Ritchie et al. (1974) could be tested if predicted USLE soil loss values for Saskatchewan soils were available. However as stated previously, there are limitations on the use of the USLE on knoll and depression topography. On the eroding areas, the agreement between all these calculations is good. There are substantial differences in the estimates of the amount of soil deposited as calculated by these three methods. However it must be pointed out that neither of the original papers claim that these calculations can be made for areas of soil deposition.

The midslope section of the St. Denis site showed a soil loss (Table 13), possibly due to water erosion. Middleton's dispersion ratio was similar for both the St. Denis and Lanigan sites at each landscape position on the slope. The dispersion index is the single variable most closely associated with the soil's inherent erodibility. The strong inverse relationship between ^{137}Cs activity and elevation supports the assumption of soil loss by wind erosion.

Within the basin areas ^{137}Cs loss or gain can be delineated (Figs. 27 and 28). Approximate calculations (Table 11) show no net losses of ^{137}Cs from the cultivated and this at first glance, rules out the possibility of significant soil loss by wind erosion. There are no data available on the deposition of soil materials moved by saltation and suspension in rolling areas subject to wind erosion. The attempted ^{137}Cs balances are particularly sensitive to the proper delineations of the areas of loss and deposition, especially the areas of the knolls and footslopes which need to be known accurately. Further investigations in identifying slope segments appear warranted.

This study has clearly shown that ^{137}Cs can be used to delineate areas of soil loss and deposition within drainage basins. The ^{137}Cs data can also provide an approximate estimate of the rates of loss or deposition of soil.

6. SUMMARY AND CONCLUSIONS

The objectives of this study were 1) to determine which soil fractions and nutrients were lost during wind and water erosion, and 2) to relate the distribution of Cesium-137 to soil movement. Distribution of ^{137}Cs in the test basins was used to test the applicability of the length-slope factor of the Universal Soil Loss Equation in the knoll and depression topography typical of much of Saskatchewan.

A rainfall simulator and wind tunnel were run at four sites in near Saskatoon. Three of the sites were in the Dark Brown soil zone and the remaining site in the Black zone. Samples of the source soil and of the eroded material (saltation and suspension in wind erosion, and suspension in water erosion) were collected. The samples were analyzed for organic carbon, total nitrogen and phosphorus content, particle size distribution, as well as ^{137}Cs. Four basins, matched pairs in cultivated fields and uneroded grassland, were sampled to determine the ^{137}Cs distribution. The basins were chosen to ensure that all water drained into the depression and that there would be no loss of ^{137}Cs from the basin by water erosion. The basins were sampled to measure as many length-slope combinations as possible. The soil samples at each depth were analyzed for organic carbon, total nitrogen and phosphorus content, particle size distribution and ^{137}Cs.

The results showed that the suspended material removed by water erosion was enriched in organic carbon, total nitrogen and clay. The wind suspension was enriched in organic carbon and total nitrogen but generally not in clay. The wind and water suspensions of the Lanigan, St. Denis and Goodale sites were enriched in ^{137}Cs, but at the Kernen site the sediment of the water erosion test was lower in ^{137}Cs than the soil. The data from the rainfall simulator and wind tunnel experiments indicate a strong relationship between ^{137}Cs and organic carbon, and clay.

The results from the basin studies show an inverse relationship between ^{137}Cs levels and elevation at the cultivated sites; in the non-eroded control basins, ^{137}Cs distribution did not vary with slope position. Wind erosion is most severe on the knolls surrounding the basins and some ^{137}Cs may have been lost from the enclosed cultivated basins. The approximate ^{137}Cs balances (Table 11) showed no net losses of ^{137}Cs from the cultivated basins assuming that the ^{137}Cs fallout pattern was the asme for the cultivated and control basins.

The length-slope in the USLE showed no consistent relationship to the ^{137}Cs distribution. Deposition occurred in the footslope and depression areas of the cultivated basins. The USLE predicts only soil loss, not deposition, and the ^{137}Cs distribution within the cultivated basins does show areas of soil loss and soil deposition. The ^{137}Cs levels can be used to give an estimate of the rates of soil loss and deposition. As ^{137}Cs is selectively removed during erosion, a simple ratio between ^{137}Cs distribution and soil movement cannot be used. An enrichment factor should be incorporated into the soil loss calculations.

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APPENDIX I

Wind and Water Erosion and Basin Soil Property Values

Table A.1 Wind erosion: soil property values.

Site	Source	Saltation	Suspension	Source	Saltation	Suspension
		^{137}Cs pC/g			Carbon mg/g	
St. Denis	0.2982	0.2816	0.4223	24.37	20.61	23.96
Kernen	0.4900	0.5286	0.5518	22.10	24.92	30.36
Goodale 1	0.4578	0.4661	0.5417	29.97	24.37	36.60
Goodale 2	0.5024	0.4361	0.6267	25.70	23.37	37.69
Lanigan 1	0.5785	0.3718	0.6686	43.28	28.57	54.17
Lanigan 2	0.6008	0.6478	0.7613	45.14	42.96	53.24
		Nitrogen mg/g			Phosphorus mg/g	
St. Denis	2.12	1.8	2.08	0.646	0.587	0.595
Kernen	2.25	2.34	2.86	0.661	0.718	0.751
Goodale 1	2.76	2.22	3.33	0.681	0.668	0.754
Goodale 2	2.41	2.21	3.24	0.671	0.660	0.765
Lanigan 1	3.73	3.34	4.70	0.822	0.778	0.945
Lanigan 2	4.17	3.78	4.66	0.844	0.754	0.886
		% sand			% silt	
St. Denis	56.0	64.5	54.1	29.1	21.2	27.9
Kernen	13.9	13.0	10.6	34.3	37.1	38.9
Goodale 1	46.1	53.1	41.3	33.0	29.7	36.2
Goodale 2	49.7	53.5	29.3	29.7	29.5	52.4
Lanigan 1	51.5	69.8	55.2	28.1	17.7	27.1
Lanigan 2	49.8	65.0	55.9	29.6	21.2	25.8
		% clay				
St. Denis	14.9	14.4	18.0			
Kernen	51.8	49.9	50.8			
Goodale 1	21.0	17.1	22.5			
Goodale 2	20.7	17.0	18.3			
Lanigan 1	20.4	12.5	17.6			
Lanigan 2	20.5	13.9	18.4			

Table A.2 Water erosion: soil property values.

	Time	Sediment	Source	Sediment	Source	Sediment	Source	Sediment
	Min.	Weight, g	^{137}Cs pC/g		C mg/g	C mg/g	N mg/g	N mg/g
St. Denis	0–20	27.20	0.3696	0.6162	20.77	42.18	2.013	4.073
2.8 cm/h	20–30	34.68	0.3696	0.5089	20.77	32.15	2.013	3.437
	30–40	45.56	0.3696	0.4690	20.77	32.92	2.013	3.204
	40–50	52.44	0.3696	0.4567	20.77	27.28	2.013	2.931
	50–60	39.52	0.3696	0.3474	20.77	25.75	2.013	2.720
	Min.		% sand	% sand	% silt	% silt	% clay	% clay
St. Denis	0–20		58.89	33.5	25.38	36.5	15.62	30.0
2.8 cm/h	20–30		58.89	45.1	25.38	31.8	15.62	23.1
	30–40		58.89	47.1	25.38	30.6	15.62	21.9
	40–50		58.89	50.6	25.38	29.9	15.62	19.6
	50–60		58.89	51.3	25.38	27.7	15.62	19.0
	Min.	Weight, g	^{137}Cs pC/g		C mg/g	C mg/g	N mg/g	N mg/g
St. Denis	0–30	12.47	0.1944	0.7233	20.86	52.84	1.953	5.07
4.6 cm/h	30–50	29.56	0.1944	0.6138	20.86	36.05	1.953	3.86
	50–60	19.58	0.1944	0.4508	20.86	31.33	1.953	3.16
	Min.		% sand	% sand	% silt	% silt	% clay	% clay
St. Denis	0–30		57.5	6.0	25.28	41.7	17.2	52.3
4.6 cm/h	30–50		57.5	37.5	25.28	30.1	17.2	32.5
	50–60		57.5	47.1	25.28	28.0	17.2	25.0

Table A.3 Water erosion: soil property values.

Site	Time	Sediment	Source	Sediment	Source	Sediment	Source	Sediment
	Min.	Weight, g	^{137}Cs pC/g		C mg/g	C mg/g	N mg/g	N mg/g
Kernen	0–20	31.06	0.5355	0.3727	25.37	33.85	2.023	2.995
2.5 cm/h	20–30	59.52	0.5355	0.4009	25.37	25.51	2.023	2.823
	30–40	78.19	0.5355	0.3289	25.37	33.55	2.023	2.834
	40–50	54.96	0.5355	0.3514	25.37	27.29	2.023	2.638
	Min.		% sand	% sand	% silt	% silt	% clay	% clay
Kernen	0–20		21.86	5.3	37.46	36.8	40.68	57.9
2.5 cm/h	20–30		21.86	7.3	37.46	38.8	40.68	53.9
	30–40		21.86	9.0	37.46	38.1	40.68	52.9
	40–50		21.86	13.4	37.46	34.9	40.68	51.7
	Min.	Weight, g	^{137}Cs pC/g		C mg/g	C mg/g	N mg/g	N mg/g
Kernen	0–20	104.47	0.5170	0.2867	25.32	30.12	2.357	2.825
4.6 cm/h	20–30	76.18	0.5170	0.3391	25.32	26.84	2.357	2.564
	30–40	101.46	0.5170	0.2448	25.32	24.77	2.357	2.511
	40–50	54.03	0.5170	0.3420	25.32	26.58	2.357	2.590
	Min.		% sand	% sand	% silt	% silt	% clay	% clay
Kernen	0–20		21.16	12.9	40.55	37.7	38.52	49.4
4.6 cm/h	20–30		21.16	16.5	40.55	37.4	38.52	46.1
	30–40		21.16	20.1	40.55	36.9	38.52	43.0
	40–50		21.16	17.6	40.55	36.8	38.52	45.7

Table A.4 Water erosion: soil property values.

Site	Time	Sediment	Source	Sediment	Source	Sediment	Source	Sediment
	Min.	Weight, g	^{137}Cs pC/g		C mg/g	C mg/g	N mg/g	N mg/g
Lanigan 2.5 cm/h	0-45	17.91	0.8642	1.1649	51.61	101.06	4.07	7.77
	Min.		% sand	% sand	% silt	% silt	% clay	% clay
Lanigan 2.5 cm/h	0-45		51.20	4.30	28.96	52.30	18.83	46.90

Table A.5 Lanigan cultivated: soil properties.

	Footslope	Midslope	Knoll		Footslope	Midslope	Knoll
^{137}Cs pCi/cm^2	13.2	10.1	3.7	Carbon	705	451	1384
	14.0	11.6	5.8	mg/cm^2	852	681	870
	13.5	5.6	2.5		768	871	786
		5.5	8.6			855	897
		12.8	2.4			977	824
		8.8				1091	
$\overline{X}$	13.6	9.1	4.6	$\overline{X}$	775	821	952
SD	.4	3.0	2.6	SD	74	227	245
Nitrogen	73	48	110	Phosphorus	16.75	12.03	31.28
mg/cm^2	75	87	103	mg/cm^2	18.42	23.45	30.21
	85	82	98		18.84	23.47	28.79
		102	112			24.33	22.12
		109	83			24.66	29.09
		107				23.53	
$\overline{X}$	77	89	101	$\overline{X}$	18.03	21.91	28.30
SD	5	23	12	SD	1.11	4.87	3.59
Clay g/cm^2	104	188	175	Fine/coarse	0.9362	1.8719	0.5277
(surface)	162	253	222	(surface)	0.8502	0.8987	0.6352
	168	233	273		1.5516	0.7522	0.7394
		309	195			0.8914	0.9982
		221	276			1.1182	0.6730
		186				1.0062	
$\overline{X}$	145	232	228	$\overline{X}$	1.1127	1.0898	0.7140
SD	35	46	45	SD	0.383	0.402	0.176

$\overline{X}$ - mean; SD - standard deviation

Table A.6 Lanigan Control: soil properties.

	Footslope	Midslope	Knoll		Footslope	Midslope	Knoll
^{137}Cs pCi/cm^2	6.43	8.61	6.37	Carbon mg/cm^2	570	832	1065
	4.94	5.52	4.50		744	664	694
	6.71	7.19	6.31		692	865	1217
		6.88	6.55			756	794
$\bar{X}$	6.03	7.05	5.63	$\bar{X}$	669	779	942
SD	0.95	1.27	0.89	SD	89	89	241
Nitrogen mg/cm^2	56	90	90	Phosphorus mg/cm^2	11.27	16.65	16.03
	69	90	88		11.20	20.67	20.75
	71	80	109		14.14	13.81	17.28
		79	89			17.14	23.72
$\bar{X}$	65	85	95	$\bar{X}$	12.20	17.07	19.44
SD	8	6	10	SD	1.68	2.81	3.48
Clay g/cm^2 (surface)	154	222	278	Fine/coarse (surface)	1.7315	1.0123	1.2287
	240	232	234		1.5000	1.0338	0.6978
	224	260	232		0.8525	0.8495	1.2823
		239	270			0.8355	0.7735
$\bar{X}$	206	238	254	$\bar{X}$	1.3613	0.9328	0.9956
SD	46	16	24	SD	0.456	0.105	0.303

$\bar{X}$ - mean

SD - standard deviation

Table A.7 Comparisons based on site positions (t - test significance).

Parameter	Footslope and midslope	Footslope and knoll	Midslope and knoll
		Lanigan Cultivated	
^{137}Cs	0.0430^{*}	0.0013^{**}	0.0298^{*}
Carbon	0.7494	0.2805	0.3809
Nitrogen	0.4086	0.0158^{*}	0.3169
Phosphorus	0.2252	0.0033^{**}	0.0382^{*}
Clay (surface)	0.0247^{*}	0.0355^{*}	0.9031
Fine/coarse (surface)	0.9372	0.0841	0.0866
$^{*}P <.05$			
$^{**}P <.01$			
		Lanigan Control	
^{137}Cs	0.2972	0.5967	0.1167
Carbon	0.1660	0.1254	0.2509
Nitrogen	0.0148^{*}	0.0080^{**}	0.1234
Phosphorus	0.0467^{*}	0.0221^{*}	0.3289
Clay (surface)	0.2387	0.1296	0.3290
Fine/coarse (surface)	0.1197	0.2537	0.7084
$^{*}P <.05$			
$^{**}P <.01$			

Table A.8 St. Denis Cultivated: soil properties.

	Footslope	Midslope	Knoll		Footslope	Midslope	Knoll
^{137}Cs pCi/cm^2	17.9	4.2	7.3	Carbon	1317	843	642
	9.7	6.4	4.7	mg/cm^2	1217	718	575
	10.8	4.4	4.5		1457	796	633
	9.4		3.8		1418		1091
	11.8		3.5		1148		593
$\overline{X}$	11.9	5.0	4.8	$\overline{X}$	1311	784	707
SD	3.5	1.2	1.5	SD	131	63	217
Nitrogen	107	82	45*	Phosphorus	27.61	22.67	23.04
mg/cm^2	116	62	40*	mg/cm^2	25.69	19.23	12.52*
	131	84	67		26.63	21.30	32.58
	125		108		31.43		34.61
	112		68		34.26		24.94
$\overline{X}$	118	76	65	$\overline{X}$	29.12	21.07	23.03
SD	10	12	27	SD	3	2	8
Clay g/cm^2	228	276	290	Fine/coarse	0.8227	0.9489	0.9110
(surface)	235	241	283	(surface)	0.8748	0.8512	0.8560
	239	230	239		0.8871	0.8793	0.6603
	173		223		0.4822		0.4482
	200		228		0.6567		0.5234
$\overline{X}$	215	249	253	$\overline{X}$	0.7447	0.8931	0.6798
SD	28	24	32	SD	0.173	0.050	0.202

$\overline{X}$ - mean

SD - standard deviation

* - soil property value not to ^{137}Cs depth; excluded from statistical analysis

Table A.9 St. Denis Control: soil properties.

	Footslope	Midslope	Knoll		Footslope	Midslope	Knoll
^{137}Cs pCi/cm^2	6.47	7.28	5.85	Carbon	862	1056	860
	7.23	6.11	4.37	mg/cm^2	1683	714	562
	5.94	3.58	6.51		889	668	1017
	6.98	8.54	3.96		1183	1002	1068
		3.97				1043	
$\overline{X}$	6.66	5.90	5.17	$\overline{X}$	1154	900	877
SD	0.57	2.12	1.21	SD	381	192	228
Nitrogen	110	110	117	Phosphorus	17.67	19.38	22.48
mg/cm^2	144	79	60	mg/cm^2	21.22	18.01	15.24
	103	77	106		19.71	13.96	18.20
	119	107	148		18.04	15.04	23.08
		104				15.97	
$\overline{X}$	119	95	108	$\overline{X}$	19.16	16.47	19.75
SD	18	16	36	SD	1.64	2.20	3.71
Clay mg/cm^2	188	159	116	Fine/coarse	1.6877	0.3992	0.4012
(surface)	240	166	271	(surface)	2.1260	0.5710	0.6445
	182	232	239		1.2883	0.5883	0.4128
	145	163	191		0.6692	0.7646	0.3342
		212				1.2596	
$\overline{X}$	189	186	204	$\overline{X}$	1.4428	0.7165	0.4484
SD	39	33	67	SD	0.619	0.330	0.135

$\overline{X}$ - mean

SD - standard deviation

Table A.10 Comparison based on site positions (t - test significance).

Parameter	Footslope and midslope	Footslope and knoll	Midslope and knoll
		St. Denis Cultivated	
^{137}Cs	0.0177^{*}	0.0029^{**}	0.8239
Carbon	0.0007^{**}	0.0001^{**}	0.2509
Nitrogen	0.0016^{**}	0.0174^{*}	0.7590
Phosphorus	0.0121^{*}	0.9175	0.0754
Clay (surface)	0.1344	0.0820	0.8619
Fine/coarse (surface)	0.2087	0.6002	0.1315
$^{*}P <.05$			
$^{**}P <.01$			
		St. Denis Control	
^{137}Cs	0.5144	0.0681	0.5655
Carbon	0.2315	0.2580	0.8703
Nitrogen	0.0754	0.5997	0.5138
Phosphorus	0.0827	0.7808	0.1410
Clay (surface)	0.9194	0.7089	0.6182
Fine/coarse (surface)	0.0570	0.0201^{*}	0.1748
$^{*}P <.05$			
$^{**}P <.01$			

Table A.11 Average NH_4^+-N, NO_3^--N and $HPO_4^=$ values in runoff water.

Site	Time min.	NH_4^+ µg/ml	NO_3^- µg/ml	PO_4^- µg/ml	Site	Time min.	NH_4^+ µg/ml	NO_3^- µg/ml	PO_4^- µg/m
Kernen 2.5 cm/h	0-5	0.21	0.60	0.03	Kernen 4.6 cm/h	0-5	0.10	0.87	0.07
	5-10	0.11	0.69	0.03		5-10	0	0.64	0.06
	10-15	0.08	0.62	0.03		10-15	0.01	0.58	0.06
	15-20	0.06	0.65	0.03		15-20	0	0.57	0.44
	20-25	0.04	0.94	0.04		20-25	0.01	0.69	0.04
	25-30	0.02	0.75	0.02		25-30	0	0.59	0.03
	30-35	0.03	0.39	0.02		30-35	0	0.58	0.05
	35-40	0.04	0.37	0.02		35-40	0	0.44	0.04
	40-45	0.03	0.39	0.02		40-45	0	0.68	0.24
	45-50	0.01	0.23	0.01					
St. Denis 2.8 cm/h	0-5	0.08	0.78	0.02	St. Denis 4.6 cm/h	0-5	0.65	0.65	0.01
	5-10	0.13	0.73	0.02		5-10	0.25	0.43	0.02
	10-15	0.11	0.60	0.03		10-15	0.22	0.22	0.01
	15-20	0.09	0.40	0.02		15-20	0.28	0.08	0.01
	20-25	0.21	0.31	0.02		20-25	0.26	0.08	0.01
	25-30	0.29	0.22	0.02		25-30	0.23	0.09	0
	30-35	0.24	0.25	0.02		30-35	0.22	0.13	0.01
	35-40	0.27	0.23	0.02		35-40	0.25	0.07	0.01
	40-45	0.24	0.22	0.02		40-45	0.25	0.08	0.01
	45-50	0.25	0.20	0.02		45-50	0.22	0.10	0
	50-55	0.31	0.32	0.01		50-55	0.21	0.12	0
	55-60	0.15	0.23	0.01		55-60	0.21	0.11	0
Lanigan 2.5 cm/h	0-5	0.04	0.67	0.01					
	5-10	0	0.27	0.01					
	10-15	0	0.33	0.01					
	15-20	0	0.23	0.01					
	20-25	0	0.20	0.01					
	25-30	0	0.43	0.02					
	30-35	0	0.20	0.01					
	35-40	0	0.23	0.01					
	40-45	0	0.13	0.01					

Figure A·1 Average Water Discharge: Kernen High Intensity

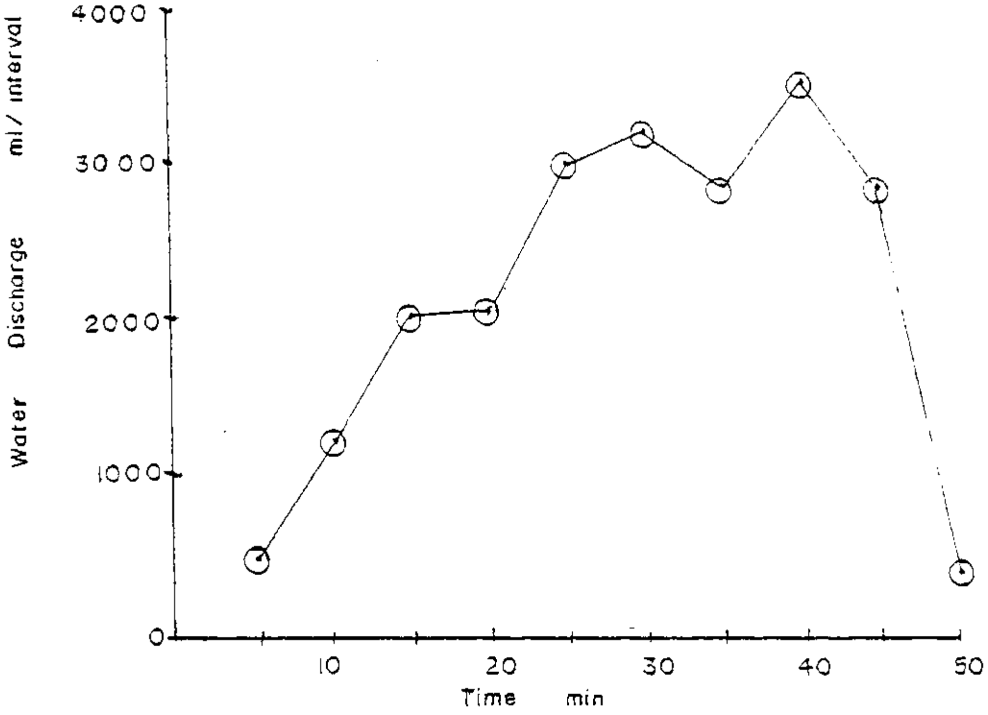


Figure A·2 Average Sediment Load: Kernen High Intensity

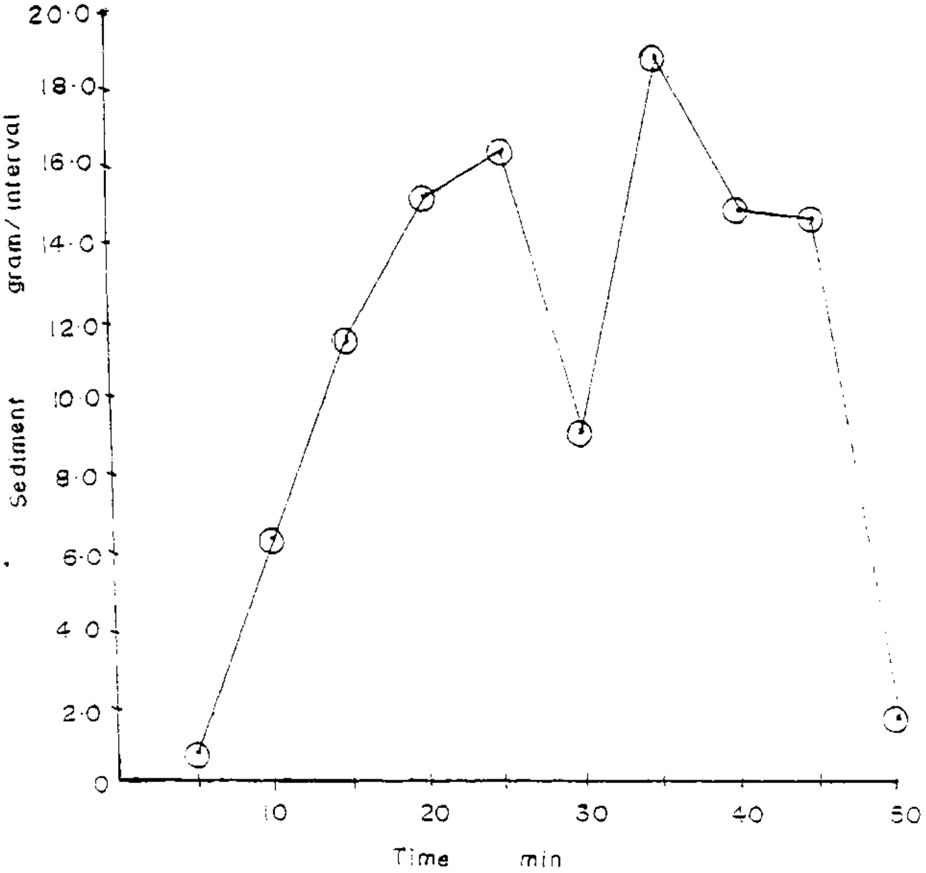


Figure A·3 Average Water Discharge : Kernen Low Intensity

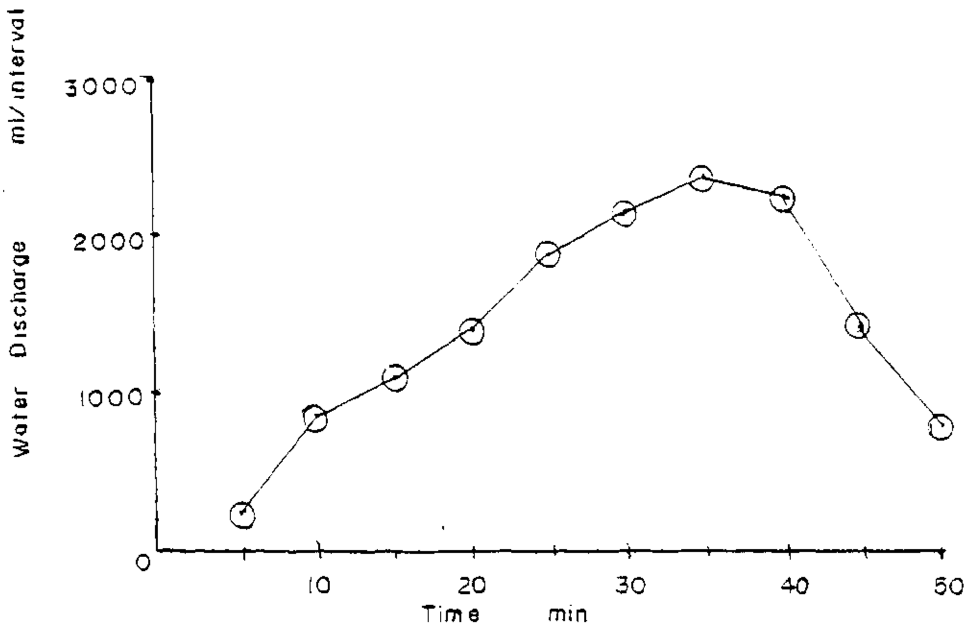


Figure A·4 Average Sediment Load : Kernen Low Intensity

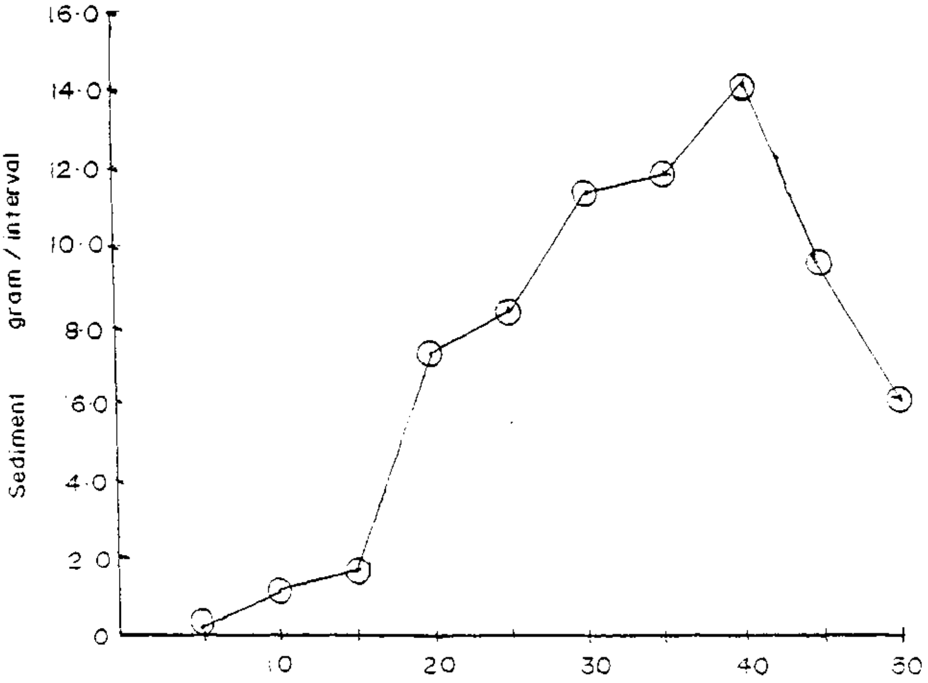


Figure A·5 Average Water Discharge : St Denis High Intensity

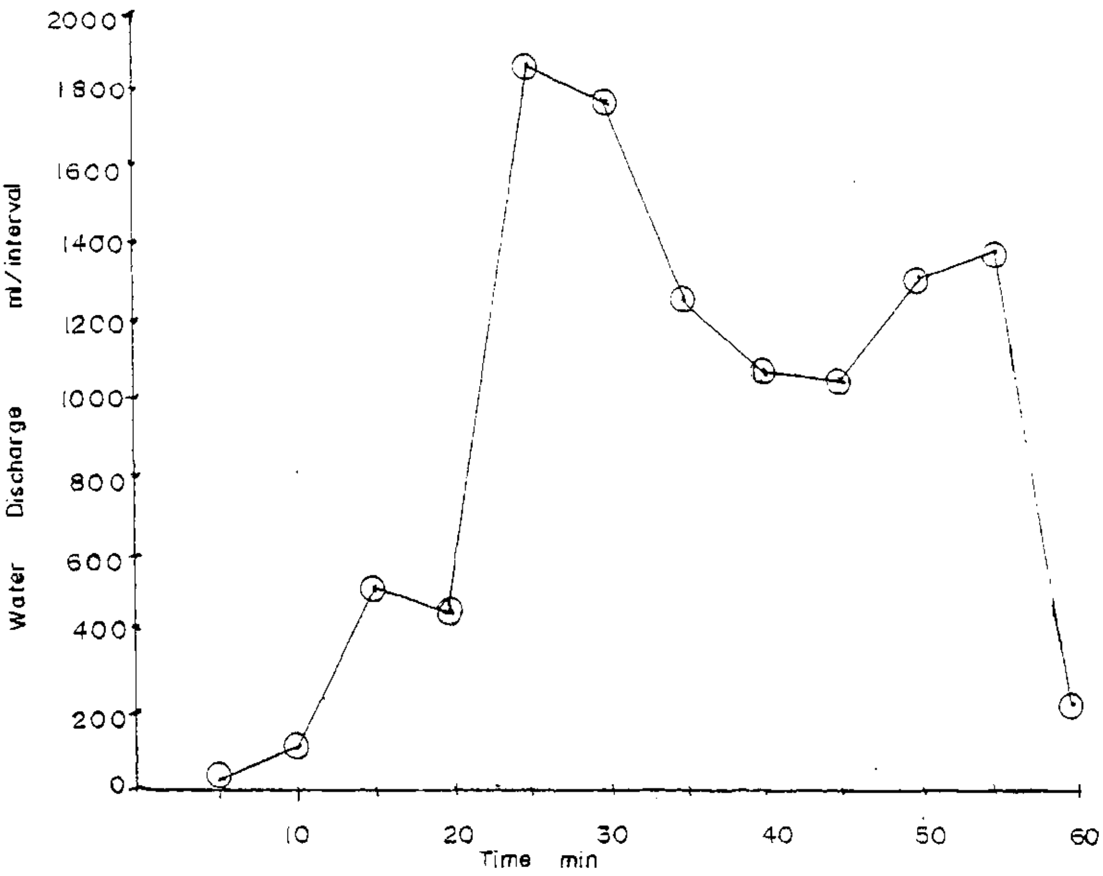


Figure A·6 Average Sediment Load : St Denis High Intensity

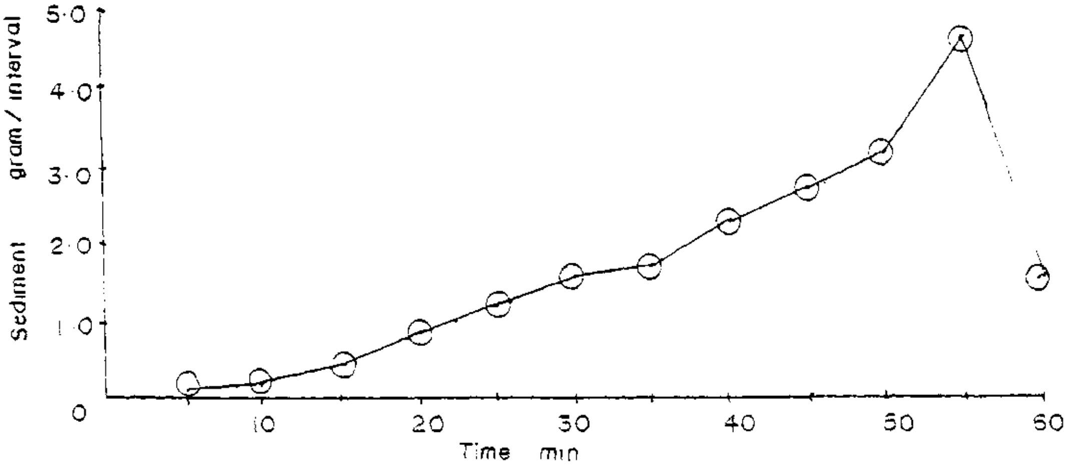


Figure A·7 Average Water Discharge : St Denis Low Intensity

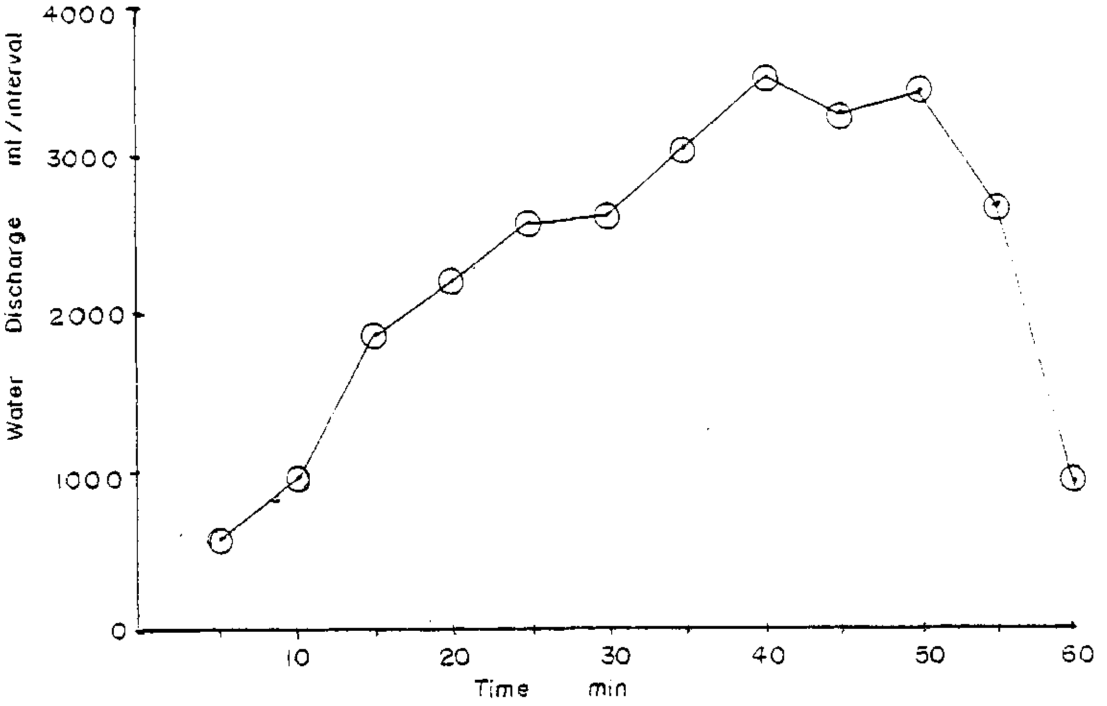


Figure A·8 Average Sediment Load : St Denis Low Intensity

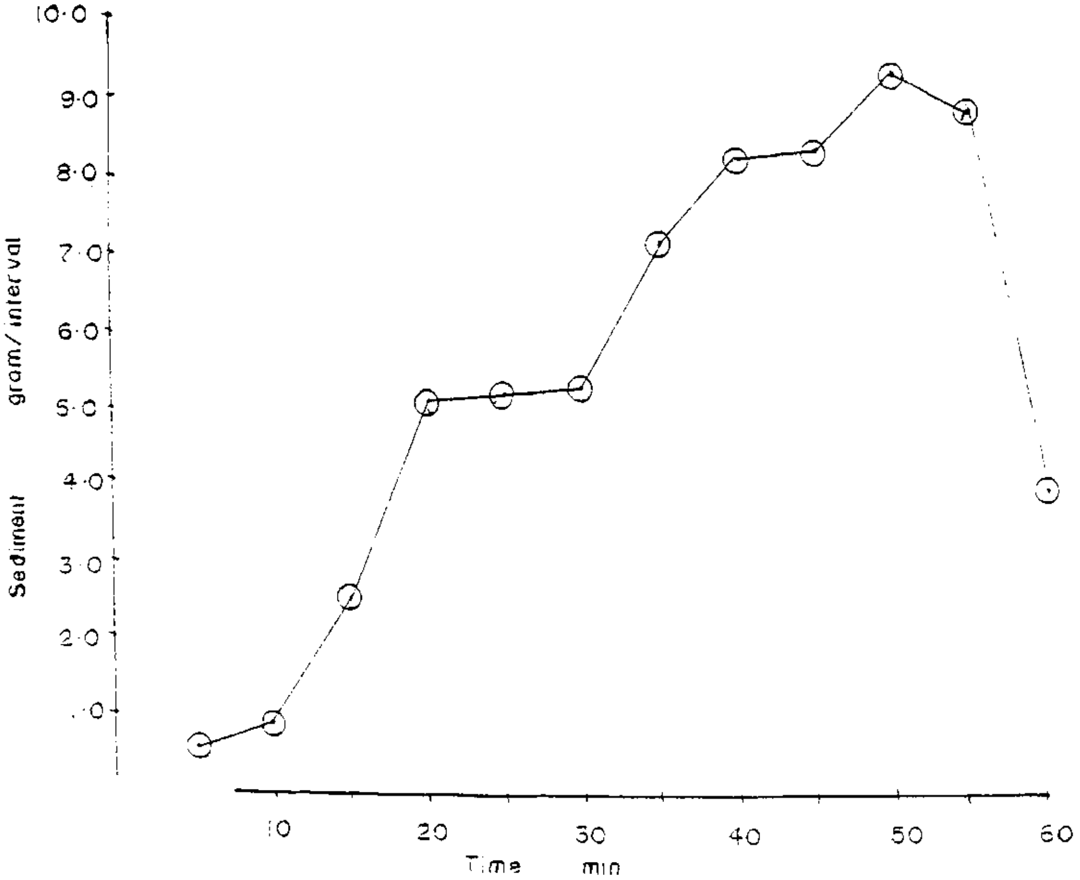


Figure A·9 Average Water Discharge : Lanigan Low Intensity

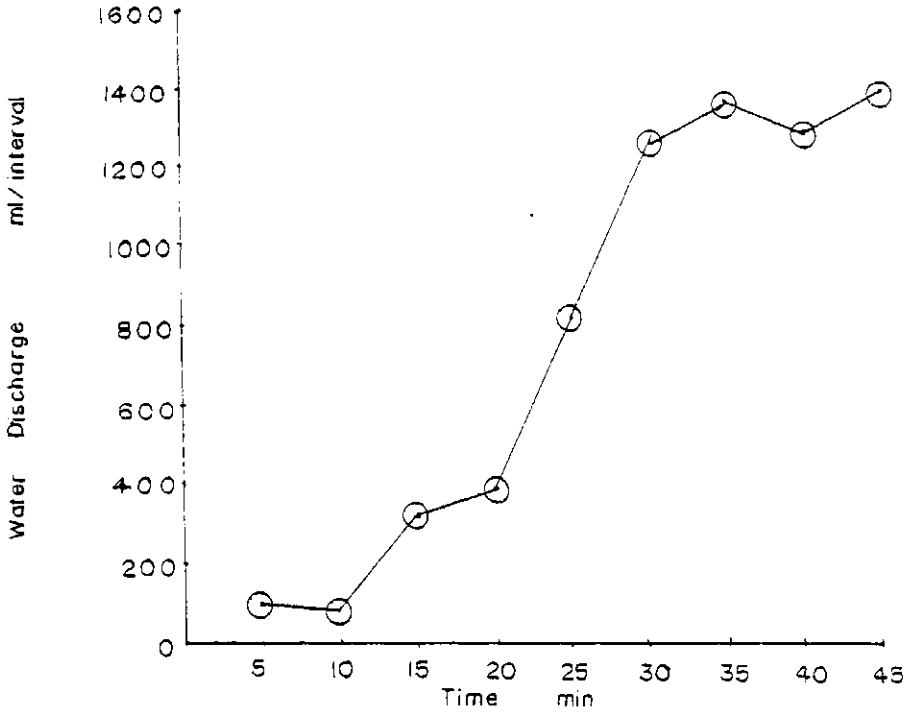
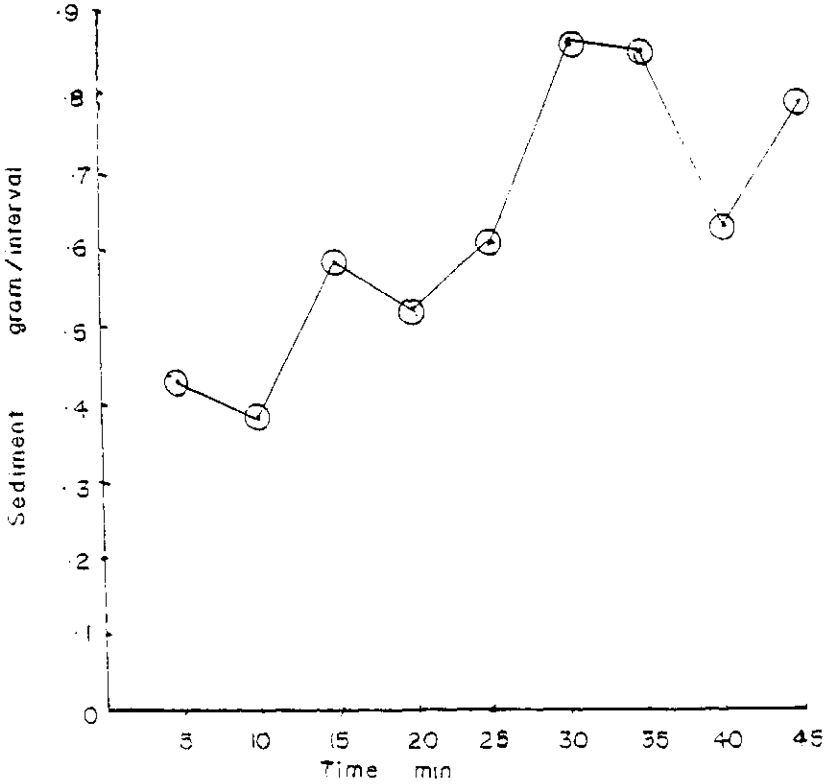


Figure A·10 Average Sediment Load : Lanigan Low Intensity



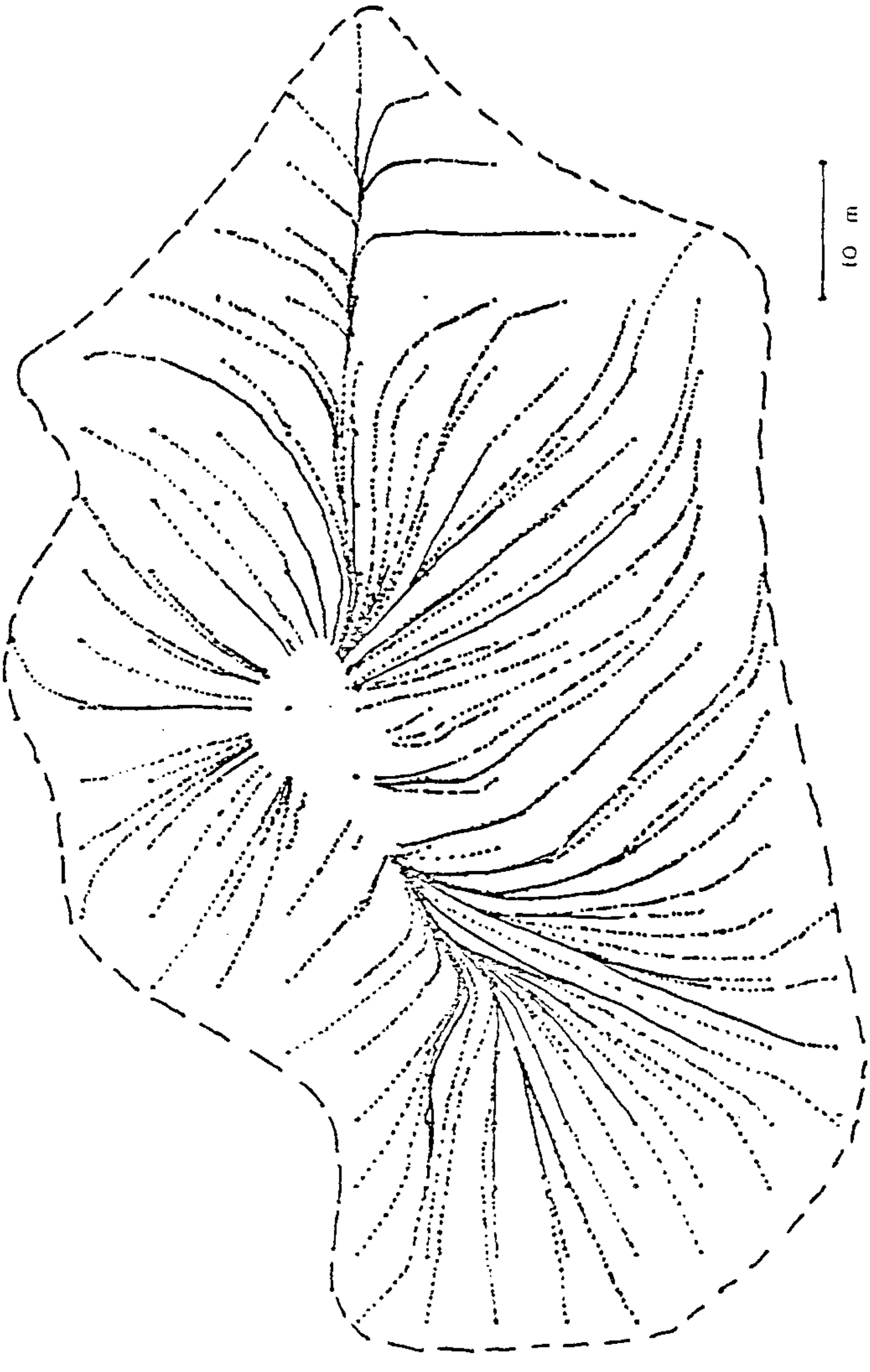


Figure A.11 Lanigan cultivated: water flow pattern.

Figure A.12 Lanigan Control: water flow pattern.

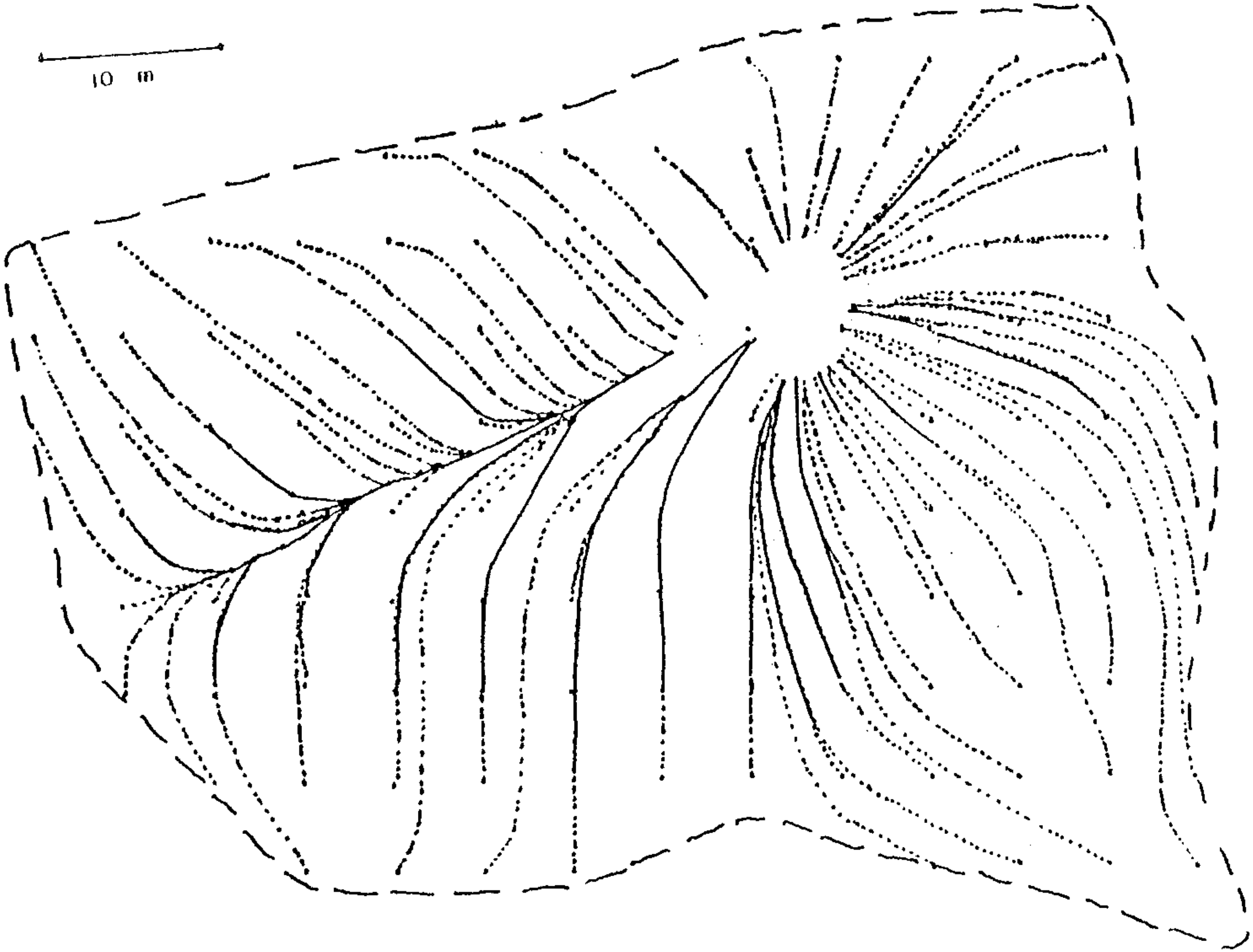


Figure A.13 St. Denis cultivated: water flow pattern.

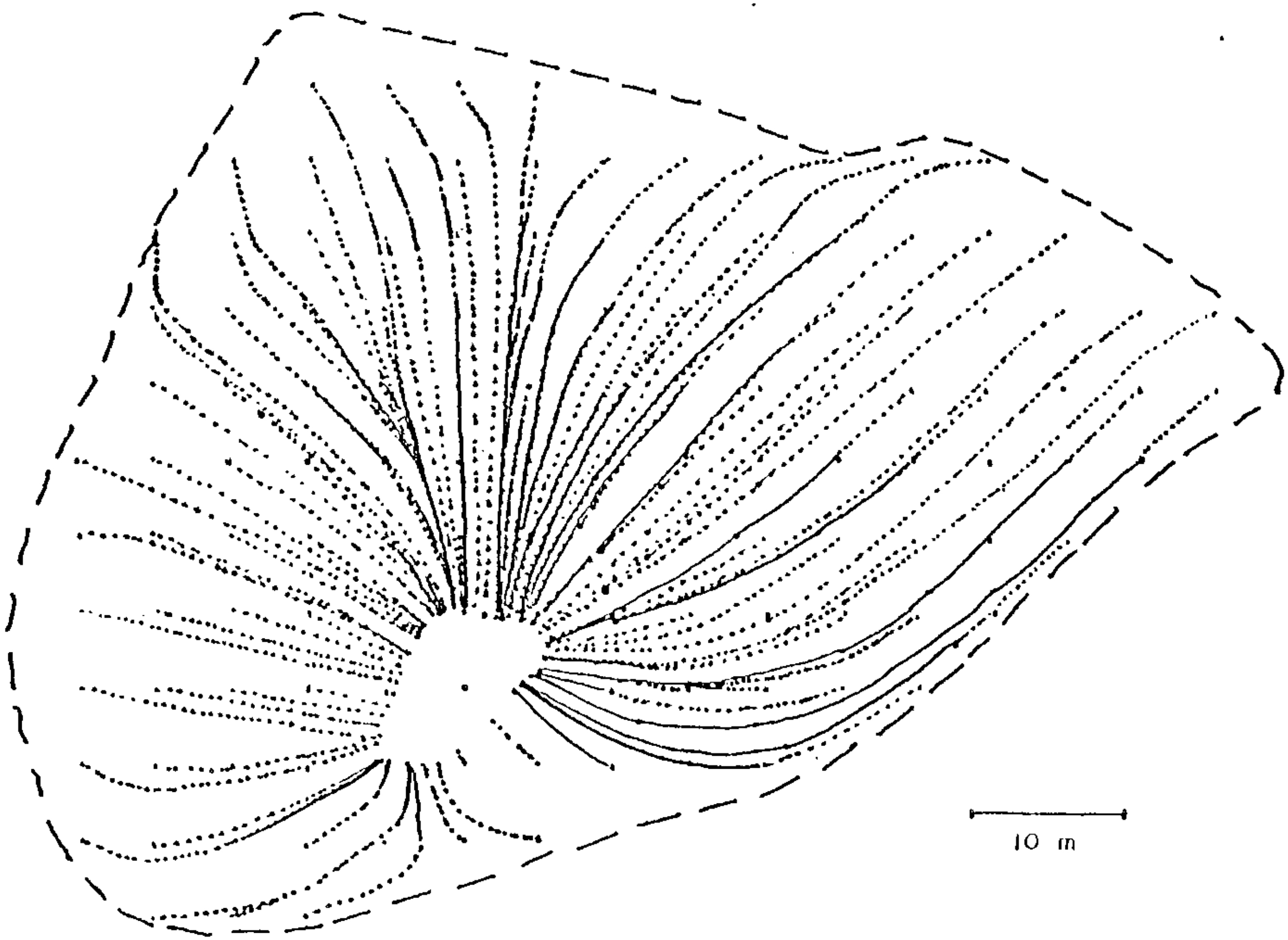
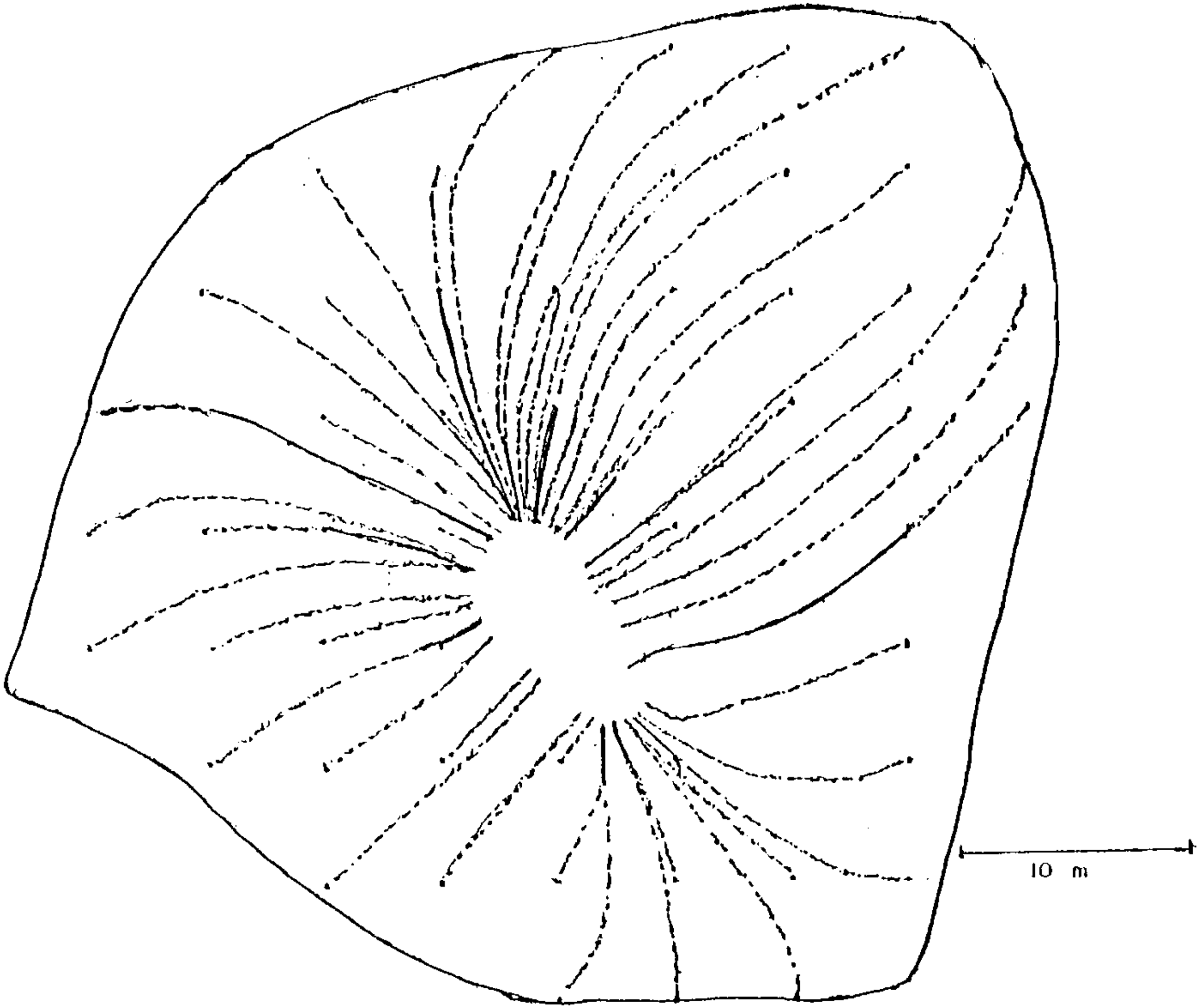


Figure A.14 St. Denis control: water flow pattern.



APPENDIX II

Explanation of Title Headings on Computer Sheets

NO:	Sample number.
DEPTH:	Interval soil depth of sample, cm.
BD:	Bulk density, g/cm^3.
EFF. LENG.:	The overall effective length for a particular sample point on the slope, m.
LENG.:	The distance from the sample point to the highest point on the slope, m.
MGC/G:	Organic carbon, mg/g.
MGN/G:	Total nitrogen, mg/g.
ELEV.:	Elevation of sample point relative to central depression point.
PCCS/G:	Cesium-137, pCi/g.
%SAND:	Sand in sample, %.
%SILT:	Silt in sample, %.
%CLAY:	Clay in sample, %.
%FC:	Fine clay in sample, %.
%SLOPE:	Slope of the sample point between the contour interval, %.
CONT.:	Distance between contour intervals containing sample point, m.
%UNDISP:	Undispersed silt plus clay in sample, %.
MGP/G:	Total phosphorus, mg/g.

Lanigan cultivated: raw data

NO	DEPTH		BD	EFF.LENG	LENG	MGC/G	MGN/G	ELEV	FCCS/G	%SAND	%SILT	%CLAY	%FC	%SLOPE	CONT	%UNDISP	MGP/G
1	0	5	1.11	99.00	99.00	26.45	3.44	.00	1.0034	37.67	42.87	19.46	8.03	99.00	99.00	16.3324	.703
2	5	10	1.01	99.00	99.00	22.25	3.41	.00	.9769	40.04	41.58	18.38	7.26	99.00	99.00	19.4307	.724
3	10	15	.99	99.00	99.00	24.65	3.24	.00	.5796	46.86	39.09	14.06	5.29	99.00	99.00	24.1520	.762
5	15	20	1.26	99.00	99.00	21.70	3.11	.00	.2241	41.43	43.18	15.39	4.59	99.00	99.00	28.8568	.746
6	20	35	1.25	99.00	99.00	4.25	.56	.00	.0000	99.00	99.00	99.00	99.00	99.00	99.00	37.1498	.711
7	0	5	.84	7.50	13.10	30.70	3.01	.45	.8687	50.17	40.44	9.39	8.19	6.40	1.56	15.0989	.652
8	5	10	.86	7.50	13.10	22.25	3.06	.45	.8628	53.14	31.86	15.01	6.92	6.40	1.56	12.7857	.700
9	10	15	1.21	7.50	13.10	22.10	2.76	.45	.8150	53.43	32.03	14.54	7.26	6.40	1.56	17.4900	.627
11	15	20	1.19	7.50	13.10	25.25	2.69	.45	.1635	51.21	37.55	11.24	4.69	6.40	1.56	27.9220	.697
12	20	25	1.17	7.50	13.10	31.96	2.33	.45	.0000	41.94	47.58	10.48	7.78	6.40	1.56	37.4468	.527
13	0	5	.86	14.70	25.90	25.30	3.11	.45	.6806	52.33	29.60	18.07	10.81	6.40	1.56	20.0160	.714
14	5	10	.97	14.70	25.90	25.36	3.03	.45	.7794	55.51	27.01	17.48	9.19	6.40	1.56	15.7033	.694
15	10	15	1.23	14.70	25.90	24.45	2.98	.45	.6468	54.96	27.29	17.76	10.31	6.40	1.56	14.1779	.711
17	15	20	1.43	14.70	25.90	22.25	3.02	.45	.4595	57.26	29.13	13.61	7.62	6.40	1.56	17.0720	.704
18	20	25	1.40	14.70	25.90	9.20	.96	.45	.0000	43.93	47.52	8.55	3.32	6.40	1.56	36.1200	.371
20	0	5	.81	13.80	24.10	37.88	3.27	.42	.9273	42.71	39.14	18.16	7.92	6.40	1.56	19.2224	.662
21	5	10	1.07	13.80	24.10	29.05	3.20	.42	.8974	36.52	45.73	17.75	7.19	6.40	1.56	19.7154	.694
22	10	15	1.29	13.80	24.10	33.15	3.12	.42	.6419	37.34	45.25	17.41	7.37	6.40	1.56	25.5102	.720
24	15	20	1.27	13.80	24.10	29.35	3.52	.42	.1190	35.27	48.79	15.94	5.22	6.40	1.56	31.7671	.710
25	20	25	1.49	13.80	24.10	8.15	1.45	.42	.0000	30.29	57.54	12.17	1.77	6.40	1.56	40.2299	.446
27	0	5	1.08	4.10	3.40	27.00	2.84	.71	.8366	35.39	46.03	18.58	7.81	4.60	2.19	24.5278	.608
28	5	10	.98	4.10	3.40	25.55	2.80	.71	.7589	34.20	48.00	17.80	7.36	4.60	2.19	22.7173	.609
30	10	15	1.24	4.10	3.40	21.40	2.49	.71	.3094	35.10	49.78	15.13	4.77	4.60	2.19	27.2240	.563
31	15	20	2.14	4.10	3.40	4.35	.37	.71	.0000	28.70	61.30	10.00	1.80	4.60	2.19	59.7536	.213
32	0	10	1.42	25.30	15.00	22.85	2.83	.70	.6475	52.93	29.76	17.81	7.77	4.00	2.50	17.7723	.564
34	10	20	1.85	25.30	15.00	16.85	2.11	.70	.1271	44.44	40.75	14.82	8.53	4.00	2.50	17.8600	.406
35	20	30	1.46	25.30	15.00	3.10	.53	.70	.0000	40.04	44.84	15.12	6.98	4.00	2.50	20.6640	.543
37	0	10	1.16	99.00	99.00	35.61	3.92	****	.3163	65.46	19.39	15.15	9.64	99.00	99.00	15.9600	.971
38	10	20	1.56	99.00	99.00	16.25	3.11	****	.0000	65.17	19.85	14.98	10.94	99.00	99.00	12.2960	.950
39	20	30	1.45	99.00	99.00	17.32	1.11	****	.0000	64.33	20.26	15.42	8.92	99.00	99.00	17.6640	.359
40	0	10	1.44	99.00	99.00	21.65	3.44	****	.4053	61.16	23.46	15.39	6.69	99.00	99.00	16.3280	.813
41	10	20	1.67	99.00	99.00	28.25	2.62	****	.0000	63.41	23.06	13.54	7.94	99.00	99.00	19.5920	.693
42	20	30	1.71	99.00	99.00	5.00	.55	****	.0000	63.16	20.74	16.10	8.94	99.00	99.00	22.9520	.387
44	0	10	1.37	5.00	7.00	33.30	3.18	.70	.4075	57.07	25.95	16.98	8.13	4.60	2.19	14.1760	.687
45	10	20	1.67	5.00	7.00	14.15	1.67	.70	.0000	55.07	24.97	19.96	13.82	4.60	2.19	15.3840	.400
46	20	30	1.60	5.00	7.00	11.16	.64	.70	.0000	50.48	31.32	18.20	12.63	4.60	2.19	15.3280	.461
49	0	10	1.46	99.00	8.10	31.80	3.63	1.49	.1681	57.49	23.78	18.73	12.28	3.60	2.81	13.2400	.862
50	10	20	1.53	99.00	8.10	14.35	2.23	1.49	.0000	56.52	23.38	20.10	11.05	3.60	2.81	12.7720	.731
51	20	30	1.41	99.00	8.10	7.21	.77	1.49	.0000	54.41	25.63	19.95	13.39	3.60	2.81	16.7047	.337
53	0	10	1.69	18.80	16.80	30.60	3.88	.95	.3255	52.87	28.85	19.28	7.24	10.60	0.94	14.1760	.777
54	10	20	1.52	18.80	16.80	14.10	1.58	.95	.0000	51.32	29.40	19.29	12.23	10.60	0.94	12.1679	.154
55	20	30	1.52	18.80	16.80	8.18	.82	.95	.0000	48.83	29.75	21.42	14.51	10.60	0.94	16.6572	.283
56	0	10	1.10	3.40	3.40	42.70	4.33	1.47	.7859	50.05	32.26	17.70	9.89	6.40	1.56	21.4640	.840
58	10	20	1.48	3.40	3.40	23.40	2.78	1.47	.0000	54.79	33.09	12.13	6.27	6.40	1.56	12.1120	.614
59	20	30	1.69	3.40	3.40	4.32	.90	1.47	.0000	44.13	40.47	15.40	9.57	6.40	1.56	13.4465	.219
60	0	10	1.20	98.40	25.40	33.70	4.02	1.00	.8259	47.21	34.37	18.42	8.26	4.60	2.50	17.2080	.774
61	10	20	1.39	98.40	25.40	34.15	3.59	1.00	.2093	43.66	38.87	17.47	11.29	4.60	2.50	13.4160	.616
62	20	30	1.52	98.40	25.40	6.46	.73	1.00	.0000	34.97	45.68	19.34	13.14	4.60	2.50	9.3120	.048
64	0	10	1.65	7.50	6.30	24.70	3.00	2.43	.1479	59.78	23.51	16.72	11.11	5.30	1.89	14.3200	.864
66	10	20	1.43	7.50	6.30	14.55	1.64	2.43	.0000	55.46	26.94	17.60	10.14	5.30	1.89	12.8216	.342
67	20	30	1.55	7.50	6.30	12.61	.63	2.43	.0000	54.01	25.98	20.01	11.52	5.30	1.89	[illegible]	.305
68	0	10	1.03	17.50	28.10	36.65	3.73	.95	.7392	49.85	32.11	18.05	8.97	9.00	1.25	[illegible]	[illegible]
69	10	20	1.42	17.50	28.10	12.30	3.87	.95	.0819	48.71	32.51	18.78	11.66	9.00	1.25	13.1200	[illegible]
70	20	30	1.62	17.50	28.10	6.96	.89	.95	.0000	43.56	34.29	22.15	15.03	9.00	1.25	13.6160	.517

Lanigan Control: raw data

NO	DEPTH		BD	EFF.LENG	LENG	MGC/G	MGN/G	ELEV	PCCS/G	%SAND	%SILT	%CLAY	%FC	%SLOPE	CONT	%UNDISP	MGP/G
1	0	5	.70	99.00	99.00	56.30	5.90	.00	2.3395	41.22	41.30	17.49	2.63	99.00	99.00	15.4510	.866
5	5	10	1.12	99.00	99.00	44.15	4.89	.00	1.1117	39.43	44.32	16.25	4.09	99.00	99.00	17.5247	.792
7	10	15	1.43	99.00	99.00	30.30	3.20	.00	.0000	44.50	40.31	15.20	4.31	99.00	99.00	16.3280	.645
8	15	20	1.46	99.00	99.00	8.40	.99	.00	.0000	39.74	46.28	13.97	4.16	99.00	99.00	18.0640	.482
9	20	25	1.42	99.00	99.00	8.32	.77	.00	.0000	24.14	52.99	22.88	16.39	99.00	99.00	26.9769	.517
10	0	10	1.02	158.00	18.80	39.80	4.20	.20	.6308	36.61	48.26	15.13	3.23	1.40	7.19	34.0012	.640
12	10	20	1.51	158.00	18.80	9.30	.89	.20	.0000	34.48	54.61	10.90	3.42	1.40	7.19	41.5920	.314
14	0	10	1.08	61.90	24.70	45.00	4.49	.50	.4579	40.00	37.77	22.23	9.60	4.00	5.00	8.2715	.648
15	10	20	1.31	61.90	24.70	19.73	1.54	.50	.0000	28.36	51.49	20.15	12.74	4.00	5.00	17.3777	.321
16	0	10	1.20	3.10	2.80	51.45	4.67	1.00	.5307	44.87	31.96	23.17	16.09	4.00	2.50	6.1757	.729
17	10	20	1.39	3.10	2.80	29.03	2.76	1.00	.0000	40.87	36.96	22.17	15.48	4.00	2.50	15.9416	.524
19	0	10	1.25	3.40	2.50	35.40	4.51	1.60	.3599	58.90	22.34	18.76	12.54	6.40	1.56	16.4160	1.012
20	10	20	1.25	3.40	2.50	20.14	2.57	1.60	.0000	57.60	21.89	20.51	15.05	6.40	1.56	13.7075	.648
21	0	10	1.06	17.50	12.80	49.85	5.19	1.10	.8120	49.70	29.36	20.95	8.29	8.00	1.25	7.6603	.792
22	10	20	1.38	17.50	12.80	22.02	2.50	1.10	.0000	43.18	35.55	21.27	9.48	8.00	1.25	13.2831	.598
23	0	10	1.21	19.70	31.60	52.55	4.61	.90	.4560	49.17	31.64	19.19	6.57	10.60	0.94	7.3754	.672
24	10	20	1.46	19.70	31.60	15.72	1.67	.90	.0000	37.77	39.42	22.81	14.77	10.60	0.94	9.7589	.389
26	0	10	1.33	9.10	20.00	44.45	4.95	1.75	.5408	55.69	27.74	19.57	11.02	4.00	2.50	15.1591	.946
28	10	20	1.46	9.10	20.00	4.99	1.63	1.75	.0000	57.95	23.06	18.99	12.62	4.00	2.50	11.8240	.554
30	0	10	1.03	99.00	99.00	59.10	5.97	****	.6126	43.82	33.65	22.54	11.18	99.00	99.00	5.5306	.796
31	10	20	1.41	99.00	99.00	33.82	3.37	****	.0000	43.75	33.84	22.40	14.54	99.00	99.00	10.6499	.644
33	0	10	1.25	10.00	6.90	42.10	4.37	.50	.5368	53.98	28.06	17.96	9.93	4.60	4.38	10.4215	.752
34	10	20	1.46	10.00	6.90	11.38	1.13	.50	.0000	50.54	32.17	17.29	12.24	4.60	4.38	12.4720	.325
36	0	10	1.36	99.00	99.00	34.00	4.16	****	.3935	56.39	23.74	19.88	10.92	99.00	99.00	12.5399	1.022
37	10	20	1.27	99.00	99.00	26.10	2.57	****	.0000	51.81	28.52	19.67	10.33	99.00	99.00	16.7150	.773
38	0	10	1.21	4.70	15.00	41.35	4.26	1.01	.5684	54.48	25.74	19.78	11.34	3.70	2.91	9.8400	.803
39	10	20	1.36	4.70	15.00	18.83	2.02	1.01	.0000	49.01	32.22	18.78	13.68	3.70	2.81	15.5393	.541

St, Denis cultivated: raw data

NO	DEPTH		BD	EFF.LENG	LENG	MGC/G	MGN/G	ELEV	PCCS/G	%SAND	%SILT	%CLAY	%FC	%SLOPE	CONT	%UNDISP	MGP/G
1	0	10	1.30	99.00	0.00	41.76	3.88	.00	.6229	42.89	35.19	21.93	12.40	99.00	99.00	11.6674	.880
2	10	20	1.27	99.00	0.00	35.20	3.43	.00	.0000	39.33	36.69	21.99	11.90	99.00	99.00	15.9760	.808
3	20	30	1.41	99.00	0.00	31.65	3.24	.00	.0000	49.94	33.86	16.20	8.48	99.00	99.00	18.7520	.876
5	0	10	1.69	6.60	5.90	27.35	2.64	2.90	.4318	52.33	30.51	17.17	4.64	4.60	2.19	18.8720	.878
6	10	20	1.47	6.60	5.90	12.25	****	2.90	.0000	39.11	36.86	24.04	14.30	4.60	2.19	21.1840	.558
9	0	10	1.49	36.60	21.80	37.40	3.48	1.90	.2802	51.31	30.20	18.49	7.28	5.30	1.88	10.0960	.754
10	10	20	1.51	36.60	21.80	18.95	2.00	1.90	.0000	57.63	24.00	18.37	10.57	5.30	1.88	8.3120	.758
11	0	10	1.25	79.70	33.70	39.10	3.59	.60	.7204	54.87	26.91	18.23	6.11	6.40	1.56	14.6880	.805
12	10	20	1.28	79.70	33.70	21.10	1.95	.60	.6991	51.04	29.23	19.72	9.58	6.40	1.56	11.7200	.712
13	20	30	1.36	79.70	33.70	29.63	2.71	.60	.0000	46.18	35.17	18.65	11.46	6.40	1.56	23.4759	.621
14	0	10	1.31	52.20	34.70	33.90	3.48	.60	.7430	53.34	28.71	17.95	6.38	5.30	1.88	99.0000	.782
18	10	20	1.53	52.20	34.70	30.70	2.82	.60	.0000	56.32	25.16	18.52	11.13	5.30	1.88	16.1760	.658
19	20	30	1.20	52.20	34.70	25.27	2.27	.60	.0000	99.00	99.00	99.00	99.00	5.30	1.88	15.5583	.448
21	0	10	1.38	29.70	20.90	24.55	2.52	2.50	.4661	54.02	28.54	17.44	10.18	10.60	0.94	17.5920	.761
22	10	20	1.50	29.70	20.90	25.25	2.52	2.50	.0000	47.78	32.11	20.11	13.56	10.60	0.94	99.0000	.582
24	0	10	1.62	8.10	11.60	24.65	2.45	3.81	.2892	53.88	28.65	17.47	10.56	5.30	1.88	19.3200	.773
25	10	20	1.32	8.10	11.60	13.37	9.99	3.87	.0000	99.00	99.00	99.00	99.00	5.30	1.88	99.0000	*****
27	0	10	1.61	23.80	26.50	25.25	2.52	2.64	.2604	60.23	24.93	14.84	8.45	8.00	1.25	99.0000	.826
28	10	20	1.34	23.80	26.50	16.85	1.95	2.64	.0000	63.52	21.86	12.63	8.81	8.00	1.25	99.0000	.826
29	0	10	1.41	44.70	34.00	30.30	3.06	.99	.6637	52.99	30.04	16.97	9.54	6.40	1.56	10.7120	.767
32	10	20	1.49	44.70	34.00	29.55	2.92	.99	.1625	55.12	27.57	17.32	11.44	6.40	1.56	17.0880	.648
33	20	30	1.46	44.70	34.00	19.24	1.80	.99	.0000	62.35	24.36	13.28	7.39	6.40	1.56	19.0560	.422
35	0	10	1.29	99.00	5.30	38.65	3.81	.45	.3436	53.21	28.95	17.84	4.84	2.70	3.75	99.0000	.810
36	10	20	1.49	99.00	5.30	19.60	2.32	.45	.0000	52.43	30.19	17.38	11.06	2.70	3.75	12.4640	.728
37	0	10	1.43	38.80	21.20	37.06	3.41	.30	.5718	67.46	20.42	12.11	8.69	6.40	1.56	16.1120	.903
40	10	20	1.20	38.80	21.20	42.80	3.98	.30	.2127	99.00	99.00	99.00	99.00	6.40	1.56	16.4720	.882
41	20	30	1.46	38.80	21.20	28.31	2.38	.30	.0000	45.82	42.04	12.14	11.58	6.40	1.56	19.9915	.546
44	0	10	1.83	7.80	8.40	31.30	3.07	1.50	.2099	69.05	18.78	12.17	6.77	6.40	1.56	15.1120	.978
45	10	20	1.61	7.80	8.40	32.15	3.20	1.50	.0000	63.96	21.11	14.94	9.71	6.40	1.56	12.2160	1.038
48	0	10	1.72	5.00	7.80	23.60	2.62	2.53	.2056	65.65	21.08	13.28	9.08	8.00	1.25	15.4240	.868
49	10	20	1.41	5.00	7.80	13.25	1.66	2.53	.0000	57.79	24.95	17.26	11.47	8.00	1.25	17.0890	.710
50	0	10	1.38	20.00	19.70	32.90	3.50	.80	.5406	60.36	25.15	14.49	5.43	8.00	1.25	12.9520	.898
54	10	20	1.37	20.00	19.70	32.50	2.45	.80	.1371	63.29	23.03	13.68	6.13	8.00	1.25	11.1920	.771
55	20	30	1.58	20.00	19.70	32.84	2.74	.80	.0000	99.00	99.00	99.00	99.00	8.00	1.25	19.2878	.715

St. Denis control: raw data

NO	DEPTH		BD	EFF.LENG	LENG	MGC/G	MGN/G	ELEV	FCCS/G	%SAND	%SILT	%CLAY	%FC	%SLOPE	CONT	%UNDISP	MGP/G
2	0	10	.77	99.00	99.00	66.10	7.90	.00	.5069	31.41	38.71	29.88	17.04	99.00	99.00	3.8210	.922
5	10	20	1.01	0.66	99.00	37.88	3.55	.00	.2540	28.62	43.17	28.21	15.72	99.00	99.00	9.3641	.660
6	20	30	1.14	99.00	99.00	29.32	2.52	.00	.0000	30.66	43.01	26.32	18.57	99.00	99.00	14.1565	.534
7	30	40	1.50	99.00	99.00	7.98	9.99	.00	.0000	22.55	42.83	34.63	25.10	99.00	99.00	13.7440	*****
8	0	10	.68	15.00	7.20	71.25	8.56	.40	.9509	37.21	35.15	27.65	12.65	8.00	1.25	11.1446	.942
9	10	20	1.05	15.00	7.20	25.60	3.53	.40	.0000	47.21	33.23	19.56	12.97	8.00	1.25	6.8235	.604
10	20	30	1.45	15.00	7.20	7.49	1.00	.40	.0000	54.35	31.96	13.68	9.85	8.00	1.25	13.2640	.340
11	0	10	.90	99.00	2.80	62.80	8.80	1.15	.6500	71.32	15.79	12.89	6.66	8.00	1.25	7.7383	1.200
12	10	20	1.74	99.00	2.80	16.97	2.19	1.15	.0000	99.00	99.00	99.00	99.00	8.00	1.25	11.2720	.671
13	0	10	1.28	3.10	10.00	58.10	6.71	.80	.5686	71.47	16.10	12.43	7.69	10.60	0.94	11.0080	1.020
14	10	20	1.22	3.10	10.00	25.62	2.00	.80	.0000	72.19	16.86	10.95	8.94	10.60	0.94	11.7760	.518
16	0	10	1.02	99.00	3.70	42.45	5.86	1.25	5.8687	63.66	20.05	16.30	9.35	4.60	2.19	12.0320	1.072
17	10	20	1.09	99.00	3.70	25.73	1.75	1.25	.0000	55.29	25.74	14.97	13.93	4.60	2.19	11.3304	.650
20	0	15	1.02	99.00	99.00	36.70	3.93	****	.2854	60.81	21.48	17.71	10.47	99.00	99.00	9.9109	.996
23	0	15	.99	6.10	8.10	44.95	5.19	2.20	.2413	62.96	21.40	15.64	9.07	16.10	0.62	9.5280	.940
24	0	10	.87	11.60	15.00	66.95	7.24	1.01	.8001	56.67	24.63	18.70	8.87	16.10	0.62	10.9600	.986
27	10	20	.97	11.60	15.00	45.34	4.58	1.01	.1627	51.57	29.35	19.08	13.77	16.10	0.62	17.4352	.665
28	0	10	.85	17.20	16.20	61.85	7.29	1.30	.4669	44.26	30.84	24.91	13.87	10.60	0.94	6.6875	.990
31	10	20	1.07	17.20	16.20	48.34	3.93	1.30	.0000	42.59	35.20	22.20	16.19	10.60	0.94	15.3346	.706
34	0	10	.80	24.70	22.50	70.25	7.13	.60	.5725	31.99	38.01	30.00	17.11	6.40	1.56	12.6258	.906
36	10	20	1.00	24.70	22.50	57.06	4.68	.60	.2646	27.25	43.93	28.82	18.90	6.40	1.56	10.7645	.677
37	20	30	1.29	24.70	22.50	42.66	3.14	.60	.0000	27.57	43.09	29.35	21.18	6.40	1.56	7.9079	.558
39	0	15	1.21	4.70	7.20	56.05	5.85	1.06	.3587	70.78	16.07	13.15	7.39	3.60	2.81	11.4800	1.003
40	0	10	.74	31.60	15.30	75.85	9.19	.43	.8032	43.70	31.63	24.67	13.67	9.20	1.09	8.9729	.986
42	10	20	1.45	31.60	15.30	22.61	2.45	.43	.0000	51.79	28.93	19.28	14.44	9.20	1.09	6.8807	.856
43	0	10	.78	12.20	8.40	76.90	8.51	.75	.8953	59.91	21.48	18.61	9.96	10.60	0.94	10.8387	1.148
45	10	20	1.22	12.20	8.40	47.82	4.33	.75	.0000	49.69	29.23	21.07	15.70	10.60	0.94	20.8387	.745
49	0	15	1.28	3.10	5.30	55.60	7.69	1.25	.2664	74.96	15.10	9.95	4.58	8.00	1.25	10.0400	1.202