MODELLING SOIL EROSION DUE TO NATURAL RAINFALL IN MANITOBA

by

Charles Ralph Glenn Wright

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CHARLES GLENN RALPH WRIGHT

A Thesis submitted to the Faculty of Graduate Studies of the University of Manitoba in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

ABSTRACT

Two water erosion sites, representing two soil types, a Gretna clay and Leary sandy loam, were monitored in 1991 and 1992. Data collection commenced in mid-April and ended in mid-September. Each site had four standard Universal Soil Loss Equation (USLE) erosion plots measuring 22.13 by 4.57 m on a uniform 9% slope. At each site four continuous crop-management system were represented; fallow, corn, wheat and alfalfa.

Soil losses were measured using a 1% Coshocton runoff sampling wheel. The rainfall-runoff erosivity factor (R) was measured with a tipping bucket rain gauge fitted with a digital recording device. Crop canopy and mulch cover measurements were taken weekly to determine the crop management (C) factor value. Soil erodibility (K) was calculated by dividing measured soil losses by the corresponding R factor value. In addition, antecedent soil moisture levels and runoff flow rates were monitored.

The sediment sampling systems, runoff recorders and rain recording systems were tested to determine their reliability. Experimentally derived USLE factor values were compared to calculated USLE factor values for each site. Field testing of the sediment sampling systems and rain recording systems showed that, for the most part, soil losses and rainfall intensity and amounts were being measured accurately. However, high intensity segments occurring within some rainstorms occasionally exceeded the capacity of the rain recording systems. These 'cloud bursts' often accounted for a significant portion of total storm rainfall and produced large soil losses.

Measured K values did not compare well with the calculated USLE nomograph K values for the experimental soils. Measured average annual R values from both sites were about 1117 MJ mm ha^{-1} h^{-1} which compared favourably to the value of 1160 MJ mm ha^{-1} h^{-1} obtained by Wall et al. (1982) for Winnipeg Manitoba. A comparison of USLE C values proved to be impossible due to fundamental differences between field measurements and the measurements required for determining USLE C factor values. Observed soil losses, soil loss ratios and soil erodibility values were extremely variable and were dependent upon rainfall characteristics, plot surface morphology and antecedent soil moisture levels.

Multiple regression was used to establish relationships estimating soil losses and soil erodibility from soil and rainfall characteristics. Since these relationships had low coefficients of determination, it was concluded that more research is needed in order to develop field measurement techniques which will be useful in helping to describe the observed variability in individual storm soil losses.

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1. INTRODUCTION

Erosion is defined as the weathering and transport of consolidated and unconsolidated material at the earth's surface. The processes of erosion are many and complex. Glaciers scour the landscape. Frost riving pries apart solid rock features. Chemical reactions breakdown the molecular fabric of earth materials. Cyclical temperature fluctuations weaken rocks through thermal expansion and contraction. Wind works relentlessly to abrade and wear away surfaces. Rainfall and its runoff continuously reduce features at the earth's surface. Driven by gravity these natural process work alone, or in combination to reduce topographic highs and fill in topographic lows.

It is a fact that our agricultural lands are being constantly subjected to erosion. Two major types of soil erosion are recognized, soil erosion due to wind, and soil erosion due to rainfall. It is the latter which is the subject of this thesis. Human activities often accelerate the natural process of erosion, frequently with devastating consequences. By developing an understanding of the processes governing erosion, we may construct a model that is capable of predicting rates of erosion on given segments of land. Once these highly erodible land units have been identified, erosion rates can be quantified under a variety of management and cropping scenarios. The model could then identify which management or combination of cropping and management practices reduce erosion to tolerable amounts, while simultaneously satisfying the needs of economic return and minimizing environmental damage.

Since the early 1900's attempts have been made at quantifying the nature of rainfall induced soil erosion. Pauls (1987) gave an excellent review of the history of soil modelling attempts. To date, the most successful model has been the Universal Soil Loss Equation (USLE).

The USLE is a six-factor empirically derived, statistical model designed to estimate long term average annual soil losses due to rainfall. Expressed as $A = K*R*L*S*C*P$, average annual soil losses, (A), are calculated through the multiplication of factors representing the combined effects of soil type (K), climatic factor (R), topography (L and S), cropping and management (C), and cultural practices (P).

The USLE is intended to be universal in that it represents fundamental erosion processes through a statistical data base. Most of information needed to define its factor values can be obtained through soil survey reports, on site field evaluation and climatological data. Adapting the equation for geographic areas outside those in which it was developed can be accomplished through data collection and modification of its factor values. The USLE predicts long term average soil losses based on a twenty-two-year climatic cycle.

In recognition of this, the Department of Soil Science, University of Manitoba, funded through the Economical Regional Development Agreement, initiated a long term study to assess the applicability of the USLE for the Canadian prairies. The project was implemented in 1984. A total of 23 standard USLE research plots, (4.6 by 22.13 meters long on a uniform 9% slope) were established throughout southern Manitoba, on five soil types with plots representing five cropping treatments over a period of five years. Two sites, a Gretna clay and a Leary sandy loam were established in 1984 and 1985, respectively. Both employ four continuous cropping treatments representing fallow, corn, wheat and alfalfa. Over the next three years, three more sites were established, each of which included an additional minimum tillage treatment. These sites were established on a Carroll clay (1986), a Ryerson sandy clay loam (1986), and a Newdale clay loam (1988),

Pauls (1987), established the first two experimental sites and attempted to evaluate the applicability of the USLE in Manitoba. Wahome (1989) focused on an evaluation the K and C factor values for Manitoba. Hargrave (1992) continued collecting soil loss data and studied nutrient losses in sediment and runoff water.

This study continues the long term objective of modifying the Universal Soil Loss Equation to suit conditions encountered on the Canadian prairies. Specifically it will examine the following areas:

1. Scrutinize the sediment sampling equipment and determine its reliability.
2. Test the reliability of the existing rain recording system.
3. Evaluate rainfall characteristics.
4. Abstract experimental data from Gretna clay and Leary Sandy loam sites since the inception of the research project.
5. Investigate the dynamic nature of the soil erodibility factor as influenced by cultivation, cumulative rainfall since last cultivation and antecedent soil moisture.
6. Make specific recommendations for the improvement of experimental field plots and the direction for future research.

2. LITERATURE REVIEW

2.1 The costs of excessive erosion

On the North American continent, agriculture may be considered to be a relatively new phenomenon. In spite of our relatively short agricultural history, already major damage to our soils has occurred as a direct result of farming practices. These damages have occurred largely in the last 100 years or so. Our survival as a species literally depends on these resources. The startling reality is that we cannot outlive our food sources. How long does man as a species hope to survive, millions, thousands, hundreds of years? The answer is hopefully the former. We must be prepared to sustain the working life span of our environment indefinitely.

The soil is the substrate from which all land based food sources arise. Therefore, we must recognize the soil as the land based medium on which life and the success of our species depends. We must ask ourselves, what damages arise due to human induced erosion? How is productivity affected? What are the costs of conservation? How much erosion can be tolerated without compromising the sustainability of our soil resources? What rates of erosion are occurring and how can we modify or reduce these rates?

Soil erosion threatens the productivity of soils and contributes to non point source pollution (Pierce et al. 1984). Damages resulting from erosion can be divided into two categories: 1) off site damages, 2) on site damages.

2.1.1 On site damages due to soil erosion

Estimates of the magnitude of the damages resulting from erosion vary widely. However, the various estimates all lead to the same conclusion: At the current rates of erosion, the world faces major losses of productive agricultural lands.

Brown (1984) estimated the current rate of loss to the world's soil resources to be 7% per decade. Furthermore, he estimated that every year, 5.7 billion tons of soil is lost in excess of new soil formation, due to wind and water erosion. One third to one half of the worlds soil resources are being managed poorly. One third of the crop land in United States is eroding above tolerable levels.

Putnam et al. (1988) used the Erosion-Productivity Impact Calculator (EPIC) model to predict long term productivity losses in the United States based on data collected in 1982. Assuming cropping and management practices were to remain the same, the EPIC model predicted a 1.8% and 0.5% productivity loss in the next 100 years due to sheet and rill, and wind erosion, respectively. However, more than 3% of the crop land will suffer yield reductions greater than 10%. This is equivalent to taking 8.9 million acres out of production.

The 1977 National Resources Inventory (NRI) predicted productivity losses of less than 8% in the United States corn belt (Pierce et al. 1985). Crosson (1985) calculated a 2.5% decline in productivity of U.S. soils since the initiation of cultivation. However, simply measuring productivity losses may be misleading. Advancements in fertilizer technology, cultivation practices, and plant sciences often mask productivity losses due to soil erosion.

Nowak (1988) provided an interesting list of hidden costs associated with accelerated erosion of crop lands. This list included such obvious factors as direct costs associated with lost fertilizers and pesticides from field units. As well, there are yield reductions when fertilizer and pesticide movements cause deficiencies under eroded areas and toxic effects due to high concentrations in depositional areas. Replanting of damaged field areas is often necessary.

More subtle losses include increased fuel costs due to reapplication of pesticides and higher drag coefficients in poorer exposed subsoils, increased wear and tear on machinery as poorer, rockier subsoils become exposed, crop yield and quality losses due to down times during critical seeding, spraying, and harvesting periods, losses of parts of fields due to severe gullying or localized erosion. Also, there are the costs associated with cleaning out ditches, culverts, drainage and irrigation structures due to sedimentation.

Assigning a dollar figure to the costs due to erosion is difficult. On the other hand, costs associated with conservation are relatively easy to determine. These include direct government pay outs to farmers for carrying out conservation oriented projects, large scale regional and local projects aimed at reducing erosion, increased cost of pesticides in conservation tillage systems, as well as costs associated with extension and education. This list is not comprehensive. The direct costs of conservation are plain to governments and land owners. However, the long term hidden costs of land degradation are not so obvious. In these stressed economic times with increased input costs and reduced commodity prices, farmers are understandably reluctant to adopt conservation practices that in the short run increase input costs and increase the risk of financial failure.

2.1.2 Off site damages

Erosion costs both the land owner and the public. Off site damages make up a large part of the erosion problem. Siltation of lakes, reservoirs and rivers is a major problem associated with erosion. Reservoir life spans are reduced, harbours must be dredged. Rivers and lakes lose storage capacity, causing extensive property damage and loss during flooding (Crosson 1985). Water quality is reduced due to chemical laden runoff from agricultural fields. Medical costs increase due to human health problems. Turbidity in lakes and rivers reduces their aesthetic and therefore their recreational value. Increases in water sediment loads also accelerates the wear and tear on pumping systems due to abrasion.

In the United States alone total off site damages are estimated to be greater than one billion dollars per year. Total costs due to accelerated erosion are estimated to be between 2.5 and 3.0 billion dollars annually (Crosson 1985). As erosion incipiently erodes away our valuable top soil, it undermines our financial resources.

2.2 Soil loss tolerance

Despite human efforts, soil erosion has always and will always take place. Fortunately, the earth has a natural capacity to regenerate and repair incipient damages arising from long term erosion, pollution, misuse and even catastrophic events.

The effects of soil erosion cannot be quantified without considering rates of soil formation. Sustainability is achieved when and only when, soil formation exceeds or equals soil erosion rates.

Soil loss tolerance is defined as "the maximum rate of annual soil erosion that may occur and still permit a high level of crop productivity to be obtained economically and indefinitely" (Wischmeier and Smith 1978). Soil loss tolerance or T values have been set between 4.5 and 11 t ha^{-1} yr^{-1} in the United States. Guidelines for selecting T values used by the North East Technical Service Centre are as follows (McCormick 1982).

1. Soils with loamy sand or sand textures to a depth of 120 cm have a soil loss tolerance of 11.2 t ha^{-1} yr^{-1}

2. Soils with moderately coarse and finer textures and no impeding layer (fragipan, claypan, or bedrock) and soils with no coarse sand and gravel within 90 cm have a tolerance of 9.0 t ha^{-1} yr^{-1}.

3. Soils with an impending layer (fragipan, claypan or bedrock) or coarse sand and gravel between 30 and 90 cm of the surface have a tolerance of 6.7 t ha^{-1} yr^{-1}.

4. Soils with an impending layer (fragipan, claypan, or bedrock) or coarse sand and gravel within 30 cm of the surface have a tolerance of 4.5 t ha^{-1} yr^{-1}.

2.2.1 Rates of soil formation

Current soil loss tolerance values are based upon rates of topsoil formation. Estimates vary from 2.5 mm in one thousand years to 25 mm in 30 years (Hall et al. 1982). A review of the literature by Schumm and Harvey (1982) concluded that natural rates of soil formation were roughly 0.6 - 15 mm in thirty years. Cultivated soils were expected to form as fast as 25 mm in 30 years under ideal conditions, but on average formed at rates of 25 mm in 100 years. Other studies suggest that significant amounts of organic matter can accumulate in tens of years under forest or grasses. However, deep soil profiles may take thousands of years to develop.

Schertz (1983) cites current estimates of soil loss tolerance values as inadequate. This view was strongly supported by Johnson (1978), who added that T values should only be considered provisional or short range. We are only buying a little time by restricting present rates of soil loss to "tolerable" limits.

Topsoil formation can be viewed as relatively rapid. The rate of weathering of parent materials is comparatively slower, roughly one t ha^{-1} yr^{-1}. McCormack et al. (1982) warn of substantial productivity losses over several hundred years at current "tolerable" levels.

Unconsolidated parent materials may weather up to 1.1 t ha^{-1} yr^{-1} while consolidated parent materials experience much lower rates (McCormick et al. 1982). The rate of soil formation is a function of climate, topography, parent material, vegetation and agriculture. Current tolerance rates may permit the farming of a continuous depth of an A horizon. However, given the rate of solum development based on parent material weathering, our soils will become progressively thinner eventually leading to the failure of the resource.

Rates of soil formation are as individual as soil types. Currently there is no adequate model to predict soil formation rates. This type of research is much needed and necessary. Without this type of model we can only hope to quantify present rates of erosion and, at best, reduce these rates. This says nothing of the long term ability of our non-renewable soil resources to continue to be a valuable asset in our own struggle against extinction.

2.3 Physical processes governing soil erosion

As our understanding of the soil erosion process increases, we become more aware of the complexities of the erosion process. A simplistic view acknowledges the main factors that influence soil erosion by rainfall. These factors include soil physical properties, rainfall and runoff processes, topography, vegetation and management (Wischmeier and Smith 1978). The interactions among these parameters are dynamic, extremely complex and detailed. Thus to understand the intent behind soil erosion modelling it is important to understand this vastly complex phenomenon.

Soil erosion is initiated through the detachment of soil particles from the soil mass and subsequent transport of the detached particles. Particle detachment occurs through rain drop impact, and the hydraulic shear generated by surface runoff. Transport is accomplished through raindrop splash and entrainment within surface runoff. Runoff can only begin when rainfall rate exceeds infiltration rate, and surface storage within small impoundments on the soil surface (Onstad 1984).

Erosion represents movement or loss. However, erosion processes are accompanied by depositional phenomenon. Thus erosion, embodies a combination of detachment, movement and depositional processes that interact to provide net movement of soil constituents.

2.3.1 Rainfall

The movement of soil in the erosion process requires energy. Energy is supplied through the forces of moving water in the form of raindrops and runoff. Therefore, rainfall both directly and indirectly is the driving force governing water erosion processes.

The kinetic energy of falling raindrops provides a mechanism for detaching soil particles and transporting soil through splash erosion. Rainfall not directly absorbed by the soil generates runoff. Runoff generated by excess rainfall detaches particles through hydraulic shear and serves as a medium for transport of both raindrop detached material and material made available directly through the processes of runoff.

In recognition of these processes, Wischmeier and Smith (1958) attempted to determine the rainfall characteristics most highly correlated to the soil erosion process. Laws and Parsons (1943) found that median drop size was a function of intensity and that the range of drop sizes at a given intensity were normally distributed. Work by Gunn and Kinzer (1949), found that terminal velocity of raindrops was a function of rain drop size. Physically, kinetic energy (KE) is expressed as:

$$KE = 0.5MV^2$$

where:

M = Mass
V = Velocity

Kinetic energy is a function of the mass of the rain drop, and based on a spherical model, is simply the density of pure water multiplied by the volume of water. Velocity is based on terminal fall speed through still air. Terminal velocity is achieved when the downward gravitational force is balanced by the upward forces of air resistance.

Wischmeier and Smith (1958) combined the data by Laws and Parson (1943) and Gunn and Kinzer (1949) to calculate the kinetic energy for individual storms. Thus, kinetic energy was computed by summing the kinetic energies of individual drops within several drop size categories for drop size distributions associated with various intensities. By summing all the kinetic energies for each intensity increment within the storm, the total storm kinetic energy was determined.

The overwhelming volume of literature directed at determining rainfall intensity-kinetic energy relationships is testimony to the wide acceptance of this theory. Several equations have been proposed:

$$KE = 9.81 + 11.03 \text{ Log } I \text{ (Zanchi and Torri 1978)}$$

$$KE = 11.89 + 8.74 \text{ Log } I \text{ (Wischmeier and Smith 1959)}$$

$$KE = z\,(1\text{-}pe^{-hI}) \quad \text{(Kinnel 1981)}$$

Where:

KE = Kinetic Energy per unit quantity of rain
I = Intensity of rain mm h^{-1}
z, p, and h are empirical constants
e is the base of natural logarithms

The relationship proposed by Zanchi and Torri (1978) was developed in Italy. Wischmeier and Smith (1959) derived their relationship based on data collected by Laws and Parsons (1943) in Washington. The relationship found by Kennel (1981) adequately described soil losses in both Rhodesia and Miami, Florida. The differences between these equations and many others may reflect the inherent temporal, seasonal and geographic variability in the nature of rainstorms.

Rainfall is the driving force in the water erosion processes. To gain an appreciation of the variability of rainfall intensity-kinetic energy relationships, it is important to understand the processes responsible for this variation. Zanchi and Torri (1978) found drop size distributions were greatly affected by climatic conditions. Wischmeier and Smith (1958) found that small cloud bursts or short rains produced a significantly larger proportion of large raindrops. McIsaac (1990) noted large differences in median drop size at various geographical locations. These differences were due, in part, to atmospheric effects. Raindrops form around nucleation sites present within the air. Air born salt particles in maritime environments provide a large number of nucleation sites around which raindrops can form. This results in raindrop distributions with a high proportion of small drops. In arid environments small drops tend to evaporate before striking the ground, favouring larger drop size distributions.

McIsaac (1990) also found that terminal velocity for a given drop size was a function of elevation. Higher elevations resulted in faster terminal velocities due to a decrease in air resistance. He suggested that calculated values for kinetic energy using the equation developed by Wischmeier and Smith (1958) be increased by 7% for each increment of 1000 m above sea level. Terminal velocity is also greatly influenced by the absence or presence of winds (Wischmeier 1959).

Rogers et al. (1967) found single storm variations of up to 30% in the ratio of actual to calculated kinetic energy when using the equation developed by Wischmeier and Smith (1959). When using formulas relating kinetic energy to rainfall intensity, one must be aware of local rainfall characteristics and have knowledge of where and how the formula employed was derived.

2.3.2 Soil erodibility

Soil loss occurs when the forces of erosion exceed the ability of the soil to resist erosion. Thus, every soil has an inherent ability to resist erosion and conversely, to erode. This ability is termed soil erodibility. Years of research by many workers have been devoted to defining soil erodibility. Wischmeier and Mannering (1969) found no less than twenty-four soil physical properties significantly influencing soil erodibility. They found soil erodibility varied up to thirty fold between different soil types.

Soil loss can be described by a steady-state sediment continuity equation (Nearing et al. 1990) given as:

$$dG/dx = D_r + D_i$$

Where:

G = sediment load (kg m^{-1} s^{-1})
x = distance down hill slope (m)
D_r = Rill detachment or deposition (kg m^{-2} s^{-1})
D_i = delivery rate of inter rill sediment to rills (kg m^{-2} s^{-1})

Sediment detachment from within rills is given by:

$$D_r = K_r(\tau - \tau_c)(1 - G/T_c)$$

Where:
K_r = rill erodibility (s m^{-1})
τ = shear stress in the rill (Pa)
τ_c = critical hydraulic stress of the soil (Pa)
G = sediment load (kg m^{-1} s^{-1})
T_c = transport capacity of the flow within the rill (kg m^{-1} s^{-1})

K_r and τ_c are physical properties of the soil and reflect the soil's inherent ability to erode. T_c represents the maximum ability of the flow to transport sediment. It is influenced by flow characteristics such as velocity, depth and turbulence. The term $\tau - \tau_c$ describes the amount of energy available for soil detachment due to hydraulic shear. When τ_c exceeds or equals τ, no soil detachment occurs and therefore no soil is eroded. The term $1 - G/T_c$ represents the sediment carrying capacity of the runoff. When sediment concentration is low, G/T_c approaches zero, and maximum entrainment can occur. On the other hand, when sediment concentration reaches or exceeds transport capacity, net deposition is occurring and therefore there is no net erosion occurring.

This equation only accounts for sediment loss through scour. Sediment production through rill side wall slumping and headward erosion is not represented. Inter rill erosion D_i is expressed as:

$$D_i = K_i I^2$$

where:

K_i = interrill erodibility (kg s m^{-2})
I = rainfall intensity (mm h^{-1})

Elucidating the nature of soil erodibility is no simple task. The seasonal variability of a soil's susceptibility to erosion is well documented (Baracharya and Lal 1992, Kirby and Mehuys 1987 and Thornes 1980). Baracharya and Lal (1992), and Mutchler and Carter (1983) found seasonal soil erodibility to approximate a cosine function which was a function of time throughout the year. Soil erodibility was highest in the late winter or early spring and lowest in the summer. Partially frozen or wet soils were more susceptible to erosion due to decreased strength, aggregate stability, and reduced infiltration rates. From spring through fall, a soil's susceptibility to erosion was lowered through consolidation that increases soil strength and reduces detachability. Where extreme moisture deficits occur late in the growing season erodibilities were lowered further. The magnitude of the variation was dependent upon texture, being higher in silty soils, intermediate for clays and loams, and lowest for sands.

2.3.2.1 Soil surface morphology

When rainfall rate exceeds infiltration rate, excess water becomes available for runoff. Excess rainfall rate can be described by the following equation (Hairsine et al. 1992):

$$R = P - I - dE/dt$$

Where:

P = rainfall rate
I = infiltration rate
DE/dt is the rate of change of depressional storage

During a rainfall event, infiltration rates may change (Wischmeier and Smith 1958), depending entirely upon the current water status of the soil. A dry soil has a much more rapid infiltration rate than the same soil in a saturated state. Infiltration rates are also dependent on soil structure as influenced by tillage, shrink and swell in certain clays (Thornes 1980), and can be impeded by surface sealing associated with raindrop impact (Gimenez et al. 1992, Nearing et al. 1990). Freebairn et al. (1989) found that on a silt loam infiltration rates prior to surface seal development were greater than 200 mm h^{-1}. Once seals developed, infiltration rates were as low as 10 mm h^{-1}. Crust formation was a function of cumulative rainfall since last cultivation. Between rainfalls, surface crusts were disrupted by the formation of small cracks and insect burrows. However, once surface crusts formed, very little rainfall was needed to renew disrupted crusts.

Surface sealing results when small particles become detached through the forces of raindrop impact and/or hydraulic shear. Some of these minute particles move with water infiltrating into the soil surface and become lodged in small micro pores. However surface sealing is not only a function of the soil itself, but also of surface characteristics. For instance, clods do not develop surface seals (Thornes 1980).

Runoff is governed by the morphological characteristics at the soil surface. Hairsine et al. (1992) stated that it is generally assumed that runoff begins when excess rainfall rate exceeds surface storage capacity. However, they point out that this assumption may not be valid. At the soil surface, runoff is initiated between depressional elements when they become overtopped with water. Adjacent surface elements may be topographically lower or not as deep as other areas on the soil surface. Thus runoff may begin across portions of the soil surface (Onstad 1984). In time, given enough excess rainfall, the entire soil surface will contribute to runoff.

Clods at the soil surface act as barriers to overland flow as well as creating depressions within which water can pond (Huang and Bradford 1992). Pools of water on the soil surface shield the soil from the erosive forces of rain drop impact (Wischmeier and Smith 1958). The degree of this shielding is governed by depth of ponding (Thornes 1980). Clod size can vary dramatically on some soils depending on choice of tillage implements and moisture content at time of tillage (Romkens 1985). Further more, clod size decreases through slaking due to rainfall. Therefore, depressional storage for a given soil is dependent upon several factors.

Surface runoff begins as sheet flow over the soil surface. If runoff is prolonged, surface morphology changes as clods slake and rills begin to form. As rills grow and propagate across the soil surface, an efficient drainage network develops. Additional modifications to the soil surface occur as depressions are filled through sedimentation. Rills concentrate runoff and convey it and soil down slope. Thornes (1980) found that where rills developed, erosion within rills was several orders of magnitude greater than from interrill areas. Meyer et al. (1975) reported that rilled plots eroded approximately three times more rapidly than non rilled plots. In contrast, Loch and Thomas (1987) and Freebairn and Wockner (1986) found that on soils resistant to rill erosion, soil movement through rills was less important. They described certain cracking clays as resistant to rill erosion.

Once initiated, rills propagate through channel scour, slumping of the banks and head ward erosion (Nearing et al. 1990). Progressive down cutting of the rills may expose subsurface layers with differing erodibilities.

Runoff is conveyed to the rills via inter rill areas. Inter rill areas develop and become more efficient at conveying water and sediment to rills areas (Loch and Thomas 1987). At some point, soil erodibility reaches a maximum and then decreases as the more easily detached particles are removed (Meyer 1985). Rill development may reach a maximum after which soil erodibility deceases as highly erodible material is removed, leaving behind a lag deposit of less erodible material that armours the soil surface against subsequent detachment (Freebairn and Wockner 1986).

In the event of extreme rainfall intensities, the whole soil surface may become inundated with water. Mass flow over the entire surface of the plot occurs (Freebairn and Wockner 1986). In this event, raindrop detachment may all but cease and flow in rills and inter rill areas is no longer distinguishable. As overland flow deepens, raindrop detachment is maximum for a thin water film and then decreases rapidly to zero at flow depths greater than three drop diameters (Thornes 1980).

As erosion increases, the soil particulate matter is preferentially removed. Thus, over time soil texture is modified as the more erodible size fractions are removed. Continued tillage mixes soil horizons and sometimes, new texturally different subsoils become exposed at the surface. In addition, lowering of the soil surface removes organic matter which binds the soil particles together. Subsoil horizons, occasionally different in texture from the original surface horizon become exposed. Thus, over time the very nature of the soil mass can change. In addition to this, surface morphology changes and the "inherent erodibility" of the soil becomes a complex and dynamic factor.

2.3.3 Vegetation

Vegetation is the primary agent responsible for soil development and stabilization. Plant canopies serve as a shield against the erosive forces of rainfall (Bui and Box 1992, Evans 1980, Moss 1989, Wischmeier and Smith 1978). Rainfall is intercepted above ground by living plant material and at the soil surface by plant residue. Surface residue also acts as a barrier to runoff water, reducing its velocity and its ability to entrain sediment though hydraulic shear which reduces transport capacity. Often, surface debris can cause localized deposition of sediment.

Rainfall intercepted by above ground portions of the canopy is converted to two main classes of secondary drop elements, large gravity drops and smaller impact drops (Moss 1987).

Rainwater flowing over the plant's surface coalesces at localised low points and is released as large gravity drops. Erosivity of gravity drops is extremely sensitive to fall height since velocity increases with fall height. Free falling gravity drops can reach up to one half of terminal velocity in 1.2 meters (Moss and Green 1987). The proportion of gravity drops reaching the soil surface is a function of the spatial characteristics of the canopy as dictated by plant species and growth stage. Low erosivity rains can coalesce on the plant surface and concentrate to be released as erosive gravity drops causing significant erosion.

The second type of secondary drop elements are impact droplets. Single raindrops striking a plant surface will often generate a number of smaller high velocity drop elements. The number, size and trajectory of these smaller drops are highly dependent on surface roughness and edge effects as dictated by leaf morphology and orientation. However, due to the small size of these drops and the rapid deceleration due to air resistance, they are not highly erosive (Moss 1989).

Plant communities further reduce erosion by decreasing the amount of rainfall available for runoff. In part, canopy storage contributes to lower runoff rates. However increased infiltration rates greatly reduce total runoff. Roots and organic matter enhance soil structure, increasing infiltration rates and aggregate stability (Morgan 1980). Evapotranspiration lowers antecedent soil moisture. Surface sealing due to raindrop impact is reduced by the shielding effects of the plant canopy (Evans 1980).

Quantifying the effects of plant cover is further complicated in agricultural systems where crop rotations are performed (Whischmier and Smith 1978). Residual root mass effects from a previous crop may last up to two years. Tillage affects the amount and character of surface residues. Crop rotations affect the length of time between successive crops and the length of time the soil is protected or left unprotected. Moss (1989) found that crops with narrow low growing leaves favoured the formation of small impact drops and were effective in reducing erosion. Bui and Box (1992) found crops like corn and sorghum were capable of intercepting rainfall and channelling it down the plant stems. Corn contributed one third of its stem flow to runoff while stem flow from sorghum was mostly accounted for by infiltration.

Plant canopies are directly responsible for protecting the soil against the erosive forces of rainfall. However, the degree of protection is very specific to a number of plant factors ranging from total canopy coverage, canopy morphology, plant soil interactions and plant climate interactions.

2.3.4 Topography

Slope steepness and slope length are important factors governing the velocity and amount of runoff generated during an erosion event. Generally soil loss will increase as slope length and gradient increase (Wischmeier and Smith 1978, Castro and Zobeck 1986).

On a uniform slope, as slope steepness increases so does runoff velocity and the ability of runoff to detach and transport sediment increases. Increasing slope length tends to incrementally add to the total volume of runoff passing a given point as length of slope increases above that point. This increases the depth and volume of runoff passing the same point and again, particle detachment and transport capacity increases.

Consider a typical landscape to be composed of many small randomly oriented interconnected slope segments of variable length. Sediment load at any point on the land surface is a function of the transport capacity of the rainfall and runoff and the amount of material available for transport (Foster and Wischmeier 1974). When the amount of available material exceeds transport capacity, deposition occurs. Transport capacity is a function of runoff amount and velocity. Decreases in one or both favour deposition.

Runoff generated at the top slope segment proceeds down slope, normal to the slope gradient. Adjacent slope segments receive run off water and convey it further down slope. Complex interactions between neighbouring slope segments affect the velocity, depth and sediment concentration of runoff water. This in turn affects the sediment transport capacity and, depending upon sediment concentration, results in net erosion, net deposition or a steady state.

Estimating the topographical factor in the Universal soil loss equation remains the most difficult of all factor values to determine (Moore and Wilson 1992). Simply averaging slope gradient results in large errors in estimating soil loss (Wischmeier and

Smith 1978). Foster and Wischmeier (1974) found that relative rates of erosion for a given slope length were dependant on slope shape. Using a uniform slope for comparison, they found that a concave slope averaged 11.1 percent less erosion. A convex slope eroded on average 34 percent more. Complex slopes usually produced more soil loss than equivalent length uniform slopes.

2.4 Soil loss modelling

Agricultural soils the world over are deteriorating due do human induced rainfall erosion. By developing erosion prediction technology, erosion prone areas can be identified. Once a specific site has been identified as an erosion risk, action can be taken to reduce soil losses from the land unit. By defining a soil loss tolerance, the maximum permissible level of soil loss can be targeted. Management scenarios involving cropping patterns and cultural practices can then be identified which will provide an adequate level of erosion protection without exceeding acceptable soil losses. Ultimately, those in charge of erodible land units can choose an appropriate management scheme consistent with their abilities and needs.

In North America, the earliest documented measurements of soil erosion, were taken in the spring of 1915 at the University of Missouri, by a young student, R. W. McClure under the guidance of Professor M. F. Miller (Woodruff 1987). This simple study involved measuring rainfall and runoff from a small diamond shaped plot, equipped with a rain barrel for collecting sediment. The study concluded that the amount of nutrients lost were larger than that removed by the crop. This small project laid the foundation for a legacy of erosion research that continues to this day. Pauls (1987) provides an excellent review of past erosion research in North America.

There are two approaches to modelling soil loss. The first one, which comprises the bulk of the literature on the subject involves empirical modelling, based on the statistical analysis of vast amounts of erosion data. The second method utilizes a mathematical process based approach that explicitly models several erosion processes and integrates them into one large computer model. The latter method is extremely complex and requires a powerful computing base. The former is simpler, less cumbersome and more user friendly. Unfortunately the simpler empirically based models are often incapable of estimating soil loss on an event basis. They are restricted to predicting long term average soil losses from stabilised systems.

In 1985, the USDA initiated the Water Erosion Prediction Project (WEPP) targeted at developing a new generation of erosion prediction technology (Laflen et al. 1992). This model is expected to be phased into use starting in 1995.

This thesis examines a simpler statistical approach to soil erosion modelling. Specifically it deals with evaluating the Universal Soil Loss Equation (USLE) for use in Manitoba. Despite the development of new technology, the USLE has been proclaimed "the world standard for an equation to estimate sheet and rill erosion . . . No other current equation or procedure for estimating erosion approaches, as a whole, the USLE in ease of application, breadth of application and accuracy" (Foster et al. 1978). Despite the development of more comprehensive models, the USLE will continue to be used because of its simplicity (Vories and von Bernuth 1990).

2.4.1 The Universal Soil Loss Equation

The USLE was developed at the National Runoff and Soil Loss Data Centre established in 1954 by the Science and Education Administration in cooperation with Purdue University. Field use began in the early 1960's. It was developed from over 10,000 plot years of data collected from 49 locations in 24 states. It is a multiplicative six-factor empirically based statistical model representing the combined effects of soil erodibility, rainfall and runoff, plant and management factors, topography and cultural practices. It predicts long term average annual soil loss due to sheet and rill erosion from uniform slope segments. Average annual soil losses are based on a 22 year climatic cycle.

The first USLE manual appeared to users as Agriculture Handbook No. 282, entitled "Predicting Rainfall-Erosion Losses From Cropland East of the Rocky Mountains" (Wischmeier and Smith 1965). Continued research provided additional improvements (Renard et al. 1974, Williams 1975, Williams and Berndt 1976, Onstad et al. 1967). For details see Pauls (1987) and Wahome (1989).

In 1978 an updated version entitled "Predicting Rainfall Erosion Losses. A guide to conservation planning" was made available for general use (Wischmeier and Smith 1978). In 1987 the Agricultural Research Service (ARS) and the Soil Conservation Service (SCS) in conjunction with several co-operators began a project to revise the ULSE. The result will be the Revised Universal Soil Loss Equation (RUSLE) (Renard et al. 1991). This equation retains the same form as the original USLE, however improvements on its factor values have not yet been completed. The current form available to conservation planners remains that which was published in 1978 by the U.S. Department of Agriculture (USDA) Hb 537 (Wischmeier and Smith 1978). The equation takes the form:

$$A = KRLSCP$$

Where:

A = Average annual soil loss per unit area, usually expressed in t ha^{-1}.
K = Soil erodibility factor based on soil physical properties expressed in soil loss per unit of rainfall erosivity (t h MJ^{-1} mm^{-1}).
R = Rainfall-runoff erosivity term based on the total kinetic energy of a storm multiplied by the storms maximum thirty minute intensity (MJ mm ha^{-1} h^{-1}).
L = Slope length expressed as a dimensionless multiplier.
S = Slope gradient expressed a dimensionless multiplier.
C = Effects of crop canopy cover expressed as a dimensionless multiplier.
P = Cultural practice factor expressed as a dimensionless multiplier.

Research plots used in this study were standard USLE erosion plots, 22.13 meters long, 4.5 meters wide, on a 9% slope, cultivated up and down slope. Under these conditions, L, S and P assume a value of one. Thus, the equation reduces to:

$$A = K*R*C$$

Under continuous fallow, C becomes unity and the equation reduces to:

$$A = K*R$$

Soil erodibility can then be calculated by rearranging to give:

$$K = \frac{A}{R}$$

The crop management factor (C) can be evaluated by taking the ratio of soil loss from the cropped treatment to the soil lost from the fallow plot. The C factor is simply a soil loss ratio between the cropped treatment and the bench mark fallow treatment. The remaining factors L, S, and P, cannot be evaluated on standard USLE erosion plots.

2.5 USLE factor values

The equation predicts soil loss from sheet and rill erosion alone. It does not predict deposition nor does it compute sediment yields from gully, stream bank and stream bed erosion. By carefully evaluating its six factor values, the equation will predict soil losses for a multi crop system for a given year within the rotation or for a specific crop stage within a crop year (Wischmeier 1976). Average values for soil loss (A) are expressed as a mass per unit area. This value represents the long term average soil losses from a specific segment of land. Based on 22 year climatic cycle this value is not representative of any single yearly soil loss for a particular crop or soil loss within a crop stage period. It cannot be overemphasised that A is based on a long term average because yearly variations in soil loss can be extremely high. It is expected that random fluctuations in storm to storm or year to year soil losses will balance out and average over long periods of time (Wischmeier and Smith 1978).

2.5.1 The soil erodibility factor (K)

The K factor represents the inherent susceptibility of the soil to resist the erosive forces generated in rainstorms. It is defined as the soil loss (t ha^{-1}) per unit of rainfall erosivity (MJ mm ha^{-1} h^{-1}). Therefore, K is expressed as t h MJ^{-1} mm^{-1}. K is a simplistic lumped parameter representing soil response to shear forces in surface flow, impact of raindrops and scouring by flow in rills (Romkens 1985). It is not sensitive to any specific processed based analysis of true soil erodibility.

Wischmeier (1971) proposed that values of K (in empirical units) can be derived for soils containing less than 70% silt using the following formula:

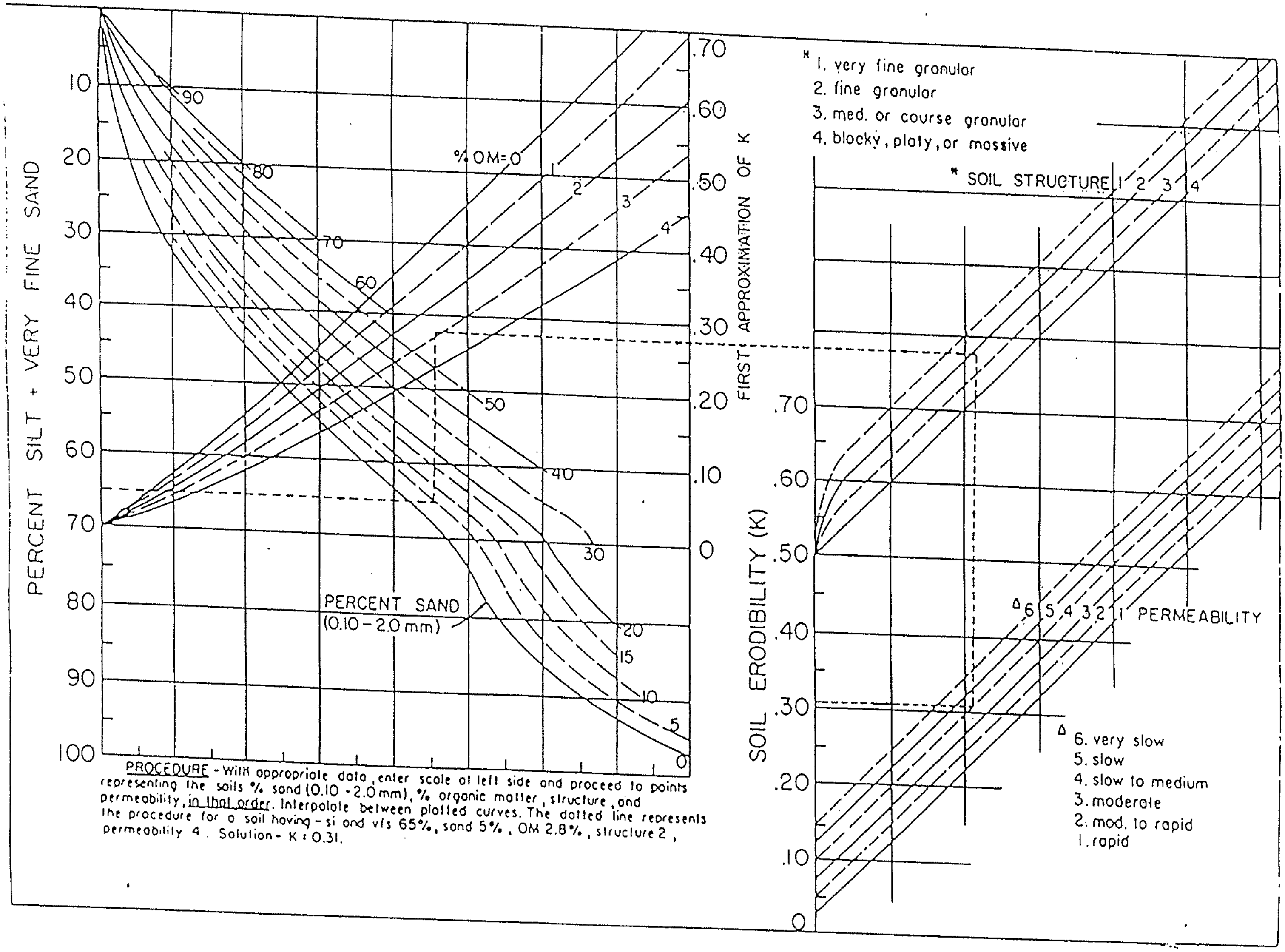
$$100K = 2.1M^{1.14}(10^{-4})\,(12-a) + 3.25(b-2) + 2.5(c-3)$$

Where:

M = (percent new silt) * (percent new silt + percent new sand)
a = percent organic matter (not exceeding 4%)
b = Structure code (1 to 4)
c = profile permeability class (1 to 6)

Values of K calculated by this formula can be converted to metric units (t h MJ^{-1} mm^{-1}) by multiplying by the metric conversion factor of 0.1317 (Pauls 1987). The terms, new silt and new sand refer to a shift in the defined boundaries of the silt and sand sized fractions in soil. Wischmeier et. al. (1971) found that very fine sand particles (0.05-0.10 mm) behaved more like silt than large sand particles. Therefore, size ranges of silt were redefined to include very fine sand resulting in the new silt parameter that includes particle size ranges from 0.002-01 mm and the new sand as 0.1-2.0 mm.

A simpler, graphical solution for K can be determined easily by use of the soil erodibility nomograph (Figure 2.1). The user enters the value of percent silt + very fine sand (new silt) on the left-hand side of the nomograph. A horizontal line is directed right, toward the family of percent sand curves. Linear interpolation within the family of new sand curves dictates the point from which a second line is initiated vertically upward to intercept the appropriate point within the % organic matter curve. Following



PROCEDURE - With appropriate data, enter scale at left side and proceed to points representing the soils % sand (0.10 - 2.0mm), % organic matter, structure, and permeability, in that order. Interpolate between plotted curves. The dotted line represents the procedure for a soil having - si and vfs 65%, sand 5%, OM 2.8%, structure 2, permeability 4. Solution - K = 0.31.

Figure 2.1 Soil Erodibility Nomograph
(scource: Wischmeier and Smith 1978)

a horizontal line the user then exits the left-hand graph for a first approximation of K. Continuing the horizontal line to intercept the appropriate curve representing soil structure locates the position from which another vertical line is initiated which is then drawn downwards to intercept the lines representative of the permeability class. Finally the last line is draw horizontally to the left and the soil erodibility factor, K can be read from the left-hand axis of the last graph. However, the K calculated from this Nomograph has english units which can be converted to metric units by multiplying by 0.1317 (Pauls 1978).

Measurements of K values on erosion plots yield widely scattered values of K. These reflect seasonal variability in true K values and variations of K as affected by cultivation, surface morphology and antecedent soil moisture conditions. Single fixed values for K are acceptable for estimating long term average annual soil losses. They are not adequate for short time periods. Mutchler and Carter (1983) found in Mississippi that measured K values ranged from a high of 164% in February to a low of 31% in August when compared to K as computed by the nomograph. An evaluation of K values by Wischmeier et al. (1971) found that K ranged from 0.03 to 0.69. Of 100 K values estimated using the nomograph, 68 were within 6.4 percent of the measured values, 90 within 11 percent, and only one deviated from the measured value by 17 percent.

Measurements of K are made experimentally from a unit fallow plot. Since K values are so sensitive to soil surface characteristics, cultivation must be carefully controlled. Type of implement, manner of cultivation and frequency of cultivation are of paramount importance (Romkens 1985). The following directions for cultivating fallow erosion plots were received via an administrative communication from D.D. Smith to runoff plot managers.

> "Plough to normal depth and smooth immediately by discing and cultivating two or more times, except for areas where wind erosion during the winter poses a serious hazard. In the latter case, discing or cultivating should be delayed until spring. Ploughing shall be each year at the time continuous row crop plots are ploughed. Cultivation shall be at new crop planting, routine cultivation times and when necessary to eliminate serious crust formation. Chemical weed control may be used, if cultivation does not control weed-growth. Ploughing and cultivation should be up-and-down slope and should not be on too wet soil."

2.5.2 The rainfall/runoff factor (R)

The R factor represents the total amount of energy incident on the soil surface for detachment and transport of the soil mass. It is a function of rainfall amount, raindrop size and impact energy of raindrops, intensity of rainfall and runoff generated by rainfall. R is expressed as the total kinetic energy (E) of raindrops multiplied by the maximum 30 minute intensity (I_{30}), its units are MJ mm ha^{-1} h^{-1}. R is the annual sum of individual EI_{30} (energy times intensity) values of erosive storms for given area. All storms greater than 12.7 mm or storms with less than 12.7 mm but with at least 6.4 mm falling within 15 minutes, are included in the EI_{30} calculation. Periods of rain separated by six hours or more define individual storm events. A yearly average of the summed EI_{30} values yields the average annual R value for a given area.

R values for a specific region are obtained from an Iso-erodent map (Figure 2.2). This map was derived using a simplified equation which predicts R based on the 2-year 6-hour rainfall depth (Wall et al. 1982). It is only an approximation of average annual R values. Ideally these maps should be compiled from recording rain gauge charts and

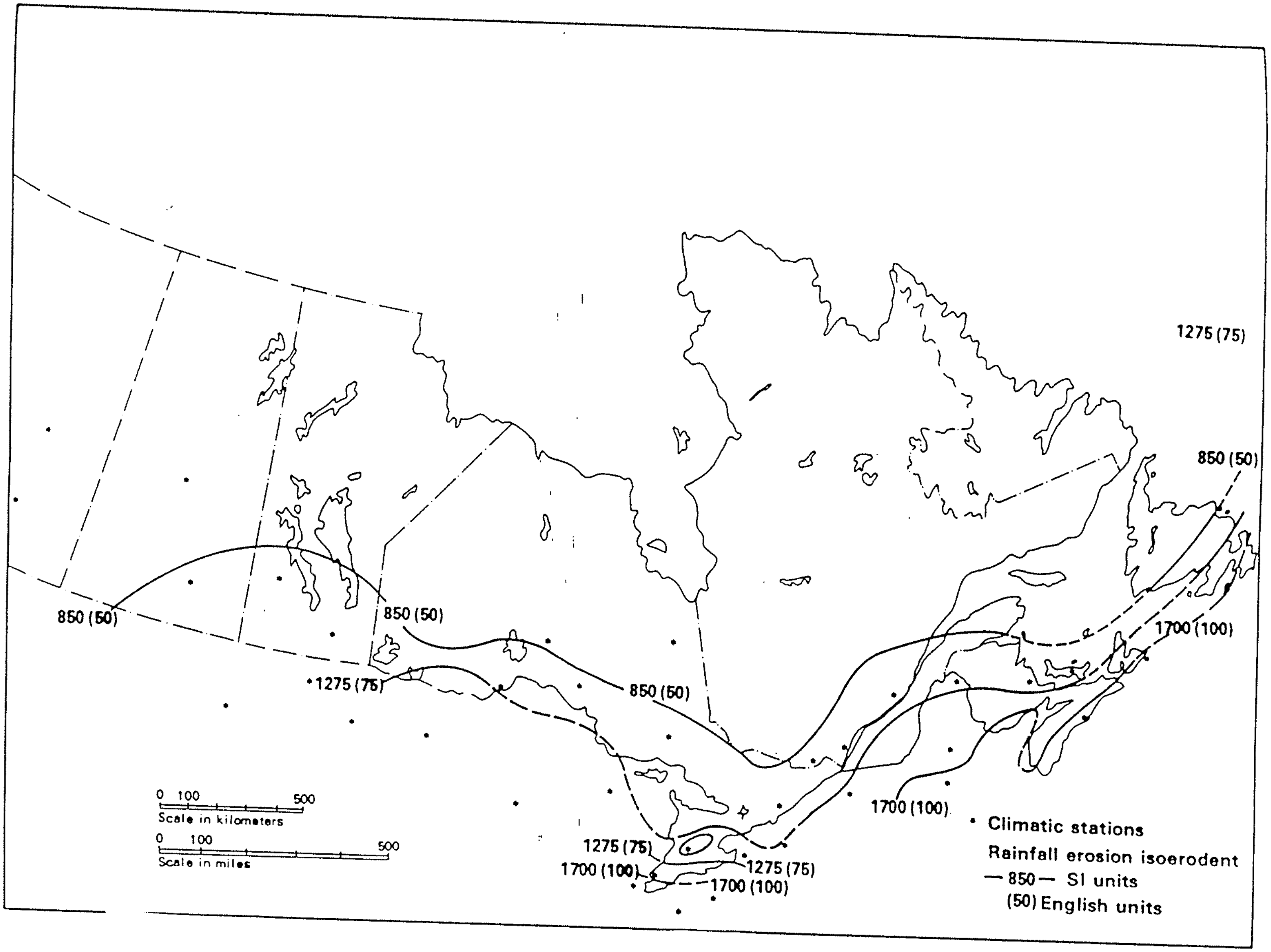


Figure 2.2 Iso-erodent map of Canada
(source: Wall et al. 1983)

represent 22 year average annual values of R for the designated areas.

Linear interpolation is used to derive R values for a specific region. To determine R values for a specific time frame within a year, the iso-erodent map can be used with an R value distribution curve (Figure 2.3). For instance given an average annual R value of 1160 MJ mm ha^{-1} h^{-1} for Winnipeg, from the iso-erodent map, it is possible using the R value distribution curve to determine the value of R between the beginning of May and the end of June. This is accomplished by delineating the portion of the average annual R which occurs within that time from the generalized R value distribution curves. By referring to Figure 2.3, it can be determined that 30% of the average annual R value falls within this time frame and thus the R value for this period is simply 0.30 multiplied by 1160 MJ mm ha^{-1} h^{-1} yielding 348 MJ mm ha^{-1} h^{-1}.

Experimentally, EI_{30} for a single storm can be extracted from tipping bucket rain gauge data. Figure 2.4 represents a typical recording for a single storm from a tipping bucket rain gauge. The equation for the kinetic energy of a given storm using the USLE is:

$$KE = (11.87 + 8.73\log_{10}I) * d$$

Where:

KE = kinetic energy (MJ m^{-2} mm^{-1})
I = rainfall intensity (mm h^{-1})
d = depth (mm) of rain falling at rate I

An upper limit of 76 mm h^{-1} is imposed on I. This is because medium drop size does not increase above intensities greater than 76 mm h^{-1} (Wischmeier and Smith 1978). The chart recording is then dissected into individual intensity increments within the

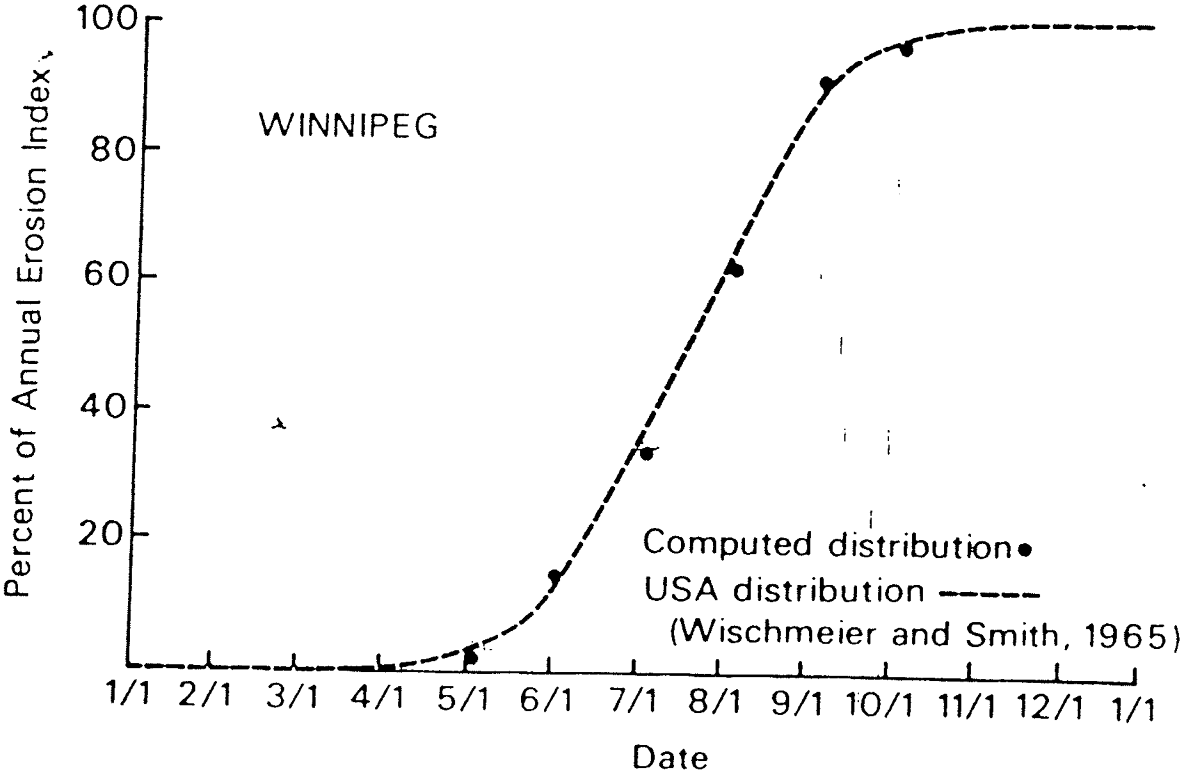


Figure 2.3 R value distribution curve for Winnipeg Manitoba (source: Wall et al. 1983)

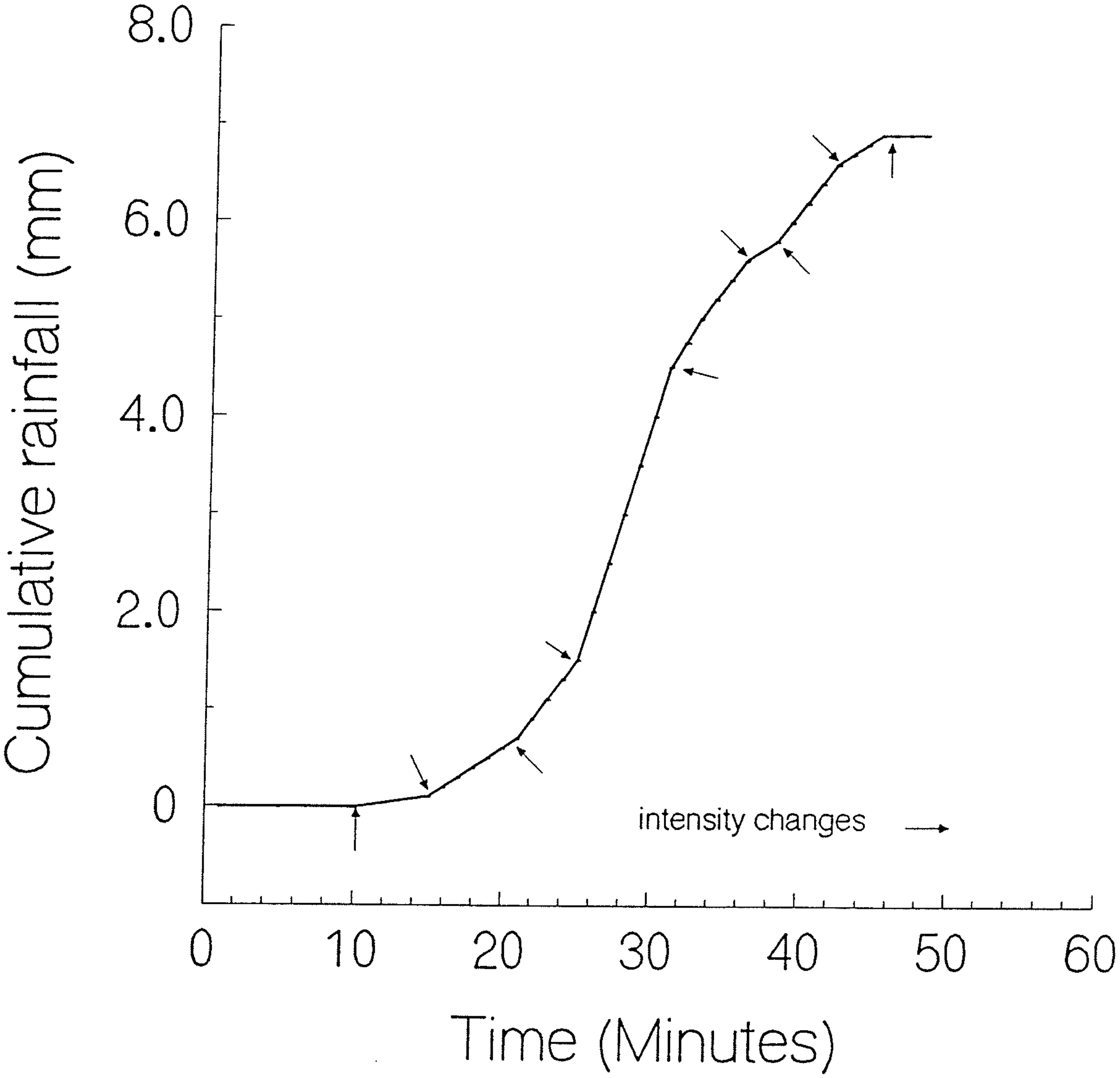


Figure 2.4 Single storm rainfall recording

storm, represented by constant slope on the chart. KE for the intensity increment is determined by using the KE formula and multiplying by the amount of rainfall at that intensity. Summing up the KE for each intensity increment yields total storm KE. The EI_{30} parameter is then obtained by multiplying total KE by the maximum 30 minute intensity (I_{30}) within the storm. EI_{30} is given as:

$$EI_{30} = \sum_{i=1}^{n} KE_i * I_{30}$$

For most regions, Wischmeier (1959) found the maximum 30 minute intensity to be more highly correlated to soil loss than the maximum 5, 15, and 60 minute intensity. Storms were classified as advance, intermediate and delayed depending on when the maximum intensity occurred. No relationship for the timing of intensity sequences within a storm could be found. The parameters most useful in estimating soil loss on unit fallow plots were rainfall intensity, a product term of energy times intensity, antecedent soil moisture and total antecedent rainfall energy since the last cultivation. The EI_{30} value alone explained a greater percentage of the total soil loss variation than any single other parameter alone or in combination.

In an analysis of seven sets of fallow plot data, the EI_{30} produced correlation coefficients with K ranging from 0.84 to 0.98. Wischmeier (1976) found that by using long term average values for the EI_{30} index, random variations in the timing and sequences of intensity increments, antecedent soil moisture, cumulative rainfall energy since the last cultivation, surface compaction by preceding rains, soil crusting and wind effects are normally distributed and these variations are expected to cancel each other over time. However, over short periods, these factors may cause large errors in either direction. EI_{30} values for a specific year within the 22 yr period ranged from less that half to more than double the 22-year average. Even 10 year averages were significantly bias results.

Soil erosion due to snow pack melt and its associated runoff and/or low intensity rains on partially frozen soil can contribute a significant portion of erosion to average annual soil losses (Wischmeier and Smith 1978). To account for this, the USLE relies on the sub factor R_s, which when added to R adjusts the average annual R value to account for soil losses caused by winter precipitation. Since this erosion occurs during the late winter and early spring, it is important to recognize this fact in calculating the monthly distribution of R. If, for a given area, R_s accounts for significant portion of the R value, management strategies can be devised which will minimize erosion during this highly susceptible period.

The procedure for estimating R_s values as outlined by Wischmeier and Smith (1978) was based on investigations of limited data. R_s is estimated by taking the December through March precipitation in inches and multiplying by 1.5. This value is then added to R which is obtained from the iso-erodent map and thus R becomes adjusted to account for soil losses due to runoff from snow melt and low intensity rains on frozen soils.

Wall et al. (1983) using a modified method developed by McCoal et al. (1976) devised an iso-erodent map for Canada. This was done, using an approximation for R as outlined by Ateshian (1974). Ateshian found that the maximum 2-year 6-hour rainfall depth was related to R as follows:

$$R = 0.41P^{2.2}$$

where:

R = Average annual rainfall erosion index
P = The maximum 2-year 6-hour rainfall (mm)

It is important to recognize that regions that have similar R values may experience very different rates of soil loss on similar soil types under identical management strategies. This is due to the seasonal distribution of rainfall. An area receiving large amounts of highly erosive rains in the spring when fields are bare or in the establishment stage will experience higher soil losses than another region which may receive the bulk of its erosive rains later in the growing season when crops are well established. If this is the case, a shift in management strategies will insure that the soil surface is well protected during highly erosive periods .

2.5.3 The cropping and management factor (C)

The C factor (Wischmeier and Smith 1978) represents the ratio of soil loss from a given cropping system to that lost under clean-tilled continuous fallow. The effects of cropping and management are combined because of the difficultly is separating crop canopy effects from management effects. A crop can be harvested with various amounts of residue left in situ. The remaining residue can be chopped, ploughed down, left on the surface or lightly incorporated into the surface. Seed beds may be left clean or various amounts of residues may be left as a protective covering. Cultivation may be performed by a wide variety of implements. Crop rotations govern the period between successive crops and the time the soil is left unprotected. Conventional tillage, minimum tillage and zero tillage all have different effects on the relative rates of erosion.

Crop canopy development is a function of soil fertility, climate and management. Therefore, crop development is not the same for different geographical regions. The change in canopy development is gradual and progressive throughout the year. Wischmeier and Smith (1978) defined canopy development by six crop stage periods:

Period F	(rough fallow)- Inversion ploughing to secondary tillage.
Period SB	(seed bed)- Secondary tillage for seedbed preparation until the crop has developed 10 percent canopy cover.
Period 1	(establishment)- End of SB until crop has developed a 50 percent canopy cover.
Period 2	(development)- End of period 1 until canopy cover reaches 75 percent.
Period 3	(maturing crop)- End of period 2 until crop harvest. This period was evaluated for three levels of final crop canopy.
Period 4	(residue or stubble)- Harvest to ploughing or new seeding.

Surface residue effects are separated from canopy effects through the use of a mulching sub factor. Crop canopies intercept raindrops and thus reduce the detachment ability of raindrops. In tall canopies, secondary drop elements may achieve sufficient velocity to become erosive. Surface mulches do not allow secondary drop elements to form. In addition to this, mulches affect the flow velocity and hydraulic shear of surface runoff.

The C factor is evaluated by selecting the appropriate crop and management scenarios from tables (Wischmeier and Smith 1978). The USLE tables used for this purpose are based on over 10,000 plot years of data from erosion plots under the influence of natural rainfall. In addition a large number of erosion studies under simulated rainfall were included in the analysis. The tables include cropping and management scenarios for various rotations, levels of spring residue, cover after planting, soil loss ratios for the various crop stages and canopy cover.

2.5.4 Topographic factor (LS)

The effects of topography are calculated through the L and S factors, with L representing the slope length factor and S representing the slope gradient factor. It is the ratio of soil lost from a given field segment to that soil lost on a 22.15 m uniform 9% slope, under otherwise identical conditions. For topographically uniform slope segments LS is given by:

$$LS = (\lambda/22.13)^m (65.41 \sin^2\theta + 4.56 \sin\theta + 0.065)$$

Where:

λ = Slope length in meters

m = 0.5 if slope is 5% or more, 0.4 on slopes between 3.5 to 4.5%, 0.3 on slopes of 1 to 3%, and 0.2 on slopes less than 1%.

θ = angle of slope

The equation was derived from crop land under natural rainfall. Slope steepness ranged from 3 to 18%, slope length from 30-300 feet. It is not known how far beyond the range of the data these relationships can be extrapolated while maintaining a high degree of accuracy.

Slope length is defined as the distance from the point of origin of overland flow to the point where slope gradient decreases enough to cause deposition or where the runoff water enters a well defined channel.

Simply taking the average slope gradient over an irregular slope can lead to considerable error (Wischmeier 1976). Within the irregular slope, uniform slope segments of equal length must be identified. Tables providing the fraction of expected soil loss from each equal length slope segment are then used to calculate a final value of LS that is representative of the slope in question.

2.5.5 Control practices (P)

The supporting practices or P factor, represents the influence of erosion control practices on soil losses. It is the ratio of soil loss with a specific support practice to the corresponding loss with up and down slope cultivation. Factors evaluated by P include tillage and planting on the contour, contour strip cropping, and terracing, among others.

This factor can be used to predict the corresponding decrease in soil loss associated by adopting a particular control practice. For example, P values can be useful in guiding decisions for determining whether or not contouring is effective. Slopes in the 3-8% range benefit most from contouring (Wischmeier and Smith 1978). As slope decreases, P values for contouring will approach unity. As slope gradient increases over 8%, P values will tend to increase and approach one. This is because on extreme slopes, contouring may be detrimental. Excess rainfall fills adjacent surface ridges, over topping may lead to a catastrophic surge of runoff causing massive soil losses. Thus, the usually useful practice of contouring may not always provide the desired benefits. P values are usually derived through tables which represent slope gradient, slope length, the controlling practice and the associated P value.

2.6 Summary

The USLE was developed in an attempt to quantify erosion and minimize the damaged caused by erosion. The USLE estimates soil losses due to natural rainfall through the multiplication of six factor values. A review of current literature reveals the erosion process to be highly complex and inadequately represented through the simplicity of the USLE. Soil losses predicted by the USLE represent long term average annual losses based on a 22 year climatic cycle. A more accurate model which is capable of predicting soil losses from specific years or even on a storm by storm basis is needed.

The soil erodibility (K) factor in the USLE is represented by a fixed factor. Soil erodibility may shift over time through changes in soil physical properties brought about by persistent erosion and/or the effects of long term agriculture. Soil erodibility can vary seasonally, and from storm to storm with changes in soil surface morphology and antecedent soil moisture content.

The rainfall/runoff factor calculates kinetic energy based on theoretical drop size distribution data and terminal velocities of individual drops. Research has shown that drop size distributions may differ geographically and that terminal fall speeds can be influenced by elevation and prevailing winds. Furthermore, the USLE multiplies the total storm kinetic energy by the maximum thirty minute intensity. This may not be the best estimator of rainfall erosivity in some areas. Complex interactions between crop canopies and incident rainfall exist, suggesting that crop growth rates and canopy morphology play important roles in governing rates of erosion.

The experimental conditions used in this study, reduce the USLE to A = KRC. Since A represents average annual soil losses based on 22 years of observation, a meaningful evaluation of the USLE in not possible due to the relatively short period of observation. However, relationships capable of improving short term estimates of soil losses will be investigated. Improvements will be based on quantifying the variable nature of K as influenced by soil surface morphology and antecedent soil moisture content. Rainfall characteristics will be investigated in order to improve the relationships between observed soil losses and rainfall erosivity. C factor values will be investigated through an analysis of soil loss ratios.

3. MATERIALS AND METHODS

This study was part of a larger, long term project dedicated to evaluating the applicability of the Universal Soil Loss Equation for the Canadian prairies. Initiated in 1984, the project's primary function was to collect at least 22 years of data using standard USLE experimental plot design criteria. Newman (1970) found rainfall patterns to be cyclical in nature and that at least 22 years of continuous rainfall data was needed to define a climatic cycle. Wischmeier and Smith (1978) recognized the need to collect long term records and based the predictive capabilities of the USLE on at least 22 years of soil loss records.

This study was in its seventh year of data collection. A meaningful and quantitative evaluation of the USLE factor values was not possible at this time. However, the data base was sufficiently large to analyze and explore some of the mechanisms governing the large variations observed in storm to storm and year to year measurements of soil losses. The objectives of this study were to test the reliability of the sediment sampling equipment, investigate the variability in measured K values and to evaluate the EI_{30} parameter.

3.1 Experimental field sites

Two water erosion sites, Miami and Roseisle, were monitored throughout the 1991 and 1992 growing seasons. Each site employed four plots representing four continuous cropping treatments, fallow, corn, wheat and alfalfa, from which soil loss data was collected. Each plot was constructed so as to conform to standard USLE plot dimensions. A slope length (L) of 22.13 m on a 9% slope (S) yields an LS factor of 1.0. Cultivating up and down the slope gradient sets the supporting practice factor, (P) equal to 1.0. Choice of slope characteristics and cultivation eliminated some of the variables in the USLE. A plot width of 4.5 meters was chosen to accommodate field equipment and created a total plot area of 100 m^2.

The sites were located along the escarpment and Agassiz beach land scape area of south central Manitoba 15 km apart, approximately 100 km south west of Winnipeg (Figure 3.1). The Miami site had a heavy clay texture, the Roseisle site had a fine sandy loam texture.

3.1.1 Miami experimental site

The Miami Site, located at NE 02-05-07W, was established in 1984 on a [1]Brundis clay. The soil is an Orthic Black, formed on inclined residual shale, developed in 40-85 cm of neutral, fine clayey dark grey to black carbonaceous non calcareous shale of the Vermilion River Formation-Morden member. The plots are well drained, very slowly permeable when moist or wet, with moderately rapid runoff. These soils typically exhibit marked shrink and swell properties. Solum depth at the site was 30-65 cm, with bedrock occurring from 40-65 cm depth.

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[1] Hargrave (1992), Wahome (1989) and Pauls (1987) referred to the Miami site as the Gretna clay. Michalyna (1992), reclassified the Miami site as a Brundis clay. To preserve consistency and avoid confusion, for readers, the original designation will be used through out the remainder of this paper

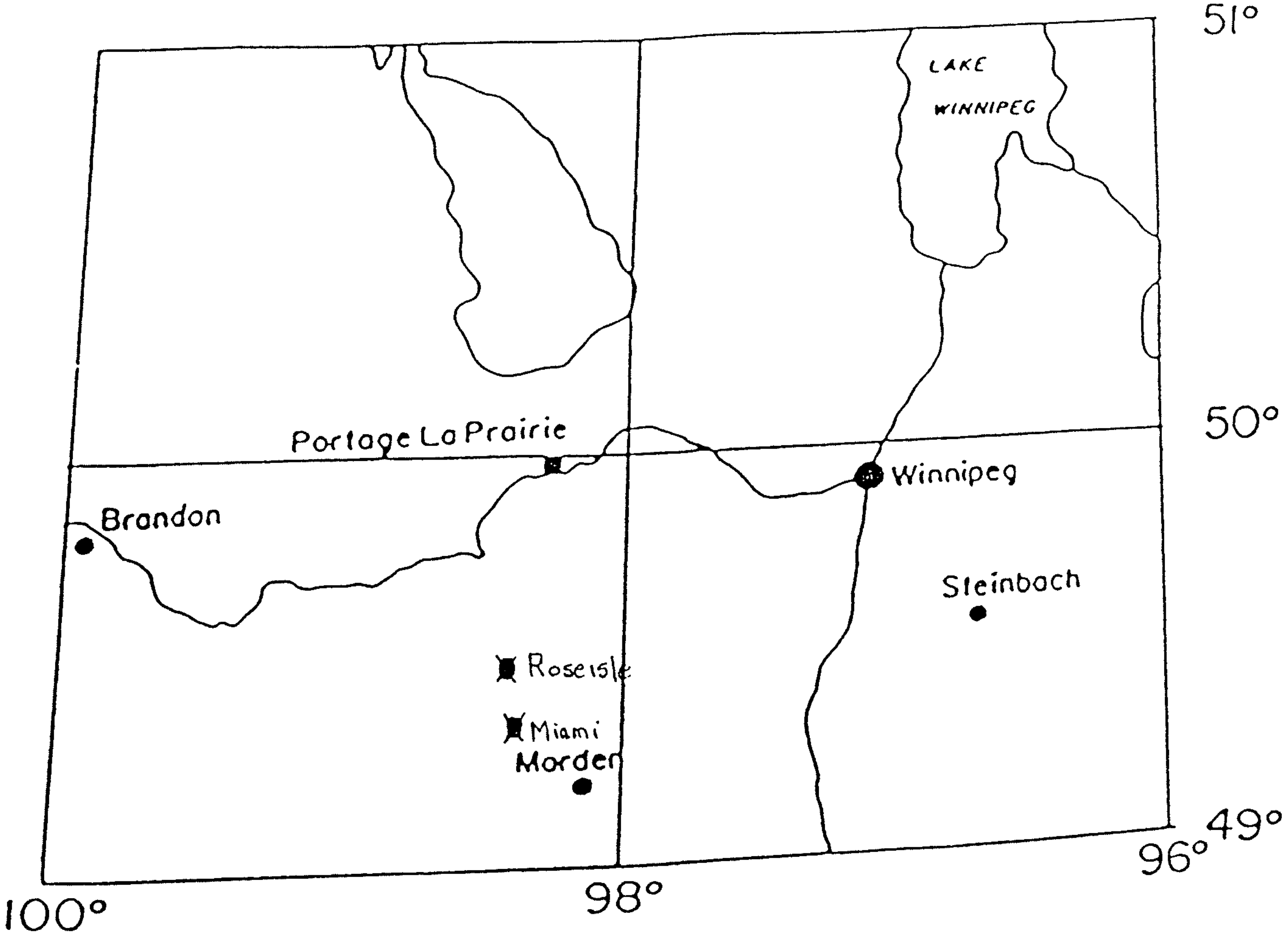

Figure 3.1 Location of experimental sites
(source: Pauls 1987)

The soil had a clay Ap horizon, 15 cm thick, a heavy clay Bm, 10-45 cm thick and a BC ranging from 10-15 cm thick (Michalyna 1992). The site had a southerly exposure, (Figure 3.2). The slopes of the four cropping treatments were: fallow 10.5%, corn 9.5%, wheat 10.3% and alfalfa 9.5%.

3.1.2 Roseisle experimental site

The second site, Roseisle, located at NW 18-06-07W, was established in 1985 on the [2]Vandal series, part of the Leary association. It is an Orthic Dark Grey developed on an inclined loamy lacustrine veneer ranging between 35 cm to 1 m thick overlying a gravelly sand. The plots are well drained with moderately rapid permeability and moderately rapid runoff. Solum depth at the site varied from 50-80 cm and was dependent upon the depth of the loamy overlay. The soil had a fine sandy loam Ap horizon, 15 cm thick, a fine sandy loam Ahe 5-10 cm thick, a sandy clay loam Btj, 25-30 cm thick, and a variable BC up to 20 cm thick (Michalyna 1992). The site had a westerly exposure (Figure 3.3). Slopes of the four cropping treatments were: fallow 10.0%, corn 10.0%, wheat 9.5% and alfalfa 9.2%

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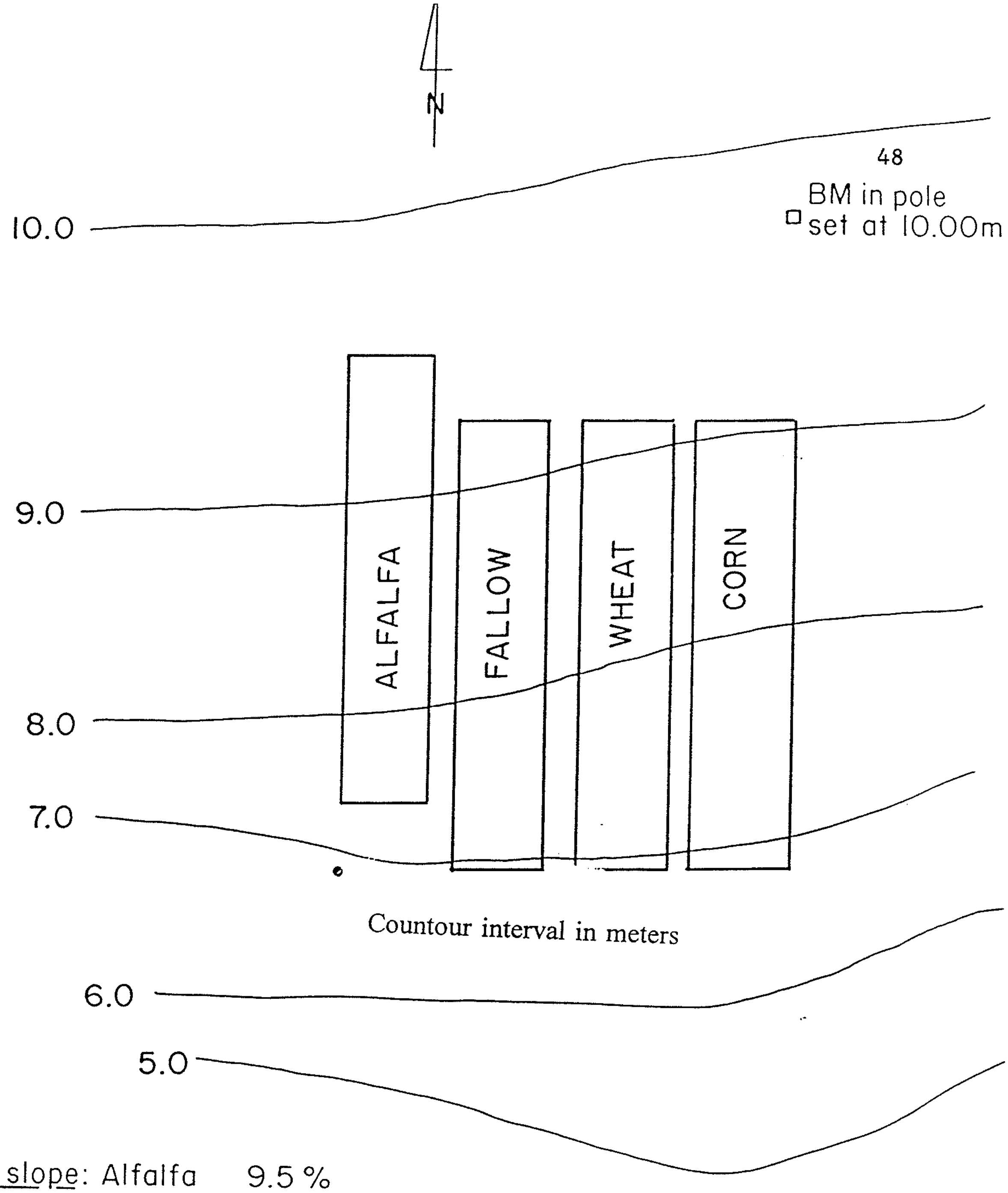
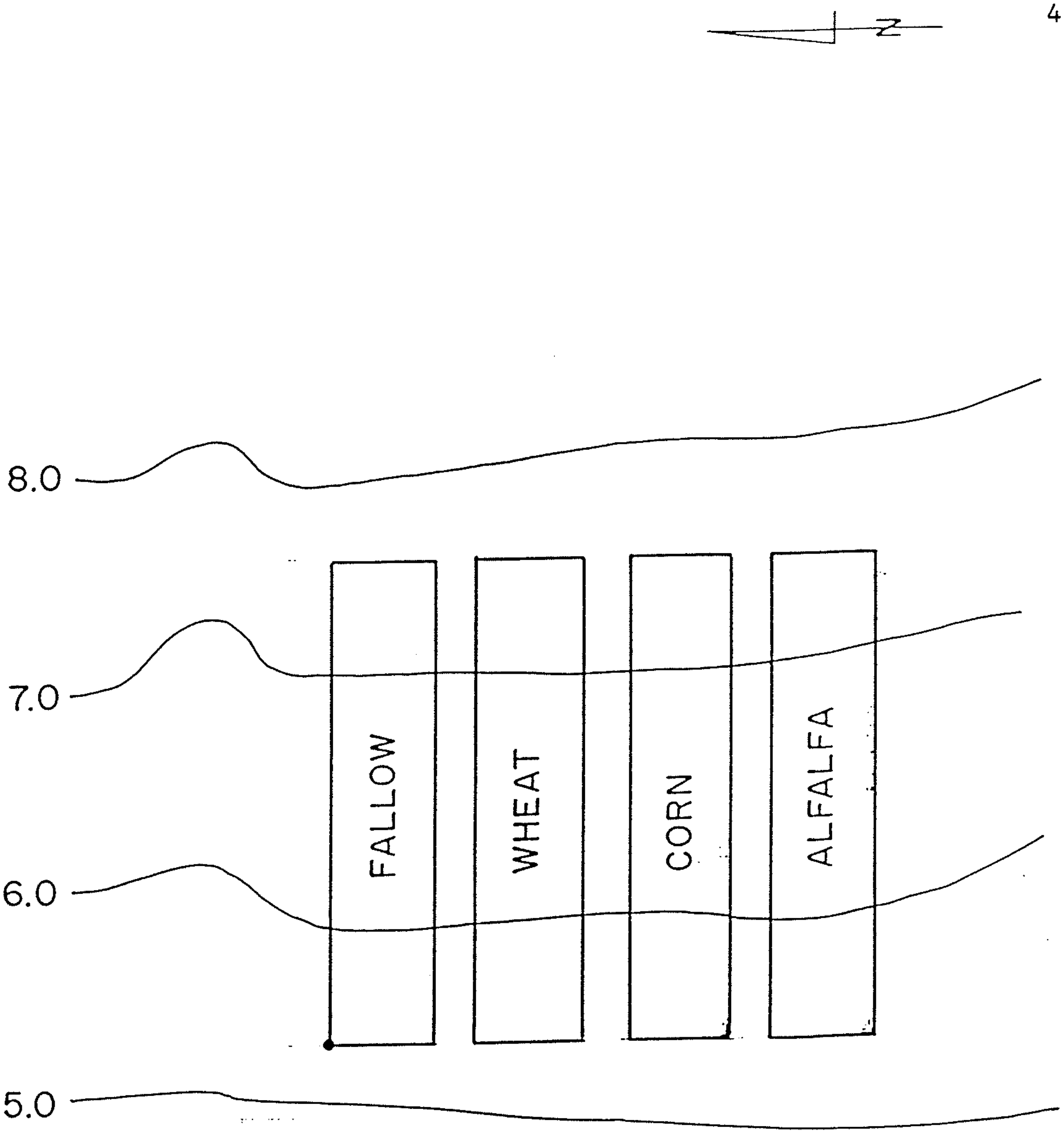
[2] Hargrave (1992), Wahome (1989) and Pauls (1987) referred to the Roseisle site as the Leary sandy loam. Michalyna (1992), reclassified the Roseisle site as a Vandal sandy loam. To preserve consistency and avoid confusion, to readers, the original designation will be used through out the remainder of this paper



Plot slope:		
	Alfalfa	9.5 %
	Fallow	10.5 %
	Wheat	10.3 %
	Corn	9.1 %

Figure 3.2 Gretna clay plot lay out (source: Michalyna 1992)



Countour interval in meters

Plot slope :	Fallow	10.0 %
	Wheat	9.5 %
	Corn	10.0 %
	Alfalfa	9.2 %

Figure 3.3 Leary sandy loam plot lay out
(source: Michalyna 1992)

3.1.3 Weather

Both sites are dominated by a continental climate with short cool summers and long cold winters. The study area is influenced by three main types of air masses. Winters are dominated by a cold dry continental polar air mass. The summers are influenced by cool moist Pacific air and occasionally warm moist air from the Gulf of Mexico (Michalyna et al. 1988). Frequent interactions between the summer air masses leads to extreme variability in inter-seasonal weather patterns.

Weather data from Morden (1951-1980), located approximately 24 km South east of Miami has recorded mean annual precipitation of 530 mm. Approximately 75% of this occurs as rain during the late spring, summer and early fall. About 25% consists of snow during the winter months (November to March). Average growing season precipitation was as follows: May-64.0 mm, June-75.8 mm, July-73.2 mm, August-71.1 mm and September-51.6 mm (Environment Canada 1982). Spring rainfall is usually normally distributed and result from the passage of slow moving low pressure systems. Summer precipitation typically occurs as localised showers and thunderstorms leading to extreme spatial variability in local rainfall amounts .

3.2 Experimental plot design

Each plot was hydrologically isolated within the slope gradient. This was accomplished by bounding the sides of the plots with a series of 2.0 x 18.0 cm spruce boards placed end to end, inserted to a depth of 8 cm below the soil surface. Total plot length was 22.13 m. The upper plot boundaries were delineated by removable steel end boards 3 mm thick by 18.0 cm wide, pounded into the soil surface to a depth sufficient to prevent up slope run on water from entering the top edge of the plots. Access onto the plots with heavy machinery was gained by removing the end boards. The lower end of the plots were defined by a 4.6 m long, by 28.6 cm wide, aluminum receiving trough. This structure functioned to convey runoff through the sediment sampling equipment. Adjacent plots where separated by 1 m wide grassed walk ways.

3.2.1 Runoff and sediment sampling equipment

Runoff flowed down the length of the plots and spilled over into the receiving trough. The trough was sloped 10% and directed the runoff into an instrument shelter which housed the sediment sampling equipment (Figure 3.4). A calibrated 15 cm high H flume was bolted onto the end of the trough. Maximum design capacity at 80% flume capacity was 5.7 $l\ s^{-1}$ or an equivalent depth of runoff equal to 205 mm h^{-1}. A stilling well attached to the side of the flume housed a float which was attached to a [3]Belfort 5-FW-1 water level recorder. A seven day strip chart provided a hydrograph of the runoff events. The H flume directed the flow of runoff onto a 30 cm diameter finned, water propelled, Coshocton sampling wheel. This wheel was equipped with an elevated

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[3] Brand name is provided for the information of the reader and does not imply indorsement or preference relative to other such systems which may be available from other suppliers.

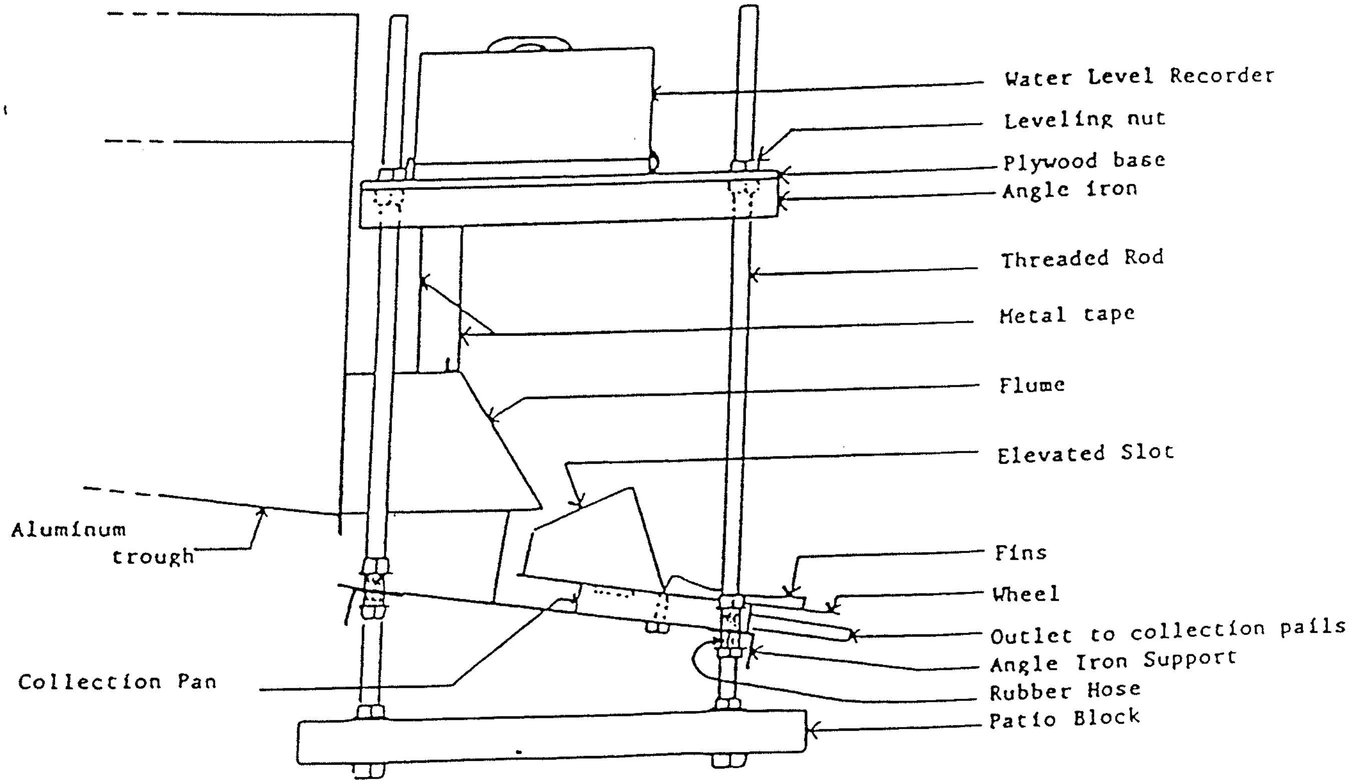

Figure 3.4 Side view of Coshocton sampler, water level recorder and lower trough end
(Source: Pauls 1987)

sampling slot located along its radius. The slot had an opening which was approximately 1% of the cross sectional area of the wheel. Runoff falling onto the wheel caused the wheel to spin. The elevated slot would then pass through the stream of runoff water once per revolution sampling a total of 1% of the runoff. The 1% sample then passed into a shallow pan underneath the wheel and was directed through flexible hoses to a series of removable plastic jugs. Excess runoff was directed out of the instrument box through a 30 cm drainage pipe installed below the sampling jugs.

3.2.2 Rainfall amount and intensity measurements

Two rain gauges, a standard type rain gauge and a recording rain gauge were installed at each site. The standard gauge measured rainfall depth to an accuracy of ± 0.2 mm. A [4]Geneq P-1000 tipping bucket recording rain gauge fitted with 0.1 mm buckets with unlimited capacity measured rainfall intensities accurately up to a maximum rate of 150 mm h^{-1} ± 3%. A [4]Geneq P-9000 time of event recorder and an [1]Omni Data DP 101 Datapod were connected to the rain gauge. The event recorder provided a seven day strip chart recording of rainfall rates and amount. The Data pod stored rainfall intensity data on an EPSOM chip. Maximum count rate of this unit was 60 counts per minute allowing maximum rainfall recording rate of 360 mm h^{-1}.

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[4] Brand name is provided for the information of the reader and does not imply indorsement or preference relative to other such systems which may be available from other suppliers.

3.2.3 Antecedent soil moisture measurements

Antecedent soil moisture samples, taken weekly from each plot at the upper, middle and lower slope positions, were sampled to two depths, 0-7.5 cm and 7.5 -15 cm. Samples weighing approximately 50 g oven dry were taken with a probe type auger. Occasionally a dutch auger was used when the soil became impenetrable to the probe auger. Moisture samples were taken while standing outside the plot boundaries. This was deemed necessary in order to minimize traffic on the plot.

3.2.4 Crop cover measurements

Weekly measurements of ground cover were taken on each plot, except for the summer fallow. Surface mulch was not distinguished from canopy cover. A modification of the point line method as outlined by Sloneker and Moldenhaur (1977) was used. The modified technique eliminated possible biases through the use of a gun sight system.

A cover counter was constructed with ten gun sights, spaced 15 cm apart placed on a 170.0 x 6.5 x 2.0 cm plank. Each gun site was constructed using one 2.0 cm round head, slotted screw and one 3.0 cm Phillips dry wall screw. The slotted screw was inserted into the plank so that the head was left protruding one centimetre from the face of the plank. The slot in the screw head functioned as the rear gun site. A dry wall screw was inserted through the opposite side of the plank directly below the slotted screw such that point of the screw protruded 1 cm from the surface. This functioned as the front site. The plank was supported at each end on an adjustable one meter high bipod.

Each gun sight functioned to define a straight line which was interpreted to be a raindrop path. If a plant part or piece of residue was sighted through a gun site, a hit was recorded. One hundred raindrop paths were simulated over the surface of each plot. This was done by placing the cover counter at five randomly selected sampling points over the plot. At each point, 20 measurements were taken, ten diagonally left of the sampling point and 10 diagonally right of the sampling point. The number of hits was taken as the percent cover over the plot.

When the plant canopy exceeded 1 meter in height a 7 m long pole with 20 makings spaced 15 cm apart was suspended diagonally across the plot at five randomly selected locations from a height of 2 m. A 6 mm diameter steel rod with an adjustable suspension point was hung at each marking on the pole so that the tip of the rod hovered 1 cm above the soil surface. The length of the rod simulated a rain drop path. If a plant part, or piece of residue touched the rod or lay directly beneath the tip of the rod, a hit was scored.

These measurements were used to monitor crop development and to define crop growth stages based on the criteria set forth by Wischmeier and Smith (1978). To account for the absence of turn plough tillage and the presence of a snow cover during the winter period, a comparative system was adopted and is given in Table 3.1 (Pauls 1987).

3.3 Field operations

Field operations began early in the spring when the soil was still partially frozen. Drainage pipes leading out of the instrument shelters were cleared by flushing with water from a large truck mounted tank. Instruments were calibrated in the laboratory and installed at the field sites. Plot boundaries were repaired as needed to prevent movement of runoff onto or off of the plot surface.

TABLE 3.1 Comparative System for Modified Crop Growth Stage Periods

Wischmeier and Smith (1978)	Modified System (Pauls 1987)
Period F (rough fallow) - ploughing to secondary tillage tillage	**Period W** (Winter) - last fall tillage to spring
Period SB (Seedbed) - secondary tillage until the crop has developed 10% canopy cover	**Period SB** (Seedbed) - first spring tillage until the crop has developed 10% canopy cover.
Period 1. (Establishment) - end of SB until the crop has developed 50% canopy cover.	**Period 1.** (Establishment) - end of SB until the crop has developed 50% canopy cover.
Period 2. (Development) - end of period 1 until canopy cover reaches 75%.	**Period 2.** (Development) - end of period 1 until canopy cover reaches 75%
Period 3 (Maturing crop) - end of period 2 until harvest.	**Period 3** (Maturing crop) - end of period 2 until harvest.
Period 4 (Residue or Stubble) - harvest to ploughing or new seeding.	**Period 4** (Residue or Stubble) - harvest to ploughing or new seeding.

3.3.1 Seeding Operations

Four different crop-management systems were maintained at each site: 1) continuous summer-fallow, 2) continuous corn (residue removed, stubble cultivated), 3) continuous wheat (residue removed, stubble cultivated), 4) continuous alfalfa. Varieties used were Pioneer 3979 corn (Zea mays L.), Katepwa wheat (Triticum aestivum) and Rambler alfalfa (Medicago sativa). Seeding and fertilizing operations were done according to the guidelines outlined in "Field Crop Recommendations for Manitoba". Weed control was accomplished by hand rouging and spot spraying with Round Up. Prior to 1984, the Gretna clay site had a continuous cropping history. Prior to 1985, The Leary sandy loam site had a cropping history of a wheat-wheat-fallow rotation.

Seeding operations began by broadcasting fertilizer (if needed) by hand. Fertilizers used were: ammonium nitrate (34-0-0), monoammonium phosphate (11-51-0) potassium chloride (0-0-62) and elemental sulphur (0-0-0-90). monoammonuim phosphate (11-51-0) was side banded in wheat at 45 kg ha^{-1} P_2O_5 .

Prior to seeding, fallow, corn and wheat plots were cultivated twice with a 2.3 m cultivator equipped with 16 shovels (15 cm wide). Corn and wheat plots were then harrowed twice to prepare the seed bed. Wheat was drill-seeded at 100 kg ha^{-1} with a 1.5 m double disk drill with a row spacing of 18 cm. The bottom two m of the plots and the plot sides were inaccessible to the drill seeder. These areas were seeded in rows by hand.

Corn was hand planted with a Jab type planter at a rate of 70,000 seeds ha^{-1}.

Plants were spaced at 20 cm intervals, with a total of total of six rows across the plot (Figure 3.5). Prior to 1991 corn row spacing was similar, but only 5 rows were planted across the plot. This resulted in unvegetated areas along the edges plots in excess of 45 cm. This may have produced an edge effect so the new row spacing was adopted.

Corn was cultivated once more during the growing season to control weeds and destroy surface crusts and rills. Fallow was cultivated once every three to five weeks in order to destroy surface crusting and rills. All plots, except alfalfa received a fall tillage operation. A yearly schedule of field operations at each site are given in Tables 3.2, 3.3, 3.4 and 3.5.

3.3.2 Harvesting operations

Crops were harvested at maturity to determine biomass and seed yields. Alfalfa was harvested at 10% bloom twice during the growing season except in 1991, when the Gretna clay site was only harvested once. Biomass samples prior to the harvesting of wheat and alfalfa were taken with a quarter meter frame at randomly selected points representing the upper, middle and lower slope positions for a total of three samples per plot. The remaining vegetation was cut 15 cm above the soil surface with a walk behind sickle mower and residues were removed with a rake.

Corn was sampled prior to harvest by randomly selecting one row for each of three slope positions. One meter within the row was randomly selected and all plants located along this transect were sampled. Harvesting was done at 65% whole plant moisture. The remaining vegetation was cut 20 cm above the soil surface with a hand

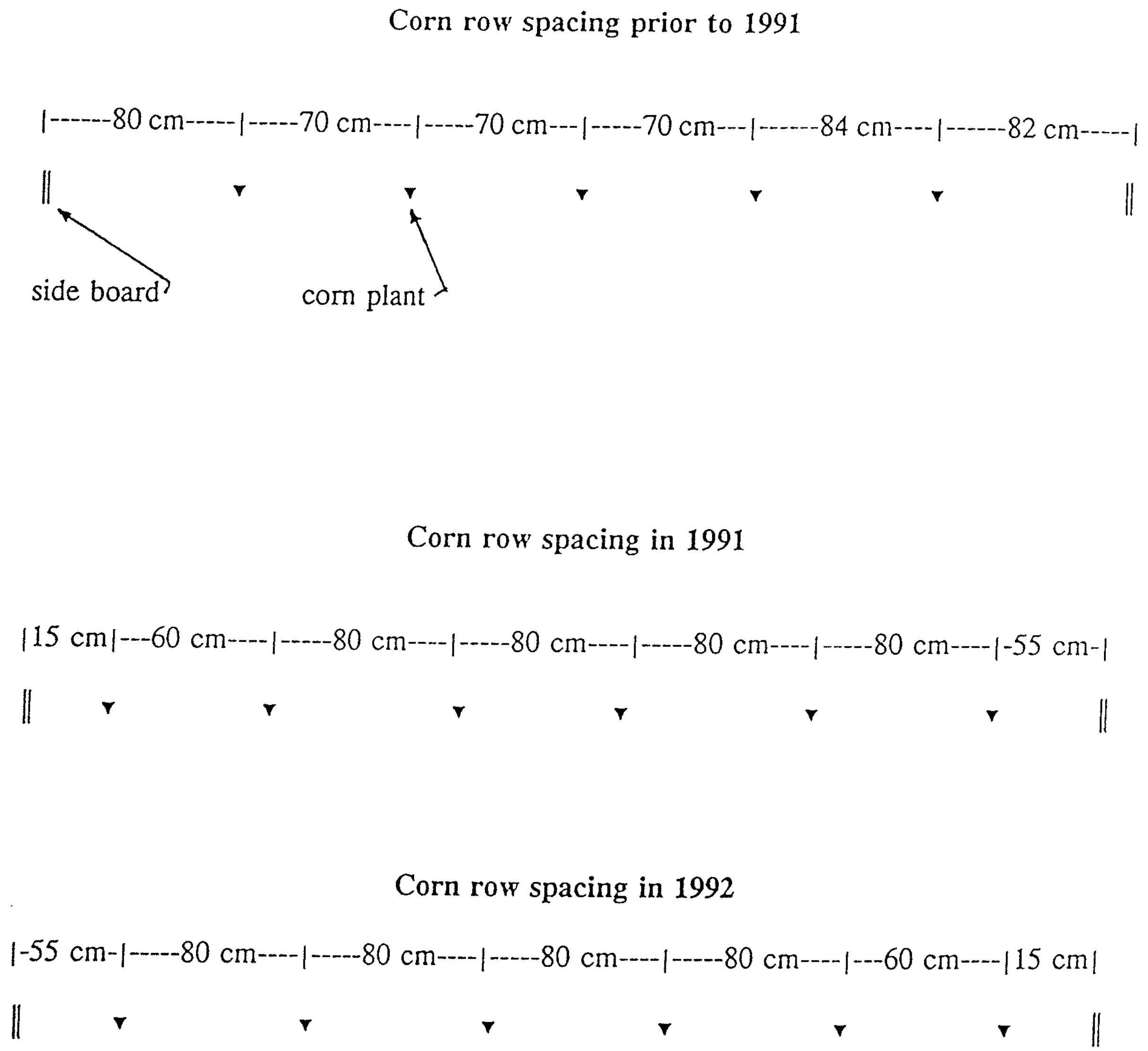

Figure 3.5 Corn row spacing across erosion plots

held sickle. Residues were removed with a rake.

TABLE 3.2 Gretna Clay 1991 Field Operations

Treatment	Date	Operation	Equipment
Fallow	May 15	two passes with cultivator	2.3m cultivator
	June 20	two passes with cultivator	2.3m cultivator
	July 23	two passes with cultivator	2.3m cultivator
	Sept. 13	two passes with cultivator	2.3m cultivator
Corn	May 15	broadcast fertilizer, two passes with cultivator and harrows, seeded	2.3m cultivator jab planter
	June 11	transplanted seedings	hand
	June 20	two passes with cultivator	2.3m cultivator
	July 7	transplanted seedlings	hand
	Sept. 12	harvested corn	sickle
	Sept. 13	two passes with cultivator	2.3m cultivator
Wheat	May 15	broadcast fertilizer, two passes with cultivator and harrows, seeded	2.3m cultivator press drill
	Sept. 5	harvested	sickle mower
	Sept. 13	two passes with cultivator	2.3m cultivator
Alfalfa	May 15	broadcast fertilizer	hand
	June 27	harvest	sickle mower

TABLE 3.3 Leary Sandy Loam 1991 Field operations

Treatment	Date	Operation	Equipment
Fallow	May 15	two passes with cultivator	2.3m cultivator
	June 20	two passes with cultivator	2.3m cultivator
	July 23	two passes with cultivator	2.3m cultivator
	Sept. 13	two passes with cultivator	2.3m cultivator
Corn	May 15	broadcast fertilizer,two passes with cultivator and harrows, seeded	2.3m cultivator jab planter
	June 11	transplanted seedings	hand
	June 20	cultivated	2.3m cultivator
	July 7	transplanted seedlings	hand
	Sept. 12	harvested corn	sickle
	Sept. 13	two passes with cultivator	cultivator
Wheat	May 15	broadcast fertilizer, two passes with cultivator and harrows, seeded	2.3m cultivator press drill
	Aug. 13	harvested	sickle mower
	Sept. 13	two passes with cultivator	2.3m cultivator
Alfalfa	May 15	broadcast fertilizer	
	June 27	harvest	sickle mower
	Aug. 30	harvest	sickle mower

TABLE 3.4 Gretna Clay 1992 Field Operations

Treatment	Date	Field operation	equipment
Fallow	May 20	two passes with cultivator	2.3m cultivator
	July 10	two passes with cultivator	2.3m cultivator
	Aug. 13	two passes with cultivator	2.3m cultivator
	Sept. 30	two passes with cultivator	2.3m cultivator
Corn	May 20	broadcast fertilizer, two passes with cultivator and harrows, seeded	2.3m cultivator jab planter
	June 25	transplanted seedlings	hand
	July 10	two passes with cultivator	2.3m cultivator
	Aug. 27	harvest	sickle
	Sept. 30	two passes with cultivator	2.3m cultivator
Wheat	May 20	broadcast fertilizer, two passes with cultivator and harrows, seeded	2.3m cultivator press drill
	Sept. 30	harvest	sickle mower
	Sept. 30	two passes with cultivator	2.3m cultivator
Alfalfa	May 5	broadcast fertilizer	
	June 24	harvest	sickle mower
	Aug. 18	harvest	sickle mower

TABLE 3.5 Leary Sandy Loam 1992 Field Operations

Treatment	Date	Field operation	equipment
Fallow	May 20	two passes with cultivator	2.3m cultivator
	July 10	two passes with cultivator	2.3m cultivator
	Aug. 13	two passes with cultivator	2.3m cultivator
	Sept. 30	two passes with cultivator	2.3m cultivator
Corn	May 20	broadcast fertilizer, two passes with cultivator and harrows, seeded	2.3m cultivator jab planter
	July 10	two passes with cultivator	2.3m cultivator
	Aug. 27	harvest	sickle
	Sept. 30	two passes with cultivator	2.3m cultivator
Wheat	May 20	broadcast fertilizer, two passes with cultivator and harrows, seeded	2.3m cultivator press drill
	Sept. 8	harvested	sickle mower
	Sept. 30	two passed with cultivator	2.3m cultivator
Alfalfa	May 5	broadcast fertilizer	
	June 24	harvest	sickle mower
	Aug. 18	harvest	sickle mower

3.3.3 Weekly sampling routine

Field plots were visited on a weekly basis. At this time strip charts on the water level recorders and the recording rain gauges were changed. The standard rain gauge was checked, total rainfall recorded and the gauge was emptied. The tipping bucket rain gauge was tested by simulating a total of 10.0 mm rainfall. Discrepancies were recorded and any problems rectified. Soil moisture samples and cover count measurements were obtained. Regular plot maintenance involved mowing of the grass borders surrounding the plots, weeding, maintaining plot boundaries and flushing the sediment collection systems.

3.3.4 Sediment sampling procedures.

After a rainfall, all plots were checked for signs of erosion. Collection jugs (1% sampling containers) were checked for samples. If no samples were collected, the troughs were flushed and readied for the next event. If samples were found in the 1% jugs, the following procedure was followed:

1.) Plot boundaries were examined to make sure runoff had not undermined them. If this happened, a sample was still collected but this was noted.

2.) Sampling wheels were examined visually to make sure they had sampled correctly. Occasionally the wheels would malfunction during a soil loss event. An uneven distribution of sediment over the surface of the wheel was usually indicative of a malfunction.

3.) Sediment collection pans beneath the wheel were examined to make sure that they had not become plugged.

4.) Fresh water was poured through the 1% collection pan to rinse residual sediment from the pan and hoses into the sampling jugs. The volume of rinse water was recorded so that total runoff could later be calculated on the basis of the jug contents.

5.) Sediment remaining on the wheel was considered to have been represented in the 1% sample. Sediment remaining in the trough had not passed through the 1% sampling system and therefore was collected as a 100% sample.

6.) Clean jugs were exchanged with the jugs containing sample, and the collection troughs were rinsed in preparation for the next event.

7.) One litre of clean water was poured into the high end of each trough and allowed to drain over the sampling wheel. If the coshocton wheel did not spin more that 5 times the bearing was considered to be faulty and a new one was installed.

8.) Rain gauges were tested for accuracy by simulating a 10.0 mm rainfall event. If the gauge was not within 3%, the difference was recorded and the gauge was recalibrated.

9.) Sediment was then taken to the laboratory. Volume of runoff in the jugs was recorded and all sediment was dried in an oven at 110°C to constant mass and weighed.

3.4 Equipment calibration and testing

3.4.1 Coshocton sampling wheel and H flume calibrations

During a soil loss event, surface runoff is generated when rainfall rate exceeds infiltration and surface ponding (Hairsine 1992). Runoff, generated by excess rainfall, flows down slope across the plot surface and spills over the lip of the sediment collection trough. The sloped trough conveys sediment laden runoff through a calibrated H flume fitted with a stilling well. Flume discharge falls a short distance directly onto the surface of a Coshocton Sampling wheel. Water falling onto the Coshocton sampling wheel causes it to spin. An elevated sampling slot located along the radius of the wheel traverses the water stream generated by the flume and samples a small portion of the runoff. Since the elevated slot has a cross sectional area representing 1% of the total area of the sampling wheel and, assuming the wheel rotates at a constant rate, the sampling wheel will sample one percent of the runoff spilling over its surface.

In the summer of 1991, the sampling wheels and H flumes were tested for accuracy by sending a given volume of water at a known rate through the sampling system. Actual runoff rates were compared to calculated runoff rates. The amount of the sampled runoff was compared to the assumed sampling rate of 1%. A flow rate of 0.72 L s^{-1} was chosen for the test because of the limited resources available for the testing at the time. This flow rate would result from 26 mm h^{-1} of rainfall going directly to runoff. Since the tipping bucket rain gauge can measure rainfall accurately up to 150 mm h^{-1}, this was deemed to be a reasonable test flow rate.

For each site, the fallow, corn and wheat sampling wheels and H flumes were tested. Alfalfa wheels were not tested at this time because they were being repaired. One flow rate was replicated three times for each plot to determine an average sampling volume for each wheel. In addition, the corn wheel at the Leary sandy loam site was tested at slower flow rates to determine if the wheel sampled consistently over a range of flow rates. Each trial was conducted with 67500 ml of water over a time span of approximately 93 seconds yielding a flow rate of 0.72 l s^{-1}. The subsequent trials on the Leary sandy loam corn wheel, were conducted with 45100 ml and 22200 ml over time spans of 150 and 130 seconds, yielding flow rates of 0.29 and 0.17 l s^{-1}, respectively.

All Coshocton sampling wheels rotated at approximately the same rate, one revolution every two seconds.

Three 20 l rectangular plastic jugs were calibrated in the lab prior to field use. Each jug had a 5 mm hole drilled 6 cm below the drainage spout. This small hole served two purposes: 1) As a overflow valve for consistent filling of the jug. 2) To control the flow rate from the jug during pouring. The jugs drained smoothly with no air entry through the spout. Thus flow rate was controlled by practising pouring runs in the lab. It was found that consistent emptying times could be achieved by practising emptying the contents of the jug in the lab. Although this method was subjective, it proved to be effective. In any case, inconsistencies in flow rates resulting from the procedure should have little bearing on the size of the aliquot taken by the sampling wheels.

A portable levelling stand was constructed out of (12.5 mm) ply-wood and a concrete patio block (Figure 3.6). Three 2 cm diameter holes were drilled through the patio block in the configuration of an equilateral triangle. One threaded rod was mounted through each hole in the patio block. A nut and washer was then fitted onto each rod. The ply-wood base with matching holes was then fitted over the metal rods. A 20 l triangular jug was then placed on the plywood surface within the boundaries of a jug reference mark. The plywood surface was then levelled, with the aid of a hand level, by manipulating the positions of the three large nuts which supported the plywood surface. Each levelled jug was then filled to capacity and allowed to drain from the small hole. Once drainage ceased, the volume of water in the jug was determined. This was done three times for each jug. The average value of three trials was taken as the

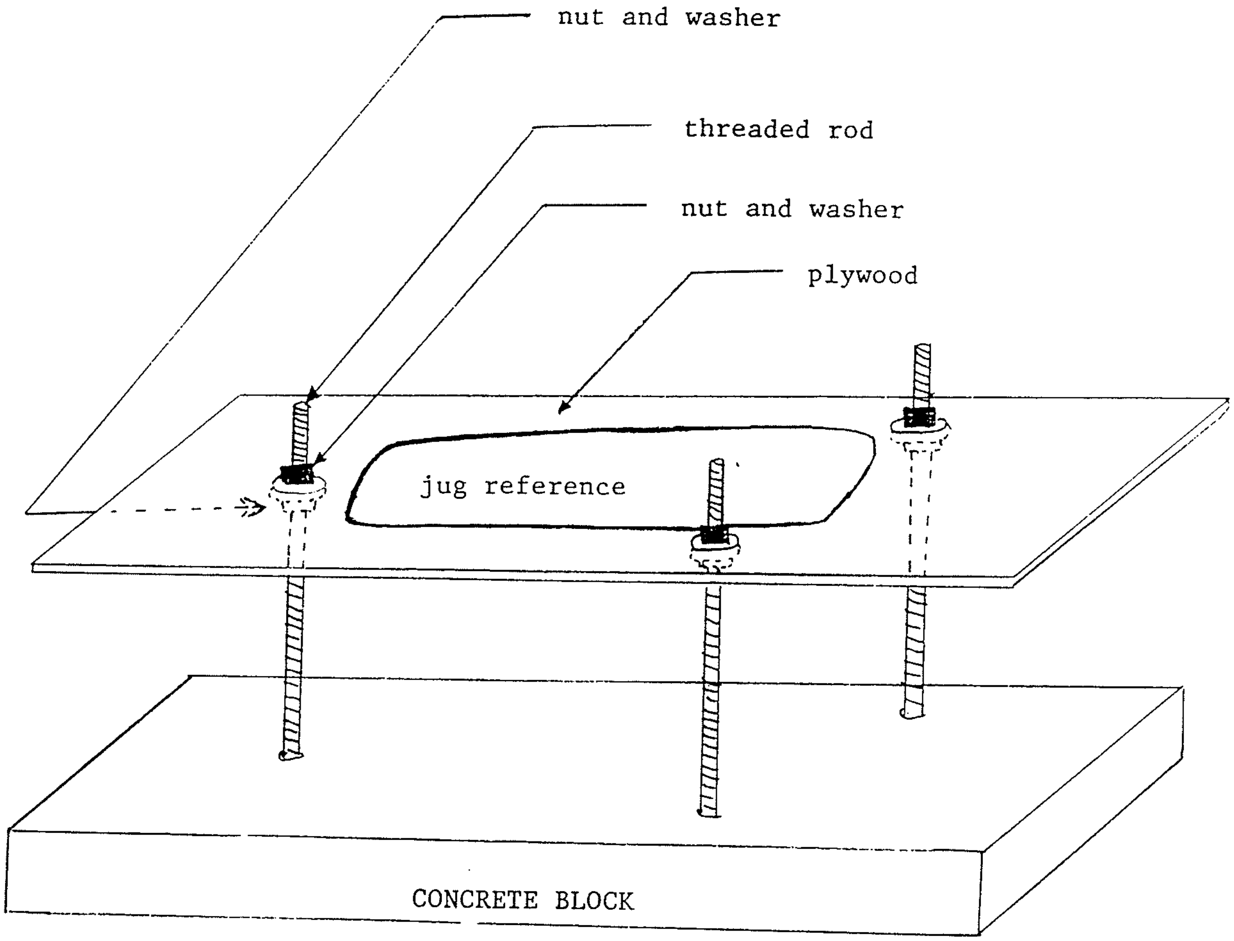

Figure 3.6 Portable levelling stand used in filling calibration jugs

volume of water in the jug. The jug was then tipped upside down and allowed to empty. Flow rates were calculated from the emptying time of each jug.

For the calibration of the sediment sampling and runoff monitoring systems, the receiving troughs and sampling systems were prewetted. The Coshocton sampling wheel was then set in motion and immediately the three jugs were emptied in succession into the high end of the receiving trough. The water level recorder measured the maximum stage in the flume on a strip chart. Actual flow rate was compared to calculated flow rate for each flume. The 1% sampling system was fitted with a pre weighed one litre collection jar. Samples were then weighed and the volume of water collected was determined.

3.4.2 Rain gauge calibration

The rainfall/runoff erosivity factor (R) in the USLE is assessed through the analysis of rainfall intensity data. Each water erosion site employed a [5]Geneq P1000 tipping bucket recording rain gauge with a precision of 0.1 mm and a maximum recording rate of 150.0 mm h^{-1}. A clock driven event recorder provided a chart record of the rainfall. In addition to the event recorder, a [1]DP 101 Datapod was connected to the rain gauge to provide a digital record of the rainfall stored on EPROM chips. The

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[5] Brand name is provided for the information of the reader and does not imply indorsement or preference relative to other such systems which may be available from other suppliers.

Datapod was capable of recording at a maximum rate of one count per second. Given the precision of the rain gauge (0.1 mm), the maximum rainfall rate that could be recorded was 360.0 mm h^{-1}.

As a check, a standard rain gauge was used to record total depth of rainfall. The standard gauge reading was then compared to total rainfall depth as recorded by the Datapod and event recorder.

Analysis of Datapod recordings revealed that during some rainstorms, short duration rainfall intensities often exceed the rated capacity (150 mm h^{-1}) of the rain gauges. The tipping bucket mechanism of the rain gauge tended to under measure rainfall because water was lost during the time the buckets were in motion between tips. Calibration curves for each rain gauge were constructed in order to quantify the inaccuracies in recording particularly intense rainfall periods.

Rain gauges were calibrated prior to test runs. A perforated aluminum pan was placed over the collection orifice of the rain gauge. A one litre volumetric flask was filled to capacity and inverted over a funnel which was equipped with a piece of tubing. A hose clamp fitted to the tubing was used to regulate water delivery to the rain gauge. The inverted volumetric flask served as a reservoir for maintaining a constant head within the funnel. Water was allowed to flow through the rain gauge for a short time. After the bucket tip rate stabilized, the number of tips was counted for fifteen seconds. Immediately after the counting was performed, a portion of the flow was collected in a beaker for 60 seconds. The volume of water collected was determined gravimetrically and flow rates calculated. Actual flow rates were converted to equivalent rainfall intensities and compared to the rate measured by the rain gauge. This was done over a range of intensities and the data plotted in the form of a calibration curve. Polynomial regression was used to derive the relationship between actual and recorded rainfall intensities.

4. RESULTS AND DISCUSSION

Data collection for the Leary Sandy loam and Gretna clay loam sites began in the spring of 1985. Pauls (1987) measured soil losses, rainfall amount and intensity, crop and mulch cover, crop biomass and seed yields, runoff characteristics and various soil physical properties throughout the growing season and into the fall of 1985. Wahome (1989) collected a similar data set for the growing seasons of 1986 and 1987. Antecedent soil moisture levels were monitored in addition to the parameters measured by Pauls (1987). Hargrave (1992) continued field operations for the 1988, 1989 and 1990 growing seasons. In addition to the parameters monitored by Pauls (1987) and Wahome (1989), Hargrave (1992) measured nutrient content in runoff and soil physical properties.

The purpose of this study was to continue data collection for the 1991 and 1992 growing seasons. Soil loss amounts, peak runoff rates, rainfall amount and intensity, crop and mulch measurements, biomass, seed yields and antecedent soil moisture levels were monitored. In addition, the sediment sampling system was tested in situ to determine its reliability. Laboratory testing of the rainfall recording system was carried out to determine maximum rainfall recording rate.

Data analysis focused on field data collected during the 1991 and 1992 growing seasons. Field measurements of soil erodibility (K) and rainfall erosivity (R) on a Gretna clay and a Leary sandy loam soil were compared to values derived using the Universal Soil Loss Equation (USLE). Further data analysis focused on improving soil loss predictions from the unit fallow plot using multiple regression techniques (see page 25, section 2.4.1 for the role of the unit fallow plot in the testing and evaluation of USLE factor values). Data collected between 1985 and 1990 was examined and used as a data base for extrapolation purposes.

4.1 Field data base

Field measurements for the erosion sites began in 1986. Due the disturbances caused at the soil surface during installation of the sites, the first two years of data, 1986 1987 were omitted from the regression analysis and when making comparisons between measured USLE factor values and those derived through estimates using the USLE. Wischmeier and Smith (1978) stated that a newly established fallow erosion plot takes at least two years to reach equilibrium. Prior to this, residual effects from previous cropping treatments will affect soil losses. In addition to the possible residual effects from previous cropping treatments and disturbances caused during installation of the sites, raw data for the 1986 and 1987 cropping years was absent from the data base. Therefore, only data from 1988 to 1992 was used in the regression analysis.

4.2 Field equipment testing

4.2.1 Accuracy of Coshocton sampling wheels.

In 1984, sampling wheels and H flumes were calibrated in the laboratory by Pauls (1987). From these experiments it was determined that the sampling wheels performed well enough to assume a 1% sampling rate for each and every wheel. Rating curves were developed for each flume and the appropriate formula was derived for converting stage, as measured by the water level recorder, to a discharge rate in $l\ s^{-1}$. In 1991, recalibration of sampling wheels and H flumes was carried out in situ (Table 4.1).

Since relatively few trials were conducted for each wheel, a meaningful statistical analysis was not possible. However, given the data set, some important conclusions can be made regarding the performance of the Coshocton sampling wheels. The slot of the Coshocton sampling wheel passed through the sampling stream every 2 seconds during a typical trial lasting 93 seconds. On average each wheel sampled 46 times during the trial, sampling approximately 773 ml from the total test volume of 67500 ml. This yielded a sample aliquot of 17 ml per rotation. Since the wheels sample a portion of the total flow at discrete intervals, the inherent differences between runs could be as high as 34 ml creating a sample error of ± 0.025% . Assuming that the wheels sample perfectly accurately, sample error would be a function of the position of the sampling slot relative to the flume stream at the start and at the end of each trial. The largest possible sample volume would be obtained when, at the instant the runoff stream first hit the Coshocton wheel, the sampling slot was just beginning to traverse under the stream and aliquot would be taken. Also if, at the end of the same run, the slot had just finished a traverse of the stream immediately prior to the end of the flow a additional aliquot would be taken. The lowest volumes of water would be sampled if, at the instant the runoff stream first hit the Coshocton wheel, the sampling slot had just passed the point from which sampling would occur, thus missing a possible aliquot. Another aliquot would be missed during this trial if at the end of the trail, the sampling slot was coming into position to take a sample but the flow rate had just become exhausted. Therefore, it is

TABLE 4.1
Coshocton Sampling Wheel and H Flume Calibrations for Water Erosion Sites

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SitePlotTrialVolumeSampleAverage
SampledSize

---

1 -----------%--------

Gretnafallow1719.91.07
2726.41.081.07
3717.31.06

corn1769.71.14
2780.61.161.16
3797.31.18

wheat1844.11.25
2816.01.211.21
3801.21.19

Learyfallow1829.21.23
2850.91.261.25
3854.61.26

corn1767.31.14
2728.11.071.10
3743.41.10

4526.01.16
5524.61.161.16[z]

6279.41.261.26[y]

wheat1737.71.09
2717.51.061.07
3726.91.07

---

[z] flow rate of 0.29 l s^{-1}
[y] flow rate of 0.17 l s^{-1}

possible that individual sample sizes may vary by as much as two aliquots thus creating a inherent range in the data set of 0.05%. The only way to diminish the magnitude of this error is by increasing the length of time for each run.

The variation between runs, within treatments was small, suggesting that each sampling wheel sampled the same amount of runoff within relatively narrow confidence limits (Table 4.1). At a flow rate of 0.72 l s^{-1} using three trials, four of the wheels (Gretna clay fallow and corn, and the Leary sandy loam fallow and wheat) sampled within the bonds of the inherent error of measurement (0.05%). Two of the wheels, the Gretna clay wheat and the Leary sandy loam corn had a sampling range of 0.06% and 0.07%, respectively. Given the rate of rotation of the Coshocton sampling wheel and the duration of the trial, it was evident that the Coshocton sampling wheels sampled consistently at the test flow rate.

The additional trials performed on the Leary sandy loam corn wheel suggested that as flow rate decreased, sampling rate increased. Two trials at a flow rate of 0.29 l s^{-1} sampled identical portions of runoff which were significantly higher than the trials at 0.72 l s^{-1}. Finally a single trial at 0.17 l s^{-1} yielded a very high sampling rate of 1.25%. It is possible that an error occurred on this run and therefore it is not possible to conclude that the sampling wheels sampled at different rates over a range of flow velocities. However, given the success of each trial and the low variation in the data, it is possible that the sampling wheels do sample at a rate which is a function of flow velocity.

In order to define the sampling characteristics of each wheel, it would be necessary to carry out a number of tests at different flow rates. Four possible scenarios exist.

1) The wheels all sampled 1% of the runoff consistently over a range of flow rates and there was no significant difference between wheels.
2) Each wheel sampled a significantly different proportion of the runoff but sampled consistently over a range of flow rates.
3) Each wheel sampled consistently with no significant difference between wheels, however sampling rate was a function of runoff rate.
4) Each wheel sampled consistently with significant differences between wheels and sampling rate was a function of runoff rate

During a large intense rainfall, runoff was generated across all plots. However, the time at which runoff was initiated, runoff rates and duration of runoff were different for each treatment. If the wheel characteristics followed scenarios 3 or 4, then measuring runoff would involve extensive wheel calibrations and a complex computer program capable of using continuous runoff data to calculate the variable rate of sampling, characteristic of each wheel. The instrumentation installed at the experimental sites was not sophisticated enough to provide the data necessary to do this.

If scenarios 1 or 2 described the sampling scheme, then calculating soil losses based on sample weights is a simple task. In the past, researchers working on this project have assumed scenario 1, i.e. all wheels sampled 1% of the runoff, as designed. However if, as the data suggests, scenario 2 occurred, then the absolute values of soil erodibility (K) and the cropping/management factor (C) will have changed. There was an insufficient data base to confidently determine which scenario was occurring. If scenario 2 occurred, calculated K and C values can be modified without compromising the mathematical integrity of the USLE.

4.2.2 Accuracy of runoff recorders

Runoff recorders were tested simultaneously with the Coshocton sampling wheels. Each runoff recorder was fitted with a seven day strip chart. Characteristically, runoff from the erosion plots is flashy, i.e. runoff rates surge and ebb rapidly in responses to changes in rainfall intensity. The smallest scale divisions on the strip chart represent 30 minute intervals. Separations between adjacent divisions is 1 mm. The pen assembly on the recorder produces a ink tracing approximately 0.6 mm wide. Rapid fluctuations of runoff rates are often masked by the thick ink trace left on the chart. Accurately determining runoff rates based on the area underneath the runoff tracing is both difficult and unreliable. However, the recordings were useful in identifying major surges within a runoff event and for determining peak runoff rates.

Each flume was calibrated in 1985 in the lab prior to installation in the field. The recent calibration of the Coshocton sampling wheels provided an opportunity to test flume calibrations against actual flow rates in the field. Actual flow rates of 0.72 L s^{-1} were used to calibrate the runoff recorders. Flow rates for every treatment were slightly underestimated, with no treatment exceeding 10% error (Table 4.2). Vertical stage divisions on the chart are separated by 2.5 mm. Data can be accurately extracted only to the nearest 0.5 divisions. At 0.72 L s^{-1}, a difference of ± 1 division results in a difference in discharge of approximately 0.1 L s^{-1}. Calculated flow rates compared favourably to actual flow rates for all treatments at the test flow rates.

TABLE 4.2

Comparison of actual and calculated flow rates for H flumes

Treatment	Flow rate	
	Actual	Calculated
	------------l s^{-1}---------	
	Leary sandy loam	
fallow	0.72	0.65
corn	0.72	0.67
corn	0.29	0.30
corn	0.17	0.19
wheat	0.72	0.71
	Gretna clay	
fallow	0.72	0.70
corn	0.72.	0.67
wheat	0.72	trace lost

4.2.3 Accuracy of rain recording system

Analysis of the recording rain gauge charts, the Datapod output and standard rain gauge data, revealed important limitations of the rain recording instrumentation. Occasionally single minute intensities in violent Prairie storms exceeded the capacity of the rain recording systems at the experimental sites. Rainfall intensity data from the chart recorder could only be extracted accurately in 15 minute intervals, thus rendering the data inadequate for detailed analysis.

For example, at the Miami site in 1991, two large storms were recorded, one on June 13 and the other on June 25. Both events produced very high single minute intensities, 1404.0 mm h^{-1} and 696.0 mm h^{-1}, respectively. A detailed analysis of the June 13 storm illustrates the short comings of the instrumentation.

The tipping bucket mechanism of the rain gauge tends to under measure rainfall as water is lost at the time the bucket is in motion during tipping. To offset this, and further complicate analysis, when the datapod count rate is exceeded, the datapod switching mechanism goes into fibrillation, resulting in recordings that are too high.

The June 13 storm showed total rainfall amounts of 38.7 mm, 38.7 mm and 43.4 mm on the chart recording, standard rain gauge and datapod, respectively. Although these inconsistencies appear to be small, they have profound effects on the EI_{30} parameter.

Table 4.3 shows a detailed analysis of the June 13 storm. Total rainfall depth was approximately 38.7 mm, according to the standard rain gauge. Datapod analysis indicated a storm duration of 162 minutes, with approximately 23.4 mm of rain falling

TABLE 4.3

Erosivity Intensity (EI_{30}) Calculations for a Single Storm on the Gretna Clay, June 13, 1991

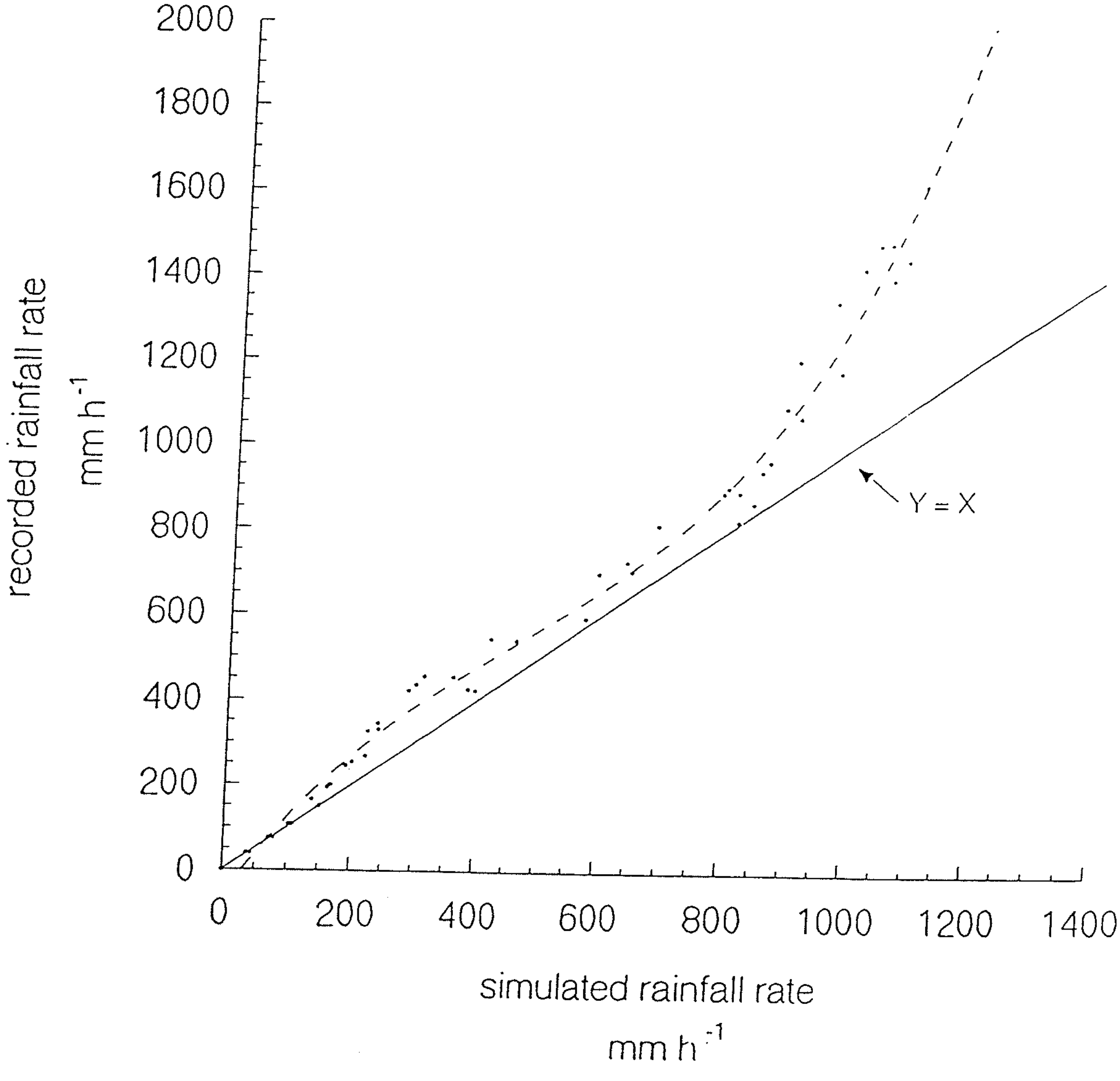
Total Rain	Total Kinetic Energy	I_{30}	EI_{30}
mm	MJ h^{-1}	mm h^{-1}	mm MJ ha^{-1} h^{-1}
Raw dat pod output			
43.4	11.62	70.4	817.91
Datapod output corrected using standard gauge			
38.6	10.23	60.8	622.27
calibration curve correction			
45.7	12.04	75.0	903.00

minute 147 alone. Thus, more than 50% of the total rainfall occurred in a single minute, with an intensity of 1404 mm h^{-1}. At no other time during this event did the rainfall rate exceed the capacity of the rain recording system. This single minute violated the capacity of two of the components in the recording rain gauge instrumentation. Firstly, the rainfall intensity, over 1000 mm h^{-1}, exceeded the recording capacity of the rain gauge (150 mm h^{-1}). Secondly, the Datapod was only capable of sensing one event a second (60 counts/minute). Raw data from the Datapod output indicated 23.4 mm, or 234 counts, occurred within this minute. Total storm rainfall recorded by the Datapod was 43.4 mm, with a single minute intensity of 1404 mm h^{-1}. Thus, a total storm EI_{30} of 817.91 MJ mm ha^{-1} h^{-1} was calculated using data from the datapod.

In an attempt to correct the obvious recording errors associated with the Datapod output, the standard gauge (38.7 mm total rainfall) was assumed to be correct. This agreed exactly with the chart recording of 38.7 mm. By subtracting from the total storm rainfall, 38.7 mm, the rainfall received prior to and after minute 147, it was estimated that 18.7 mm of rain fell during minute 147. This amount corresponded to an intensity of 1122 mm h^{-1} and a total storm EI_{30} of 622.27 MJ mm ha^{-1} h^{-1}. The use of the raw data resulted in an error of more than 30% in the EI_{30} parameter.

Since the tipping bucket mechanism underestimated high intensity rainfall periods, a calibration curve was developed for the rain gauge at each site (Figure 4.1 and 4.2). This was accomplished by simulating high intensity rainfall events in the laboratory and developing a regression line to compensate for water losses occurring during the time the tipping bucket mechanism was tipping. Using the regression formula, actual rainfall during minute 147 of the June 13 storm on the Gretna clay would have been 1541.1 mm h^{-1} or 25.0 mm. This would have resulted in a total rainfall for the storm of 45.0 mm with an EI_{30} of 903.00 MJ mm ha^{-1} h^{-1}. However it may not be valid to use the calibration curve in this instance because of the good agreement between the standard gauge and the tracing on the recording chart.

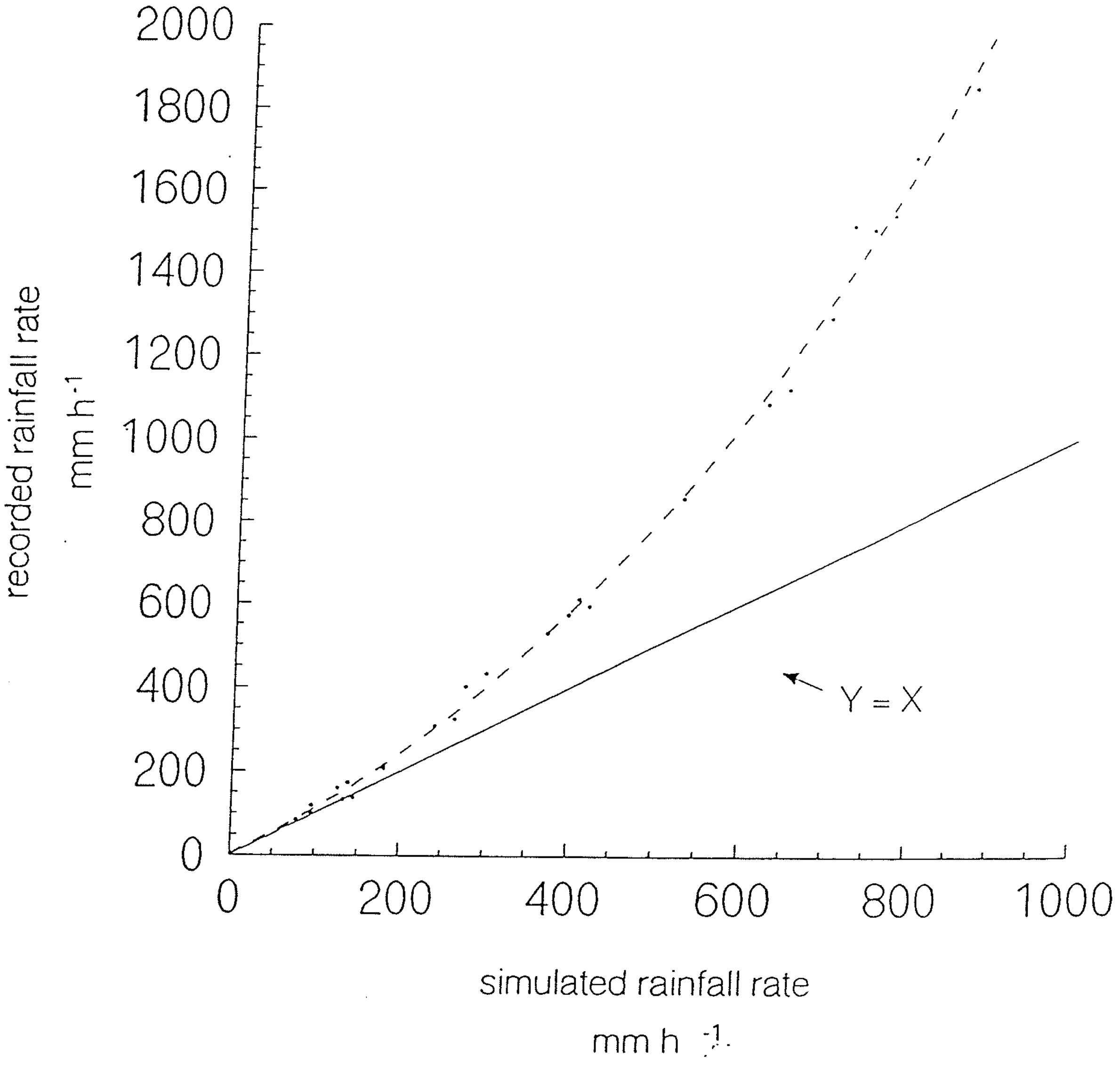
In light of the surprising fact that prairie storms are capable of delivering large volumes of water in short cloud bursts, care must be taken when interpreting rainfall intensity data. Also, instrumentation capable of precisely and accurately recording



$$Y = 2.13*X - 2.7*10^{-3}*X^2 + 2.0*10^{-6}*X^3 - 63$$

$$R^2 = 0.988$$

Figure 4.1 Gretna clay rain gauge calibration curve



$$Y = X + 9.7*10^{-4}*X^2 + 4.9*10^{-7}*X^3 + 4.0$$

$$R^2 = 0.996$$

Figure 4.2 Leary sandy loam rain gauge calibration curve rainfall on a minute by minute basis must be used in studies attempting to measure the kinetic energy of rainfall events. Even some of the most sophisticated equipment falls far short of being able to monitor the sporadic nature of high intensity rainfall events. In addition to this, rainfall simulators, used in erosion studies, which provide a constant intensity rate may not be representative of natural storms.

It is possible to recalibrate the rain gauge used in this study to tip at 0.25 mm intervals while still meeting the maximum design recording rate of 150 mm h^{-1}. This would reduce the rate at which the Datapod would have to count and increase its count rate to 900 mm h^{-1}. Rain gauge calibration curves could then be recalculated and the appropriate corrections applied to the storm segments with intensities within the range of 150-900 mm h^{-1} This would provide a relatively inexpensive solution to the rainfall recording problem. However intensities greater than 900 mm h^{-1} could not be measured accurately. The most effective way to monitor rainfall intensity would be with an electronic weighing type gauge.

Rainfall data analysis of storm segments which exceeded the capacity of the rain gauge but not the Datapod count rate, i.e. >150 mm h^{-1} and $<$ 360 mm h^{-1}, were corrected using the rain gauge calibration curves. If the intensity of the storm exceeded 360 mm h^{-1}, the standard gauge was taken to be correct and the appropriate modifications to the Datapod output were performed prior to determining the EI_{30} value for that particular storm.

Table 4.4 shows a summary of the high intensity events occurring at the water erosion sites since 1987. Interestingly, no high intensity errors were ever recorded at

TABLE 4.4
Datapod Errors Generated by High Intensity Storms Occurring on Gretna Clay

Scenario	Data Pod recording	Rain Intensity	Rain Total	EI_{30}
	mm min^{-1}	mm h^{-1}	mm	MJ mm ha^{-1} h^{-1}
	August 3 1989			
raw Datapod output	11.4	684	23.8	263.12
corrected values	13.4	804	25.8	314.70
	May 31 1990			
raw Datapod output	34.0	2040	93.6	1446.13
corrected values	26.4	1584	86.0	1018.03
	June 11 1990			
raw Datapod out put	7.8	468	32.8	522.84
corrected value	--	--	--	--
	June 13 1991			
raw Datapod out put	23.4	1404	43.4	817.91
corrected values	18.6	1122	38.6	622.27
	June 25 1991			
raw Datapod output	14.0	840	45.2	853.00
corrected values	11.6	696	42.8	749.62
	July 14 1992			
raw Datapod output	12.8	768	32.2	387.53
corrected values	10.4	624	29.8	318.59
	July 18 1992			
raw Datapod output	10.2	612	19.2	141.58
corrected values	9.2	552	18.2	107.73

the Leary sandy loam site. However, analysis of data from three other water erosion sites currently operated by the University of Manitoba showed that, on occasion, high intensity events occurred at these sites.

4.3 Soil losses

When interpreting soil loss data generated from the research plots, great care must be taken to identify events when sampling errors occur. The Coshocton sampling wheels occasionally failed due to excessive sediment loading or bearing failure. The sediment collection systems were also prone to malfunction. Sediment collection pans may have become blocked and over flowed, delivery hoses may have become plugged, leakage at the jug connections may have occurred. Sampling collection jugs may have overflowed or harboured small punctures allowing all or a portion of the contents to be lost. Plot boundaries may have been undermined by excessive runoff allowing runoff to flow off of the plots or runoff to enter the plots. Care was taken when collecting samples to note any malfunctions that have occurred. After each rainfall event a qualitative visual examination of the plots and sampling systems was performed and accurate field notes kept. Field notes included a visual assessment of the relative rates of erosion between the treatments based on rill development and other soil surface characteristics.

The expected annual rates of soil loss from the experimental cropping treatments were as follows, fallow > corn > wheat > alfalfa (Hargrave 1992, Pauls 1987, Wahome 1989, Wischmeier and Smith 1978). However, relative rates of soil loss between the treatments for individual soil loss events, often did not follow the expected trends. Relative soil loss rates were influenced by crop development, field operations and antecedent soil moisture conditions. Plants and plant residues shielded the soil surface from the erosive forces of raindrops decreasing particle detachment rates and also acted as barriers to overland flow, reducing transport capacity of the runoff. Field operations such as seeding and periodic cultivation, affected surface storage capacity and ponding, the availability of erodible material, soil surface drainage efficiency, and infiltration rates. Soil moisture levels governed infiltration rates and the ability of the soil surface to absorb rainfall.

4.3.1 Influence of soil surface morphology

Surface roughness influences surface ponding and the flow characteristics of surface runoff. Surface retention is an important factor affecting runoff volumes, peak runoff rates and length of the runoff period. Thus, a rainfall which occurs on a very rough soil surface will produce lower rates of erosion than that same rainfall occurring on a smooth, highly eroded soil surface.

Before attempting to interpret field data it is important to understand how the surface of a plot changes with time relative to cultivation intervals. When the soil is cultivated, clods are produced randomly upon the soil surface. Immediately after cultivation surface roughness and storage capacity are at a maximum. As rainfall strikes the soil surface, surface clods begin to slake, reducing surface relief resulting in reduced surface storage capacity. Slaking of surface clods occurs during most rainfall events whether or not surface runoff and erosion have occurred. During an erosive rainfall event, excess rainfall collects in depressions created between adjacent clods and forms small surface ponds. Small surface ponds shield the soil surface from raindrop impacts, this reducing particle detachment. In addition, small surface ponds function as miniature reservoirs which reduce the velocity of inflowing runoff resulting in sediment deposition. Once initiated, runoff forms rills across the soil surface which are efficient channels for conveying sediment laden runoff. Antheral areas also change and become progressively more efficient at conveying runoff into rills. At some point, after much rainfall and erosion has occurred, surface storage capacity becomes negligible and water not infiltrating into the soil readily flows across the plot surface. Subsequent cultivation restores maximum surface roughness and reduces the erodibility of the soil surface. A highly rifled soil surface erodes more readily than a freshly cultivated soil surface.

Observation of runoff plots indicated that rills initially formed individually near the base of the plot and, as time progressed, migrated by headward erosion up slope and often branched out to form dendritic networks which covered the entire plot surface. The rate at which a plot changed from the freshly cultivated surface to a highly incised efficient drainage plain was a function of rainfall intensity and total amount of rainfall received since the last cultivation. Periodic cultivation disrupted drainage networks formed at the soil surface and reduced the tendency of the soil surface to erode. Thus on the fallow plot, for any particular site, soil erodibility was largely dependant on the physical condition of the plot surface.

4.3.2 Comparison of soil losses from crop management treatments

Soil loss data from the experimental sites is summarized in Tables 4.5 and 4.6. In the spring, fallow, corn and wheat plots were cultivated. Following cultivation, wheat and corn plots were harrowed twice to prepare the seed bed. Harrowing reduced clod size which decreased soil roughness and surface storage capacity. Seeding of corn plots was done by hand, thus further disturbances to the soil surface were minimal. In contrast, wheat was seeded with a press drill, leading to further clod destruction. In addition, the compaction wheels on the wheat seeder produced small ridges on the soil surface which may have acted to channel runoff down slope. Observation of the erosion plots following a seeding operation, revealed that surface roughness was the greatest in the fallow plot and the least in the wheat plot. Thus, in the spring, with low residue coverage, and a highly ridged pulverized soil surface, the wheat treatment would be expected to be the most erodible treatment, followed by corn and fallow.

At the Gretna clay site, a storm occurring shortly after seeding on May 30, 1991 resulted in 0.12, 0.07, and 0.07 t ha^{-1} of soil loss from the wheat, fallow and corn plots, respectively. In 1992 at the Gretna clay site, an event on June 3 caused measured soil losses of 0.54, 0.46 0.42 t ha^{-1} for the wheat corn and fallow plots, respectively. At the Leary sandy loam site in 1992, erosion during the first soil loss event after seeding on May 20, was 0.22 and 0.11 t ha^{-1} for the wheat and fallow plots, respectively. The

TABLE 4.5
Measured Soil Losses from Gretna Clay for 1991 and 1992

Date	Rain	EI_{30}	Measured Soil Losses			
			Fallow	Corn	Wheat	Alfalfa
	mm	MJ mm ha^{-1} h^{-1}	t ha^{-1}			
1991 May 15			seeding operations			
1991 May 30	36.2	155	0.07	0.07	0.12	0.00
1991 June 13	38.6	622	>12.00	22.14	>3.35	0.00
1991 June 15	13.2	15	1.10	0.70	0.30	0.00
1991 June 20			cultivated fallow and corn			
1991 June 25	45.2	750	20.60	29.33	6.36	0.00
1991 June 30	43.4	163	30.36	34.12	5.01	0.00
1991 July 1	11.7	7	3.14	1.54	0.34	0.00
1991 July 2	12.6	3	1.08	0.44	0.08	0.00
1991 July 6	17.0	58	11.13	8.80	1.82	0.00
1991 July 12	58.0	166	23.45	20.62	4.95	0.00
[y]total soil losses			90.93	95.62	18.98	0.00
1992 May 20			seeding operations			
1992 June 3	24.6	86	0.42	0.46	0.54	0.00
1992 June 16	16.0	61	0.16	0.14	0.07	0.00
1992 June 21	10.2	12	0.09	0.07	0.04	0.00
1992 June 24	7.4	16	0.36	0.16	0.05	0.00
1992 June 30	31.6	25	0.80	0.00	0.00	0.00
1992 July 10	9.2	7	0.07	0.00	0.00	0.00
1992 July 10			cultivated fallow and corn			
1992 July 14	29.8	318	9.25	7.02	0.04	0.00
1992 July 15	3.4	5	0.93	0.41	0.00	0.00
1992 July 18	17.2	108	14.17	[z]3.00	0.07	0.00
1992 July 27	12.4	61	0.77	[z]	0.00	0.00
1992 August 8	11.2	67	0.43	0.13	0.00	0.00
[y]total soil loss			12.51	8.38	0.74	0.00

[z] sampling system error

[y] comparative yearly soil losses excluding soil loss events in which sampling errors occurred

TABLE 4.6
Measured Soil Losses from Leary Sandy Loam for 1991 and 1992

Date	Rain	EI_{30}	Measured Soil Losses			
			Fallow	Corn	Wheat	Alfalfa
	mm	MJ mm ha^{-1} h^{-1}	t ha^{-1}			
1991 May 15			seeding operations			
1991 May 30	24.4	64	0.17	0.12	0.08	0.00
1991 June 13	25.4	162	5.84	3.47	3.05	0.00
1991 June 20			cultivated fallow and corn			
1991 June 25	36.8	268	2.44	[z]	4.53	0.00
1991 June 30	33	89	1.36	[z]	0.77	0.00
1991 July 02	21.4	15	0.09	0.00	0.00	0.00
1991 July 06	10.2	11	0.12	0.00	0.00	0.00
1991 July 12	68.4	366	11.10	[z]	4.4	0.00
[y]total soil loss			6.01	3.59	3.13	0.00
1992 May 20			seeding operations			
1992 June 21	17.4	62	0.11	[z]	0.22	0.00
1992 June 24	11.8	60	[z]0.48	1.26	[z]0.52	0.00
1992 July 10			cultivated fallow and corn			
1992 July 14	24.2	135	1.25	0.34	0.45	0.00
1992 July 18	8.4	12	0.15	0.05	0.03	0.00
1992 July 27	10.8	2	0.33	0.11	0.06	0.00
1992 August 8	8.4	34	0.72	0.16	0.02	0.00
1992 August 13			cultivated fallow			
1992 August 29	20.6	61	0.13	0.05	0.01	0.00
[y]Total soil loss			2.58	0.71	0.57	0.00

[z] sampling system error

[y] comparative yearly soil losses excluding soil loss events in which sampling errors occurred

sampling system on the corn plot failed, preventing a measurement of soil loss for this event. Thus, early in the spring, wheat tended to be the most erodible treatment For the most part, subsequent soil loss events at both sites followed the expected rates of losses between the treatments, i.e. fallow > corn > wheat >alfalfa. At no time during the study did the alfalfa treatment record soil loss at either site. Alfalfa plots were very well established with thick mulch layers protecting the soil surface. On some occasions the alfalfa plots experienced runoff. However runoff samples were free of sediment and any residue left behind in the troughs after runoff events consisted only of plant debris.

Four to six weeks after seeding, the corn and fallow plots were cultivated to control weeds, break surface crusts and destroy surface rilling. This operation had marked effects on the relative rates of soil loss between the treatments. Cultivating the fallow involved two passes with the field cultivator. Corn received two passes as well, however to avoid crop destruction cultivator shanks corresponding to corn rows were removed. The result was that a smaller percentage of the total plot area was cultivated. In addition, cultivation was shallower. The end result was that surface roughness was much greater on the fallow than on the corn plots because fallow received a much deeper and complete cultivation run than the corn. The increased surface roughness on the fallow treatment increased surface storage and ponding, resulting in reduced runoff rates and lower soil losses.

During the study period, three prolonged wet periods occurred at the Gretna clay site. This provided a unique opportunity to measure soil losses during a series of closely spaced soil loss events and to assess the effects of changing soil surface morphology after cultivation. Soil moisture levels were at or near saturation after the first event during a prolonged wet spell and therefore the effects of antecedent soil moisture were minimized. Crop canopies did not change significantly during this short time and therefore the effects of increases in crop canopy cover were minimal.

The first wet period occurred between May 25 and June 2, 1991 at the Gretna clay site (Table 4.5). Following cultivation of the corn and fallow on May 20, a series of four runoff events occurred in less than one week. During the first soil loss event (May 25) corn and fallow lost 29.33 and 20.6 t ha^{-1}, respectively. For the second event (May 30), corn and fallow lost 34.12 and 30.36 t ha^{-1}, respectively. The first event showed the corn plot lost almost 50% more soil than the fallow plot. During the second event corn plot lost almost 15% more soil than the fallow plot. Soil losses for the third event (June 1) on corn and fallow were 1.54 and 3.14 t ha^{-1}, respectively. In this case, fallow lost more than twice as much soil as corn. The following day fallow again lost twice as much soil as the corn.

Results from another inter-cultivation period at the Gretna clay site show a similar trend. Corn and fallow soil losses for June 3 were 0.46 and 0.42 t ha^{-1}, respectively for the first event which occurred 13 days after seeding in 1992. On June 16 corn and fallow lost 0.14 and 0.16 t ha^{-1}, respectively. The following storm on June 21 resulted in corn and fallow losses of 0.07 and 0.09 t ha^{-1}, respectively. Finally on June 24 corn and fallow losses were 0.36 and 0.16 t ha^{-1}, respectively. During a another wet period in 1992 at the Gretna clay site the same trend was observed. Cultivation occurred on July 10. Soil losses for corn and fallow during an event on July 14 were 7.02 and 9.25 t ha^{-1}, respectively. A second storm occurring on July 15 resulted in 0.41 and 0.93 t ha-1 from the corn and fallow plots, respectively. Again, twice as much soil loss was lost from the fallow as the corn.

The data set clearly shows that after cultivation, and over successive runoff events, fallow soil losses relative to corn at the Gretna clay site, were small at first and then progressively increased over time. This was because the high clay content at this site leads to the production of large clods during cultivation. Since the corn received a less vigourous cultivation, clods on the fallow were more numerous and bigger. Thus clods on the fallow plot had to break down before significant soil losses could occur.

The same trend was observed when comparing soil losses between fallow and wheat. As the number of runoff events since the last cultivation increased, the relative rates of erosion between fallow and wheat increased dramatically. Subsequent cultivation of the fallow, resulted in lower relative rates of erosion between the treatments until surface roughness, and hence surface storage on the fallow plot was again reduced through slaking and enhanced drainage network development.

Soil loss measurements at the Leary sandy loam site were plagued by numerous sampling errors. A detailed comparison of soil loss rates between the treatments, relative to inter-cultivation periods is difficult. However, in all cases, cultivation resulted in lower relative rates of erosion from the fallow than from the other treatments. Clod production at the Leary sandy loam site after cultivation was not as pronounced as at the Gretna clay site. The sandy nature of the soil hampered the development of large clods during cultivation runs. Cultivation did however destroy surface rills and reduced the tendency for the cultivated plots to erode. Soil losses from fallow and wheat where 5.84 and 3.05 t ha^{-1}, respectively on June 13, 1991. Fallow and corn were cultivated on July 20. Five days later a soil loss event occurred in which the fallow and wheat plots lost 2.44 and 4.53 t ha^{-1}, respectively. A system malfunction in the corn prevented measurements of soil loss from this treatment. Clearly, cultivation of the fallow resulted in lower rates of erosion relative to the wheat treatment. On August 8, 1992 at the Leary sandy loam site soil losses for the fallow, corn and wheat plots were 0.72, 0.16 and 0.02 t ha^{-1}, respectively. Fallow was cultivated on August 13. A storm on August 29 produced soil losses from fallow, corn and wheat of 0.13, 0.05 and 0.01 t ha^{-1}, respectively. Prior to cultivation the fallow plot was eroding 4.5 times more than the corn plot and 36 times more than the wheat plot. Following cultivation, the next erosive storm produced 2.6 times more soil loss from the fallow as compared to the corn and 13 times more soil loss from the fallow as compared to the wheat.

Through cultivation, surface rills and inter rill areas were destroyed, reducing drainage efficiency of the plot surface. Cultivation also produced clods at the soil surface. Clods impeded surface drainage by slowing down runoff. Pooled water between clods shielded the surface of the soil from the erosive forces of raindrops. Thus, the inherent ability of the soil to erode and hence the soil erodibility factor (K) was therefore influenced by soil surface morphology.

4.3.3 Effects of antecedent soil moisture

For any given soil, infiltration rates are a function of moisture content; dry soils have higher infiltration rates that wet soils. Total runoff volumes and flow rates generated during a storm should be influenced by the moisture content of the soil prior to the rainfall event. The erosive potential for a given storm should be a function of surface roughness and antecedent soil moisture levels.

The effects of antecedent soil moisture on the relative rates of erosion from the cropping treatments can be seen when comparing soil losses between the treatments, after a particularly wet period (Table 4.7). At the Gretna clay site in 1992 soil losses resulting from a storm occurring on June 2 on the fallow, corn and wheat were 1.08, 0.44, and 0.08 t ha^{-1}, respectively. Prior to this storm, the soil was at or near saturation, following 22 hours of rainfall from a previous storm. On June 5, three days later, a small storm produced 1.3 mm of rainfall with no erosion. A storm occurring on July 6 on a somewhat drier soil surface resulted in soil losses from the fallow, corn and wheat of 11.13, 8.8, and 1.82 t ha^{-1}, respectively. On July 12 after five days of no

TABLE 4.7
Effects of Antecedent Soil Moisture Content on Soil Loss Ratios on Gretna Clay in 1992

Date	Rainfall	[z]Antecedent soil water content			Soil loss			[y]Soil loss ratios		
		Fallow	Corn	Wheat	Fallow	Corn	Wheat	Fallow	Corn	Wheat
	mm	%			$t\ ha^{-1}$					
July 2		33.5	33.5	33.5						
July 2	12.6				1.08	0.44	0.08	1	0.41	0.07
July 3		31.3	29.2	29.8						
July 6	17.0				11.13	8.80	1.82	1	0.79	0.16
July 9		25.3	27.3	23.9						
July 12	58.0				23.45	20.62	4.05	1	0.88	0.17

[z] average gravimetric water content in upper 15 cm of the soil profile
[y] losses from the cropped treatments divided by losses from the fallow treatment

measurable precipitation, a third storm caused losses from fallow, corn and wheat of 23.45, 20.62, and 4.05 t ha $^{-1}$ respectively. Soil moisture levels prior to this storm were lower than the previous two events.

By examining the soil loss ratios from these three events it can be seen that as the soil dried, corn and wheat tended to experience increased rates of erosion relative to the fallow treatment, i.e. fallow tended to become less prone to erosion relative to corn or wheat.

Tillage increases surface porosity (Freebairn et al. 1989), which may lead to higher infiltration rates into the fallow plot. When the soil is saturated, difference in infiltration rates between the treatments may be small. Since fallow lacks a protective canopy and has a more highly developed and efficient surface drainage network, erosion will be high. Once the soil dries, the differences between treatments in initial infiltration rates may be greater and thus, the fallow may absorb a significant portion of the rainfall relative to corn and wheat treatments. Thus fallow became less prone to erosion relative to the other plots.

In an attempt to account for the effects of antecedent soil moisture levels, soil moisture data was collected on a weekly basis at the erosion sites. These measurements were intended to provide an estimate of the soil moisture content prior to a given rainfall erosion event. Unfortunately, small non erosive rainfall events often occurred between the time that soil moisture sampling was performed and the time that erosive rainfall events took place. The above complicated and confounded attempts to quantify pre-storm antecedent soil moisture levels. In order to accurately gauge soil moisture levels prior to a given event, it would be necessary to take more frequent measurements of soil moisture or develop a model which estimates fluctuations in soil moisture levels based on frequent sampling points, and variations in daily temperature and precipitation.

4.4 The soil erodibility factor (K)

The Universal Soil Loss equation employs an empirical constant called the soil erodibility factor (K) to evaluate the susceptibility of the soil to the forces of rainfall induced erosion. The K factor is a simplistic lumped constant representing the soils susceptibility to erosion while under the influence of the combined effects of shear forces in surface flow, the scouring action of runoff and the impact of raindrops on the soil surface. Each soil is assigned a fixed K value based on texture, organic matter structure and permeability (Wischmeier et al. 1971). K represents the inherent ability of the soil to erode. Experimentally, K can be calculated by dividing soil losses from the experimental fallow plot by rainfall erosivity, R. Soil erodibility is expressed in units of t h MJ^{-1} mm^{-1} and is the amount of soil loss per unit of rainfall erosivity.

4.4.1 Measured and estimated K factor values

Measured and estimated K values for the Gretna clay and Leary sandy loam are represented in Table 4.8. Estimated K values were derived from a nomograph developed by Wischmeier et al. (1971) (see section 2.5.1) and are based on the soil physical properties measured at each site (Table 4.9). Measured K values were derived by dividing soil losses measured on the fallow plot by the cumulative rainfall erosivity values (EI_{30}) for each storm causing soil loss as well as for those storms which did not cause soil loss but met the requirements of an erosive event as outlined by Wischmeier and Smith (1978). An erosive storm is defined as a rainfall event separated by at least six hours without measurable precipitation yielding more than 12.7 mm of rainfall, unless at least 6.4 mm fell in 15 minutes. Those rainfall events which did not meet Wischmeier's criterion but resulted in measurable soil losses were included in the summed EI_{30} values used for determining measured K values. Values for K calculated by the USLE nomograph represent long term averages based on 22 years of observations. Measured values of K do not agree well with the

TABLE 4.8
A Comparison of Measured and Estimated Soil Erodibility (K) Factor Values for Two Soil Types

year	Fallow Total Soil Loss	Rainfall Energy	Soil Erodibility (K)		
			Measured		
			K = A/R	Average	USLE (K)
	t ha^{-1}	MJ mm ha^{-1} h^{-1}	----------t ha MJ^{-1} mm^{-1}-------		
		Gretna clay			
1988	15.51	546.19	0.0284		
1989	12.11	692.51	0.0175		
1990	193.92	2200.73	0.0881	0.0650	0.028
1991	90.93	911.16	0.0100		
1992	26.65	850.31	0.0313		
		Leary sandy loam			
1988	3.95	516.37	0.0076		
1989	5.30	685.73	0.0077		
1990	32.57	1794.97	0.0181	0.0123	
0.027					
1991	21.12	999.74	0.0211		
1992	2.58	40.04	0.0064		

TABLE 4.9
Soil Physical Properties for Estimating K Values from Universal Soil Loss Equation Nomograph

Soil Type	Sand	Silt	Clay	Silt +	Organic	Structure	
Permeability				v.f .Sand	Matter	Code	Code
Gretna C	21.0	28.6	50.4	30.1	4.3	4	6
Leary SL	74.5	14.5	11.0	25.2	0.3	4	2

Source, after Pauls (1987)

values calculated by the nomograph. The nomograph is most accurate for medium textured soils and is not valid when the sand fraction exceeds 65% or the clay fraction exceeds 35% (Wischmeier et al. 1971). The Gretna clay and Leary sandy loam soils are at opposite ends of the textural spectrum and both fall outside the textural range of soils for which the nomograph was developed. The Gretna clay has clay content of 50.4% while the Leary sandy loam has a sand content of 74.5%. In addition, the nomograph does not account for soils with more than 4.0% organic matter. Soils of the Canadian Prairies are located outside the area in which the nomograph was developed. Consequently, Canadian soils often have levels of organic matter in excess of 4.0% and have a different assemblage of clay minerals (Pauls 1987). This illustrates a need for further research and modification of the nomograph to suite Canadian conditions.

In an investigation of soil erodibility on Mississippi soils, Mutchler and Carter (1983) found that single fixed K values were satisfactory for estimating long term average losses but were not adequate for short time intervals. In addition they found that K values varied seasonally, being higher in the spring and lower in the fall (see section 2.5.1). In the present study, measured annual average K values ranged from 0.0100 to 0.0881 and from 0.0064 to 0.0211 MJ mm ha^{-1} h^{-1} for the Gretna clay and the Leary sandy loam, respectively (Table 4.8). The importance of long term observations for determining K values cannot be over emphasized (Romkens 1985).

4.4.1 Variability of K by storm

Soil erodibility for individual storms for the study period are shown in Figure 4.4, 4.5, 4.6, and 4.7. Values for soil erodibility are highly variable, ranging between 0 and 0.44 t h MJ^{-1} mm^{-1} for the Gretna clay and from 0.0 to 0.030 for the Leary sandy loam. Soil erodibility values were usually lowest for storms occurring immediately after

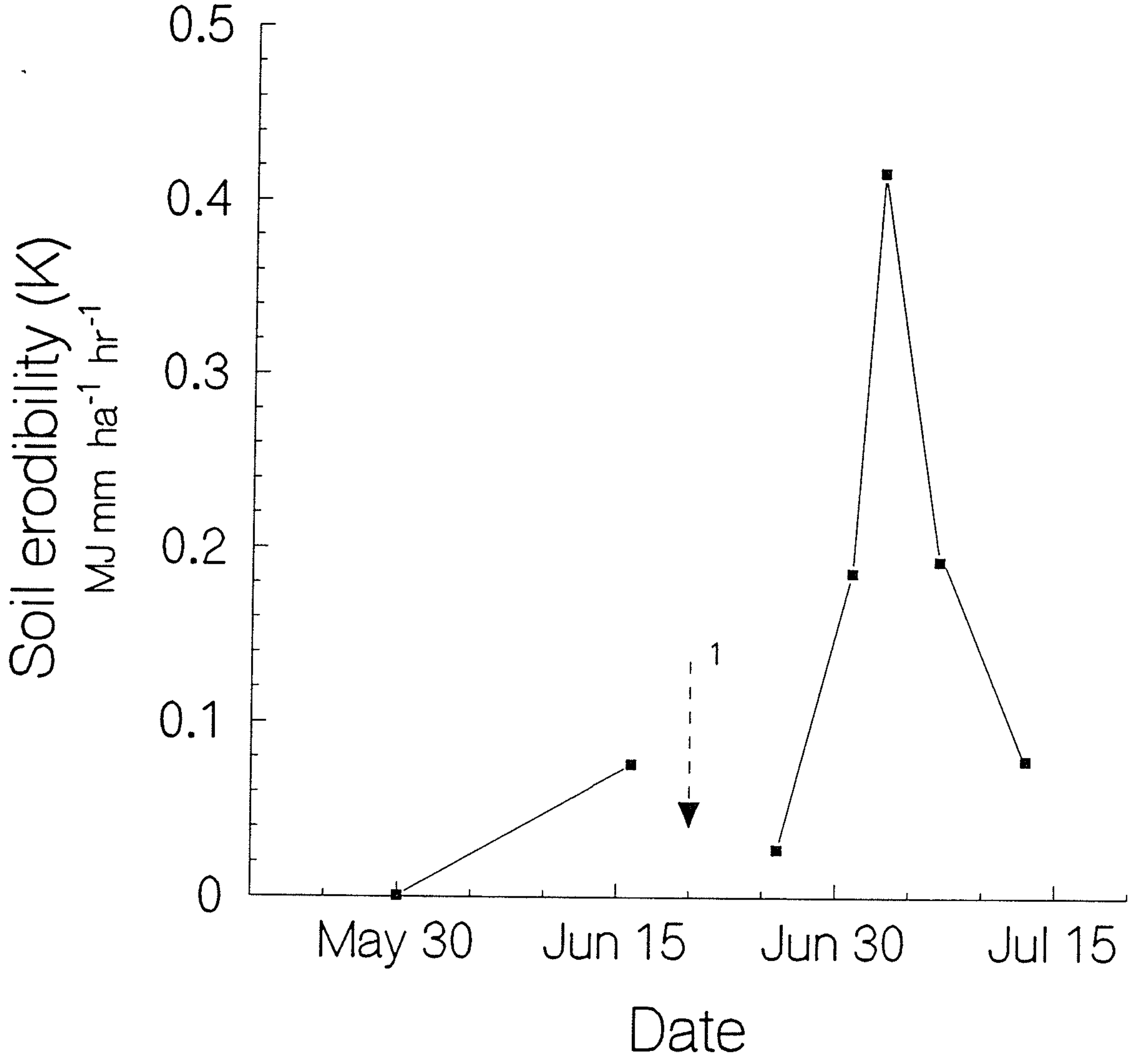


Figure 4.3 1991 Storm by storm variation in measured soil erodibility (K) for Gretna clay. Numbered vertical lines represent cultivation runs

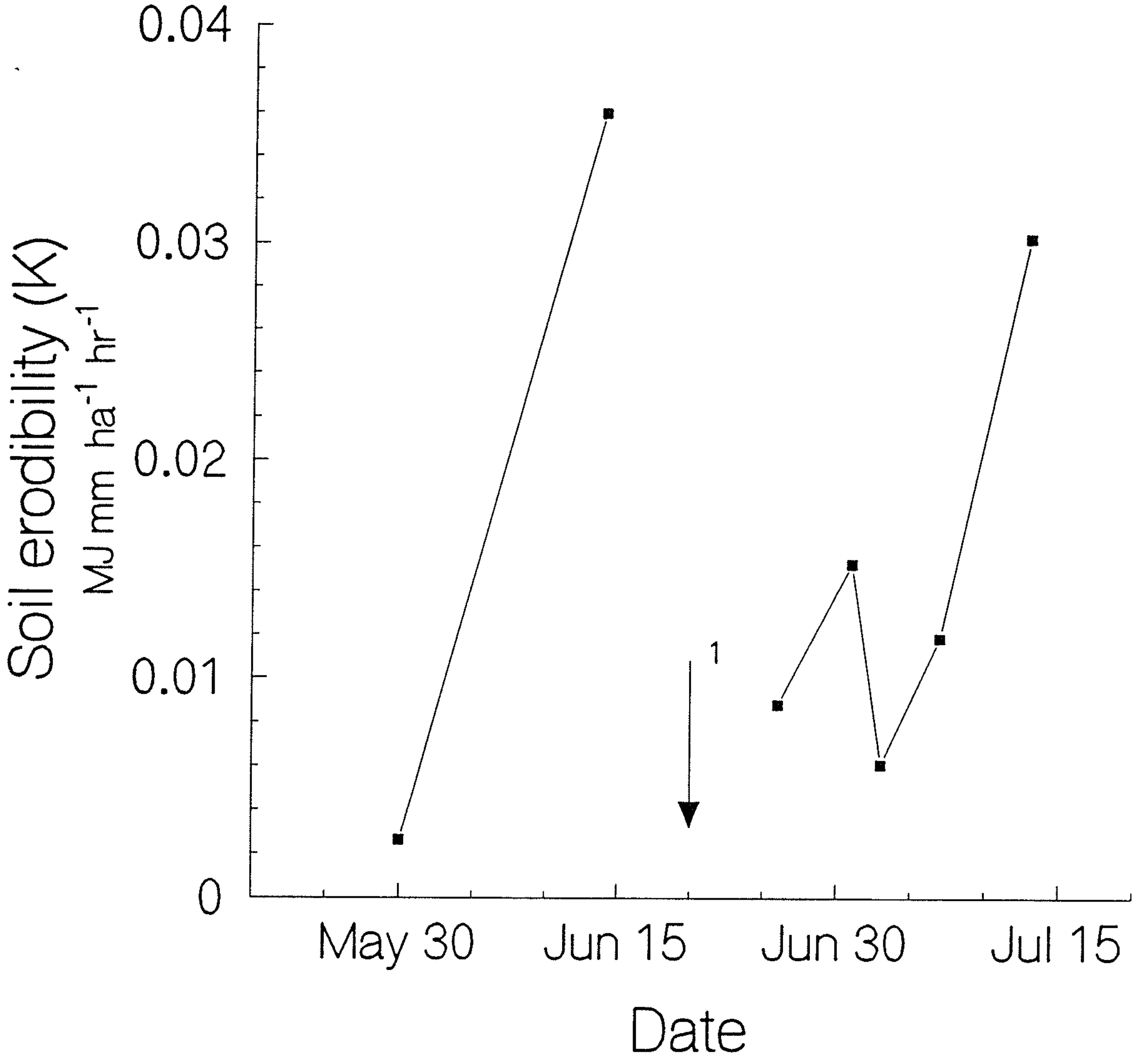


Figure 4.4 1991 Storm by storm variation in measured soil erodibility (K) for Leary sandy loam. Numbered vertical lines represent cultivation runs

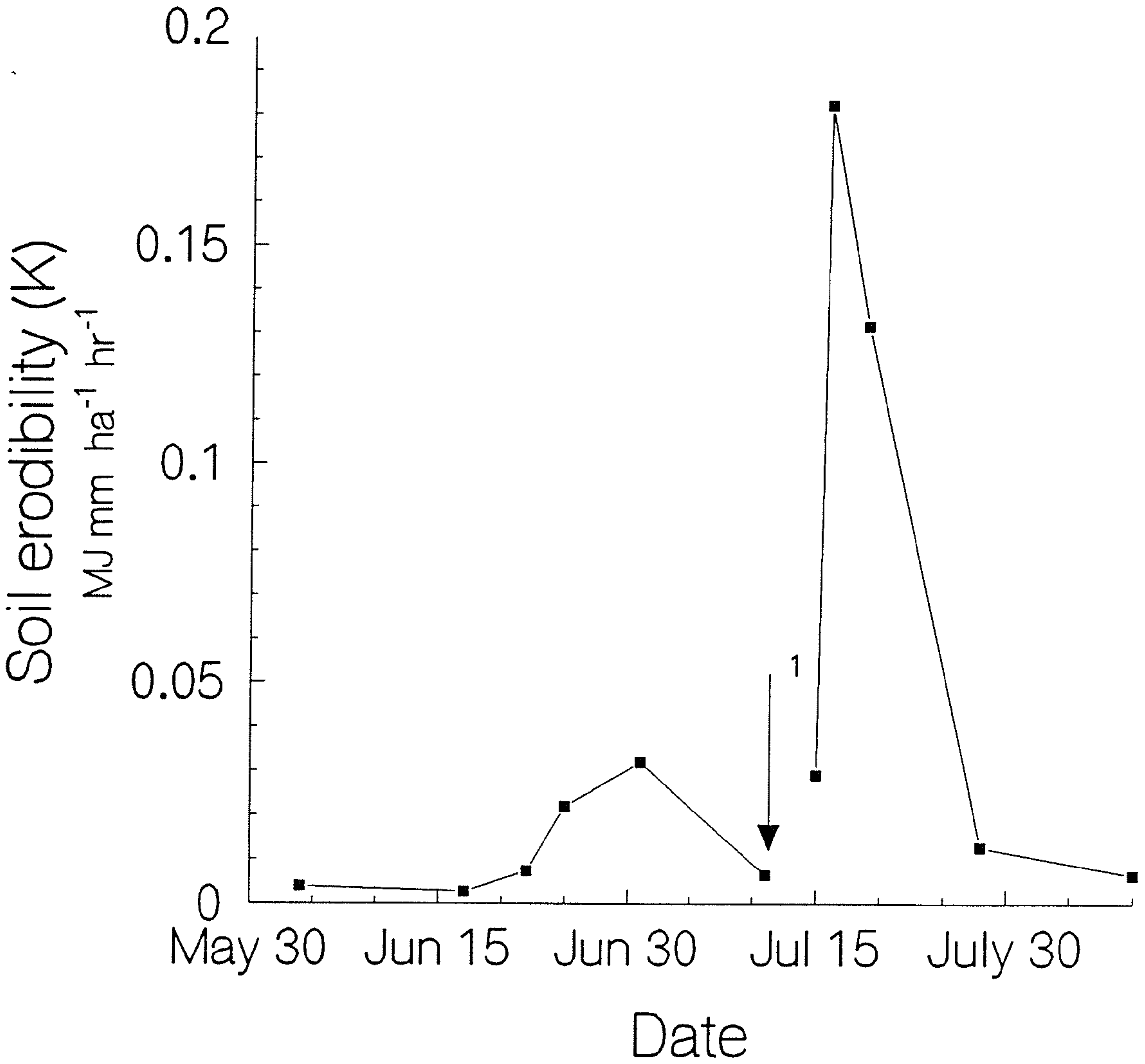


Figure 4.5 1992 Storm by storm variation in measured soil erodibility (K) for Gretna clay. Numbered vertical lines represent cultivation runs

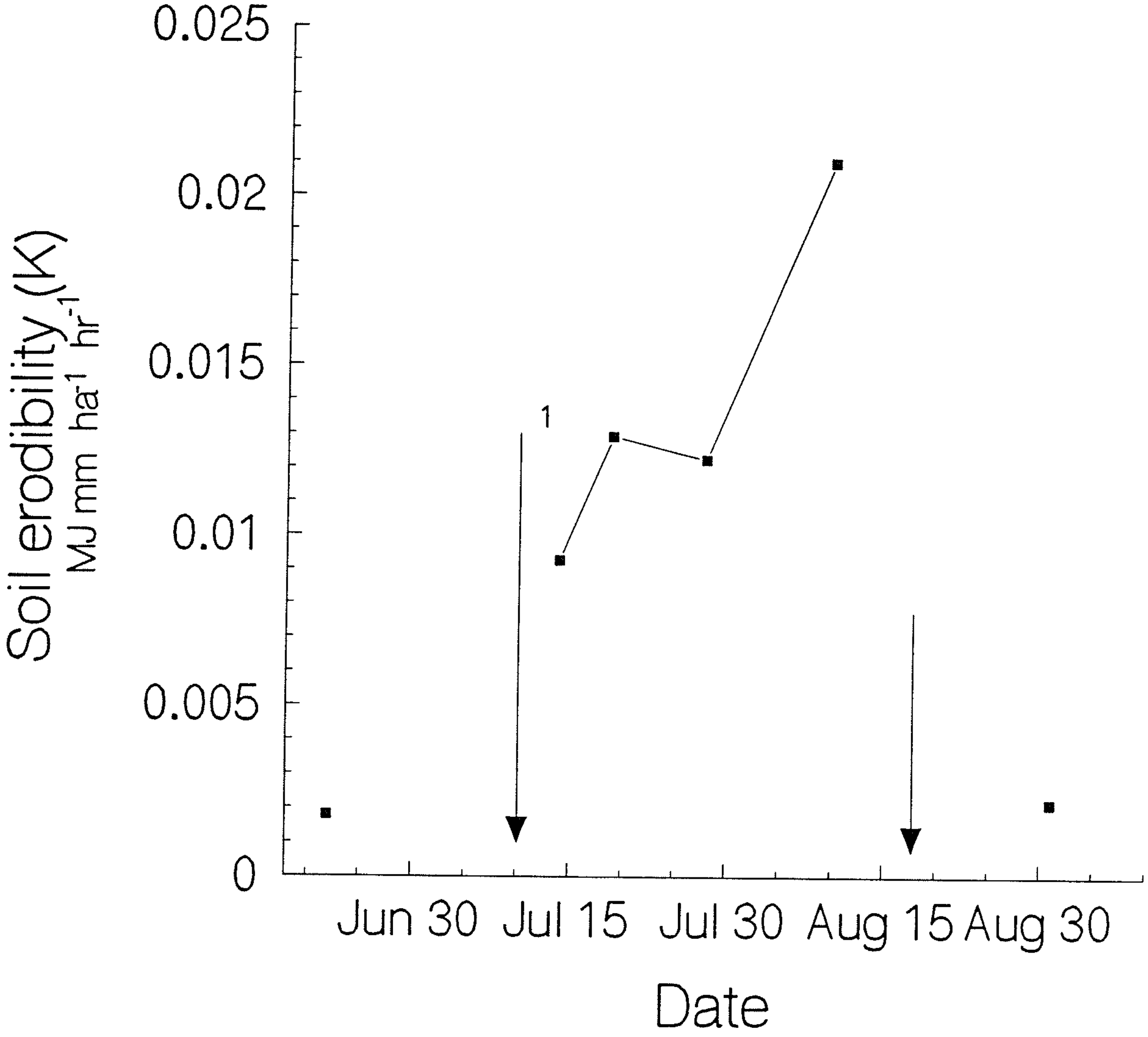


Figure 4.6 1992 Storm by storm variation in measured soil erodibility (K) for Leary sandy loam. Numbered vertical lines represent cultivation runs

cultivation. Variations in soil erodibility seemed to be a function of the combined influences of surface roughness and antecedent soil moisture levels. Interpreting the erratic trends in soil erodibility was difficult.

After a series of rainfall events, following cultivation, surface roughness will diminish and drainage efficiency across the plot will increase. The potential for erosion will be high as compared to a freshly cultivated soil surface. However, fluctuations in antecedent soil moisture levels strongly influence the capacity of the soil to absorb rainfall and produce runoff. A highly rifled plot surface that is very dry, may have a lower soil erodibility value than that same soil after a recent cultivation if soil moisture levels are high.

Soil erodibility values as calculated by the USLE represent long term average values based on 22 years of observations. The variation found in K as a result of cultivation and antecedent soil moisture levels is expected to balance out over the long term (Wischmeier and Smith 1978). This hinders research efforts aimed at validating or modifying USLE K values unless expensive long term studies are undertaken. More research is needed so that a reliable predictor of soil erodibility can be found. It should reflect the seasonal variations in soil erodibility, plus the effects of field operations and antecedent soil moisture levels. In addition validation of predicted K values for local modifications must be relatively simple and inexpensive. In the current study even after six years of soil loss measurements from the experimental plots, a reliable estimate of K could not be made due to the insufficient length of the observation period.

4.5 Rainfall/runoff erosivity (R) factor

The rainfall runoff factor in the USLE represents the combined energy available from rainfall and runoff to detach and transport soil particles from the soil mass.

Experimentally, average annual values of R can be calculated by summing up individual storm EI_{30} values for erosive storms during each year, and dividing the total by the number of years of observations. Wischmeier and Smith (1978) defined an erosive storm to be a rain event separated by at least six hours of no measurable precipitation, in which at least 12.7 mm of rain fell. Storms less than 12.7 mm were included in the calculation of R only if more than 6.4 mm fell in 15 minutes. The erosivity of a storm is determined by calculating the storms total kinetic energy and multiplying by the maximum 30 minute intensity (see section 2.3.1). Values for R are expressed a MJ mm ha^{-1} h^{-1}.

Table 4.10 compares measured yearly R values to the estimated annual average R value for Winnipeg as calculated by Wall et al. (1983). Measurements at the experimental sites were initiated in mid April and terminated in mid September. Therefore, measured values did not fully represent a complete season of rainfall. However, since relatively little rainfall was received in the early spring and late fall, measured values for R should be only slightly less than actual R values. Average annual R values measured at the Gretna clay and Leary sandy loam sites were 1267 and 966 MJ mm ha^{-1} h^{-1}, respectively. Since the experimental sites were located less than 15 km apart, it is possible to average R values from both sites, in which case the average annual measured value for R is 1117 MJ mm ha^{-1} h^{-1}. This compares favourably with the value for R as calculated by Wall et al. (1983), 1160 MJ mm ha^{-1} h^{-1}. In fact, the apparent similarity in these values may be quite significant given that Wall et al. (1983) used a very simplified method for computing R.

TABLE 4.10
Estimated and Calculated Average Annual R Values for the Experimental Sites

year	Rain fall erosivity (R)		
	Calculated		ᶻEstimated
	--------MJ mm ha^{-1} h^{-1}---------		
	Gretna	Leary	
1988	546	516	
1989	693	685	
1990	2200	1918	1160
1991	2155	1279	
1992	742	434	
	average 1267	966	

ᶻEstimated average annual R for Winnipeg (Wall et al. 1983)

4.5.1 Adequacy of R factor calculations

Occasionally storms not meeting the criteria of an erosive event as defined Wischmeier and Smith (1978) caused soil loss at the experimental sites. On the other hand, periodically, an erosive event produced no erosion. As a result, three possible scenarios exist when comparing rainfall events which caused soil losses:

1) An erosive event which resulted in soil loss.
2) An erosive event that did not result in soil loss
3) A non erosive event that did result in soil loss

Tables 4.11 and 4.12 categorize the storms in an attempt to quantify the errors associated with calculating average annual R values based on the strict criteria which define a storm as erosive or non erosive. The annual R value for 1991 at the Gretna site was 2155 MJ mm ha^{-1} h^{-1}. Two events delivering a total of 83 MJ mm ha^{-1} h^{-1} did not produce soil losses. Therefore, R was over estimated by 4.0%. One minor non erosive

TABLE 4.11
Classification of rainfall events occurring on the Gretna clay for 1991 and 1992

date	rainfall		EI$_{30}$
	depth	duration	
	mm	min	MJ mm ha^{-1} h^{-1}
	1991		
[z]Erosive events causing soil loss			
May 30	36.2	467	155
June 13	38.6	163	622
June 15	13.2	487	15
June 25	42.8	142	750
June 30	43.4	1200	163
July 01	24.0	1355	10
July 06	17.0	867	58
July 12	27.8	306	166
12-Jul	30.2	862	133
			total 2072
[z]Erosive events with no soil loss			
July 16	10.4	28	54
May 9	22.6	502	29
			total 83
[z]Non-erosive events causing soil loss			
June 26	2.4	373	2
			total 2
	1992		
[z]Erosive events causing soil loss			
June 3	13.2	50	86
June 3	0.4	32	0
June 16	16.0	168	61
June 30	31.6	3921	25
July 14	29.8	355	318
July 18	17.2	489	108
July 27	12.4	379	61
August 8	11.2	23	67
			total 648
[z]Erosive events causing soil loss			
May 27	10.4	583	18
June 17	17.2	475	76
			total 94
[z]Non-erosive events causing soil loss			
June 3	11.0	524	18
June 21	10.2	540	12
June 24	7.4	110	16
July 10	4.0	67	7
July 10	5.2	346	4
July 15	3.4	25	5
			total 62

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[z]erosive event as defined by Wischmeier and Smith (1978)

TABLE 4.12
Classification of rainfall events occurring on the Leary sandy loam for 1991 and 1992

date	rainfall		EI_{30}
	depth	duration	
	mm	min	MJ mm ha^{-1} h^{-1}
	1991		
[z]Erosive events causing soil loss			
May 30	24.4	549	64
June 13	25.4	130	162
June 25	32.0	196	268
June 30	33.0	1368	89
July 2	21.4	2338	15
July 11	37.8	284	251
July 12	30.6	912	116
			total 1265
[z]Erosive events not causing soil loss			
May 5	26.8	1471	14
			total 14
[z]Non-erosive events causing soil loss			
May 26	4.8	39	10
June 6	6.4	106	8
June 6	3.8	106	3
			total 21
1992			
[z]Erosive events causing soil loss			
June 21	17.4	674	62
June 24	11.8	103	60
July 14	24.2	391	135
July 18	8.4	495	12
August 8	8.4		34
August 29	20.6		61
			total 364
[z]Erosive events not causing soil loss			
July 4	11.8	103	60
August 9	15.8	1473	10
			total 70
[z]Non-erosive events causing soil loss			
July 26	8.8	109	25
July 27	2.0	13	2
			total 2

[z]erosive rainfall event as defined by Wischmeier and Smith

event produced soil loss, making the true R value 2074 MJ mm ha^{-1} h^{-1}. However, in 1992, the annual R value was 742 MJ mm ha^{-1} h^{-1}. From this, 94 MJ mm ha^{-1} h^{-1} was delivered in storms which did not produce soil loss, resulting in 14.5% over estimation of R. However, offsetting this, were six soil loss events which were considered to be non erosive, accounted for 62 MJ mm ha^{-1} h^{-1}. As a result the true R value was 710 MJ mm ha^{-1} h^{-1}.

In 1991 at the Leary site, total annual R was found to be 1279 MJ mm ha^{-1} h^{-1}. Since one erosive event delivered 14 MJ mm ha^{-1} h^{-1} but did not result in soil loss, R was overestimated by 1.1%. On the other hand, three non erosive events produced 21 MJ mm ha^{-1} h^{-1}, giving an actual R value of 1286 MJ mm ha^{-1} h^{-1}. In 1992, the total annual R value was 434 MJ mm ha^{-1} h^{-1}. Two storms did not produce soil loss but accounted for 70 MJ mm ha^{-1} h^{-1}. The resulting over estimation of R was 19.2%. In contrast, two non erosive events delivering 27 MJ mm ha^{-1} h^{-1} resulted in soil loss, giving an actual R value of 391 MJ mm ha^{-1} h^{-1}.

In summary, the average calculated annual R value for the 1991 and 1992 growing seasons at the Gretna clay site was 1449 MJ mm ha^{-1} h^{-1} while the true average annual R value was 1392. At the Leary site for 1991 and 1992, the measured average R value was 857 MJ mm ha^{-1} h^{-1} while the true R value was 839 MJ mm ha^{-1} h^{-1}. While it is apparent that storms which are classified as erosive some times do not cause erosion, and those which are non erosive occasionally do cause erosion, the differences tend to balance out over the long term. Therefore the criteria outlined by Wischmeier and Smith (1978) for calculating average annual R values appeared to be valid at the experimental sites.

4.6 Crop-management (C) factor

The effects of cropping and management on soil losses were accounted for by determining specific soil loss ratios for certain crop stage periods (see section 2.5.3). The C factor was derived by dividing the soil lost from the cropped treatment by the corresponding soil loss from an otherwise identical fallow treatment. The amount of soil loss will be dependent upon the crop species, the growing conditions affecting crop development and crop management strategies.

A clean tilled, continuous fallow plot represents the highest potential for erosion. Therefore, soil loss ratios are usually less than one. A value of C less than unity represents a reduction in the potential for erosion. Values for C are generally expected to be highest in the spring when crop cover is minimal, and then decrease as a function of crop growth and canopy development. Absolute values of C will be influenced by management practices such as the amount of spring residue cover, timing of tillage, harvesting operations and choice of farm implements. Since C values represent the ratio of soil lost from the cropped treatment to that which was lost from the fallow, experimentally derived C values not only reflect the crop factors, but they are also strongly influenced by condition and management of the fallow plot from which soil loss comparisons were made.

In an attempt to compare C values derived by Wischmeier and Smith (1978), Pauls (1987) and Wahome (1989) found that the experimental cropping systems were not represented adequately in the USLE data base. In addition, Pauls (1987) found it was necessary to modify the crop growth stages defined by the USLE to account for a winter period (see section 3.2.4). To further complicate a direct comparison, crop stage periods are identified on the basis of canopy cover. Measurements carried out over the course of this study, lumped crop canopy and mulch cover estimates. Unfortunately this rendered a comparison between USLE C factor values and experimentally derived C factor values impossible.

4.6.1 Crop growth

Crop growth and development was monitored weekly throughout the growing season. Crop canopy and mulch cover measurements were obtained using a modified point line method and are summarized in Figures 4.7, 4.8, 4.9 and 4.10. Crop growth and plant density were greater at the Leary sandy loam site. Severe surface crusts often formed on the Gretna clay, thus hindering germination. Surface crust were particularly troublesome at this site in the corn plot. Consequently, the corn crops growing on the Gretna clay were poor and large bare patches were evident throughout the plot. Late in the fall at the Leary sandy loam, as crops neared maturity, corn plots became subject wildlife predation. Thus, cropping systems were poorly represented once this occurred. Corn plants were often found broken and chewed. This lead to artificially high cover counts. The wheat plot near maturity would become flattened, likely due to deer bedding down in the plot and feeding on the grain. This made harvesting and residue removal difficult, and also affected plot surface conditions after harvesting up until fall cultivation. Alfalfa plots were well established and growth was rapid. Thick mulch layers were evident at both sites and hence cover counts were high, even after harvesting. Consequently, no soil erosion was detected for the 1991 and 1992 growing seasons.

4.6.2 Soil loss ratios

Soil loss ratios for the cropping treatments are summarized in Tables 4.13 and 4.14. Since the soil loss ratios reflect the relative rates of soil loss from the cropped treatments, trends are similar to those of actual soil losses from each treatment. Section

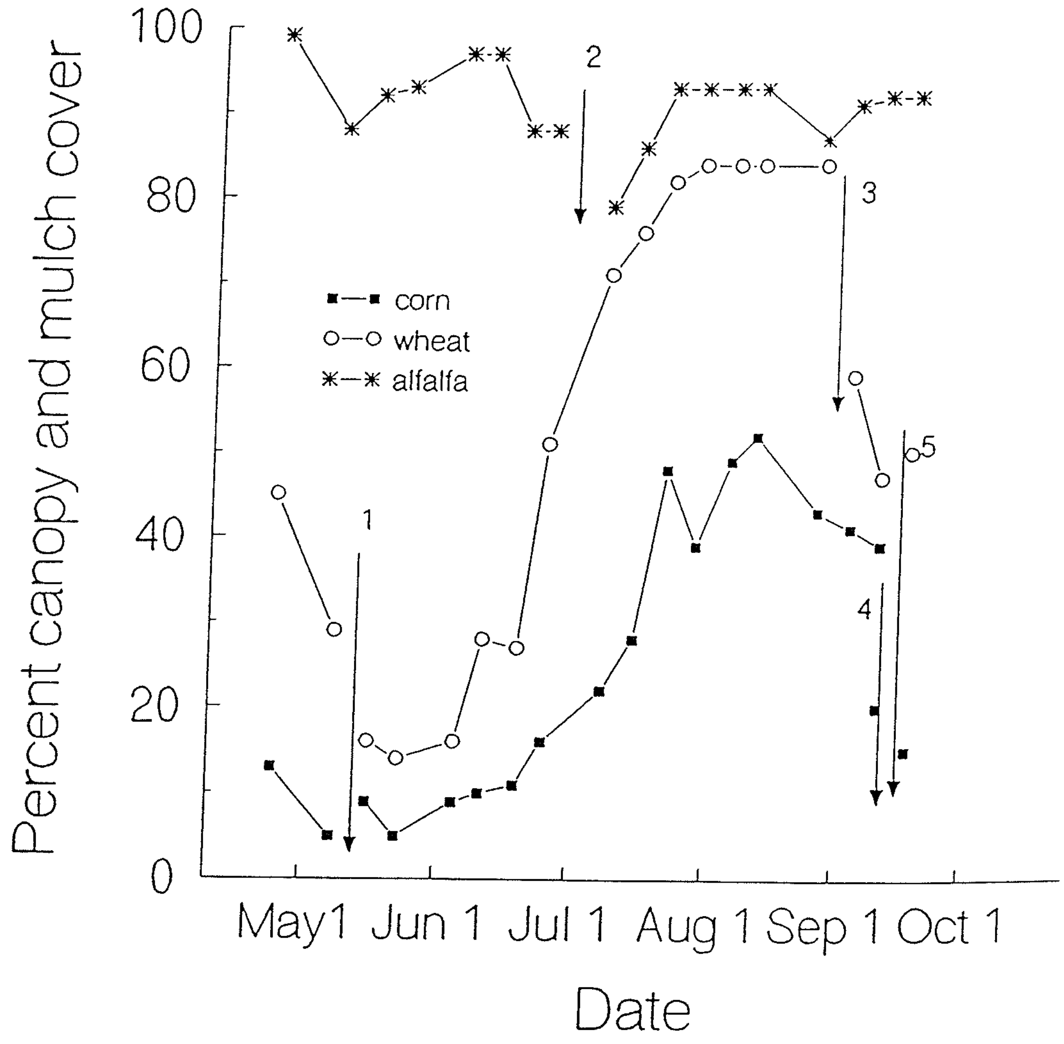

Figure 4.7 1991 crop canopy and mulch cover measurements for the Gretna clay Numbered vertical lines represent timing of various field operations: 1 seeding; 2 cut alfalfa; 3 harvested wheat; 4 harvested corn; 5 fall tillage

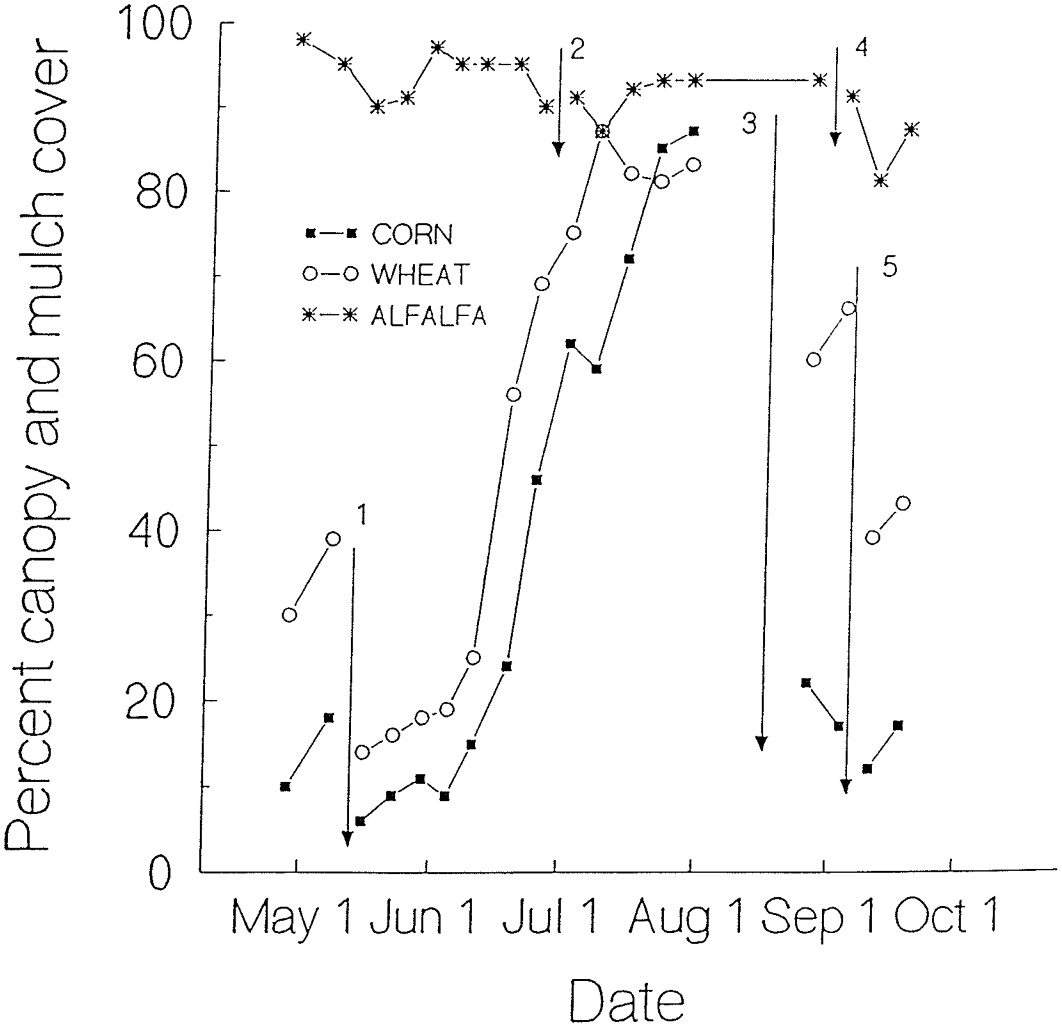

Figure 4.8 1991 crop canopy and mulch cover measurements for the Leary sandy loam. Numbered vertical lines represent timing of various field operations: 1 seeding; 2 cut alfalfa; 3 harvested wheat and corn; 4 cut alfalfa; 5 fall tillage

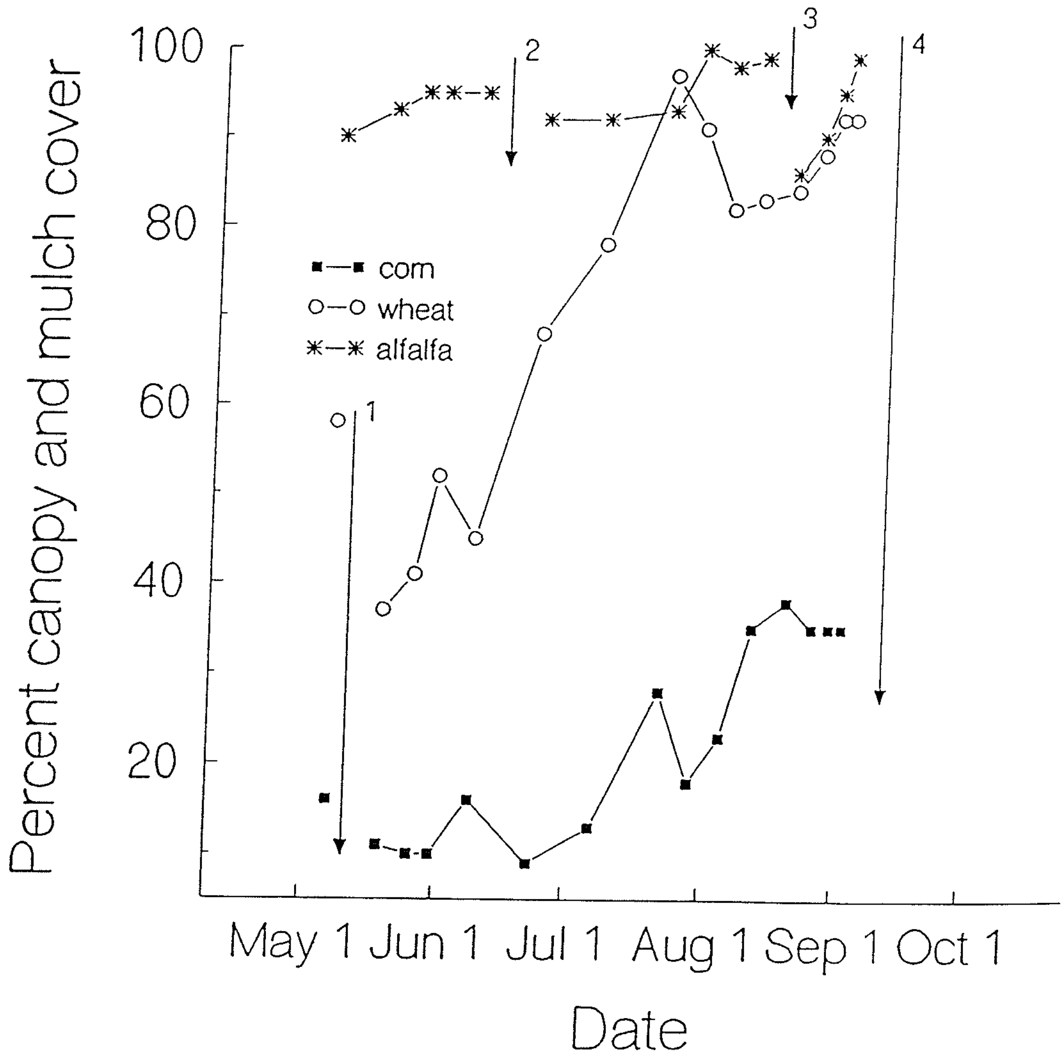

Figure 4.9 1992 crop canopy and mulch cover measurements for Gretna clay. Numbered vertical lines represent timing of various field operations: 1 seeding; 2 cut alfalfa; 3 cut alfalfa; 4 harvested wheat and corn and performed fall tillage

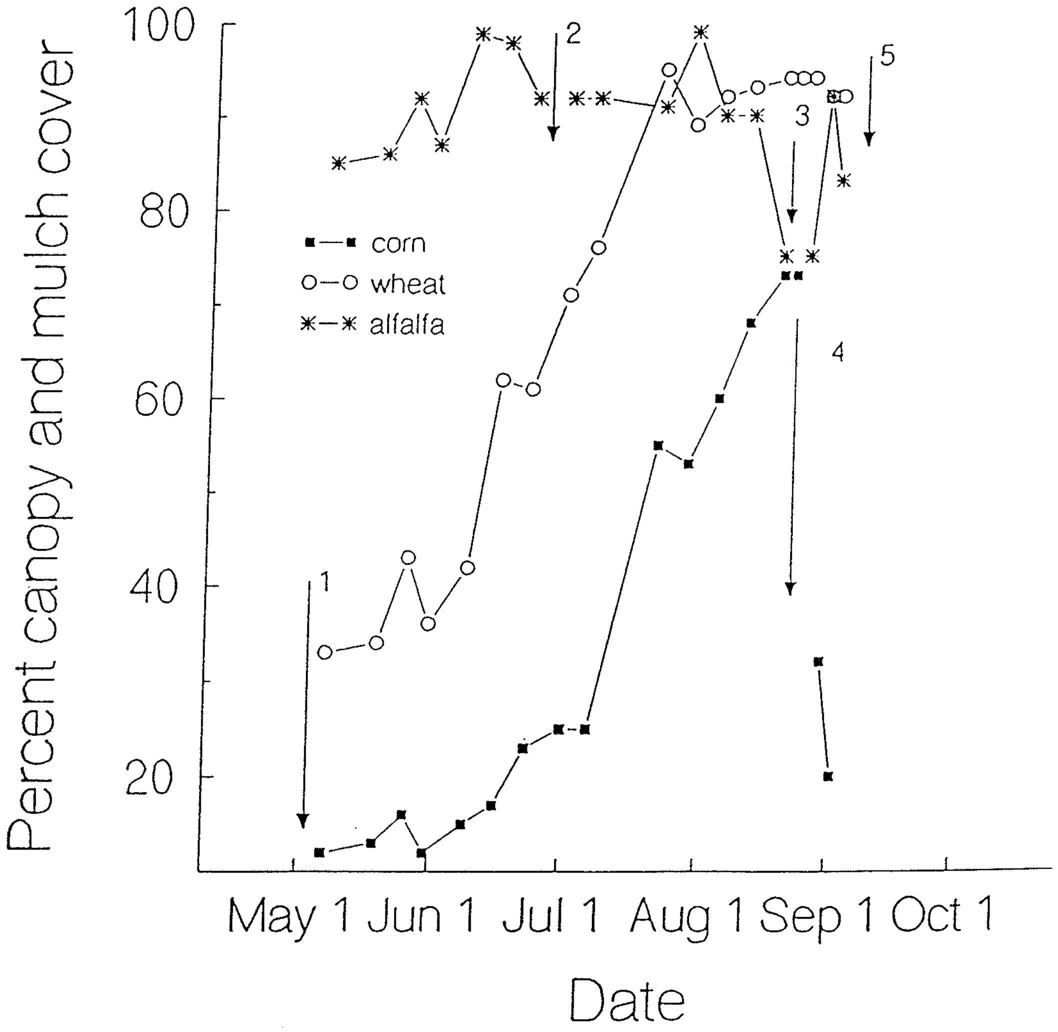

Figure 4.10 1992 crop canopy and mulch cover measurements for Leary sandy loam. Numbered vertical lines represent timing of various field operations: 1 seeding; 2 cut alfalfa; 3 cut alfalfa 4 harvested corn; 5 harvested wheat and performed fall tillage

TABLE 4.13
Measured Soil Loss Ratios from Gretna Clay for 1991 and 1992

Date	Rain	Measured Soil Loss Ratios		
		Corn	Wheat	Alfalfa
	mm			
1991 May 15 seeding operations				
1991 May 30	36.2	1.00	1.71	0.00
1991 May 15	13.2	0.64	0.27	0.00
1991 May 20 cultivated fallow and corn				
1991 May 25	45.2	1.42	0.31	0.00
1991 May 30	43.4	1.12	0.16	0.00
1991 June 1	11.7	0.49	0.11	0.00
1991 June 2	12.6	0.40	0.07	0.00
1991 June 6	17.0	0.79	0.16	0.00
1991 June 12	58.0	0.88	0.21	0.00
yearly average		1.05	0.21	0.00
1992 May 20 seeding operations				
1992 June 3	24.6	1.09	1.28	0.00
1992 June 16	16.0	0.88	0.44	0.00
1992 June 21	10.2	0.78	0.44	0.00
1992 June 24	7.4	0.45	0.14	0.00
1992 June 30	31.6	0.00	0.00	0.00
1992 July 10	9.2	0.00	0.00	0.00
1992 July 10 cultivated fallow and corn				
1992 July 14	29.8	0.76	0.004	0.00
1992 July 15	3.4	0.44	0.00	0.00
1992 July 18	17.2	[z]0.21	0.005	0.00
1992 July 27	12.4	[z]0.00	0.00	0.00
1992 August 8	11.2	0.43	0.00	0.00
yearly average		0.67	0.06	0.00

[z] sampling system error

TABLE 4.14
Measured Soil Loss Ratios from Leary Sandy Loam for 1991 and 1992

Date	Rain	Measured Soil Loss Ratios		
		Corn	Wheat	Alfalfa
	mm			
1991 May 15 seeding operations				
1991 May 30	24.4	0.70	0.47	0.00
1991 June 13	25.4	0.59	0.52	0.00
1991 June 20 cultivated fallow and corn				
1991 June 25	36.8	[z]0.00	1.86	0.00
1991 June 30	33	[z]0.00	0.77	0.00
1991 July 02	21.4	0.00	0.00	0.00
1991 July 06	10.2	0.00	0.00	0.00
1991 July 12	68.4	[z]0.00	0.39	0.00
yearly average		0.60	0.52	0.00
1992 May 20 seeding operations				
1992 May 21	17.4	[z]0.00	2.0	0.00
1992 June 10 cultivated fallow and corn				
1992 June 14	24.2	0.27	0.36	0.00
1992 June 18	8.4	0.33	0.20	0.00
1992 June 27	10.8	0.33	0.18	0.00
1992 August 8	8.4	0.22	0.03	0.00
1992 August 13 cultivated fallow				
1992 August 29	20.6	0.38	0.08	0.00
yearly average		0.28	0.22	0.00

[z] sampling system error

4.3 details the factors which influence soil losses from the treatments and compares soil losses among the treatments. Thus to eliminate redundancy, the reader is referred to section 4.3 and its subsections.

In general, soil loss ratios were greater than unity for the corn and wheat following seeding operations. This reflected differences in surface roughness across the plots, i.e. fallow was rougher than corn, followed by wheat, then alfalfa. (see section 4.3.2). Thus, following seeding, corn and wheat were more susceptible to erosion than the fallow plot. Wheat was the most sensitive plot at this time of year. Following seeding, soil loss ratios generally declined with time. This trend was broken each time the fallow plot was cultivated. Prior to cultivation, soil loss ratios were low, following cultivation ratios dramatically increased then gradually declined over successive events. Cultivation of the fallow plot resulted in rill destruction and produced a very rough surface. Thus, fallow temporarily became less prone to erosion and soil loss ratios were temporarily depressed. However, as the fallow plot began to lose its surface roughness following successive rainfall events, and rilling progressed, soil loss ratios declined. This was due to a combination of an increase in the tendency of the fallow plot to erode and from the decreased tendency for the cropped treatments to erode as canopy development progressed. Soil loss ratios were at a minimum late in the season when crop canopies were well developed.

Since soil loss ratios were dependent upon the fallow plot, time of year and crop growth and development, yearly averages were highly variable and were dependent upon when an erosive storm occurred. Thus, if a particulary erosive event occurred early in the spring, or immediately after cultivation, soil losses from the corn or wheat would tend to be very high and yearly average C values would remain high. In 1991 on the Gretna clay, the yearly average C value for corn was 1.05 which suggests a field in corn was more likely to erode than a similar fallow field. Upon examining the soil loss ratios for individual storms through the year, it was evident that of eight storms, only two produced soil loss ratios in excess of one. Both storms occurred after cultivation on May 25 and May 30 and resulted in soil loss ratios of 1.42 and 1.12, respectively. Five events produced soil loss ratios ranging from 0.40 to 0.88, two being below 0.50. By chance, the events occurring in late May of 1991 were large and had occurred immediately following cultivation of the fallow plot, and caused significant soil losses on the corn plot. When soil loss ratios were much lower, the corresponding events, by chance, were small. As a result, the corresponding decrease in erosion was not adequately represented in the yearly total erosion and hence the C value appeared high.

The importance of long term observations cannot be over emphasized when attempting to derive appropriate C values for use in soil loss modelling. Wischmeier and Smith (1978) used over 10,000 plot years of data to characterize C values for a number of cropping and management systems. Like the other the USLE factor values, at least 22 years of data must be collected to adequately characterize the average C values. By using an extended period of observation, random variations in storm timing relative to antecedent plot conditions tend to balance out.

4.7 Relationship of soil loss to soil, weather and management variables

The USLE was designed to measure long term average annual soil losses from natural rainfall, due to sheet and rill erosion . It was not designed to predict soil losses accurately on a storm by storm basis nor, even yearly soil losses. The model is based on a 22 year climactic cycle and thus needs at least 22 years of data to balance out random variations in storm by storm soil losses (See section 2.5.2 pp 38-39). The shortness of this study precludes the possibility of accurately and confidently defining any of the USLE factor values. The following is an attempt to improve USLE soil loss predictions using the existing data base generated over the last five years.

4.7.1 Soil loss variability from fallow

Average annual soil losses (A) from the fallow treatment should be equal to the product of soil erodibility (K) and the rainfall erosivity index (R). Thus USLE predicts soil loss from the fallow treatment is $A = K*R$. Since K is a fixed value for any given soil, then soil loss (A) is a function of the rainfall erosivity index (R). Since R is the average annual sum of the individual storm erosivity index, (EI_{30}) values, and A is the average annual soil loss resulting from individual storms, it follows that individual storm soil losses must be highly correlated to individual storm EI_{30} values.

Linear regression using storm energy (EI_{30}) as the independent variable and soil loss from the fallow plot (A) as the dependent variable from individual storms, yielded the following equations for the two experimental sites:

$A = 0.0598{*}EI_{30} + 1.063 \quad R^2 = 0.46$ Gretna clay

$A = 0.0139{*}EI_{30} + 0.7288 \quad R^2 = 0.21$ Leary sandy loam

Soil erodibility from the fallow was observed to be highly variable. Therefore, the basic assumption that A depends only upon R does not hold, i.e. soil loss from the fallow seemed to be influenced by cultivation, rill development, and antecedent soil moisture conditions. The low R^2 values indicated that when used alone, the EI_{30} value was a poor predictor of soil loss. This was likely due to the short period of observation at the experimental sites. Average annual soil losses represent expected rates of soil loss on an annual basis averaged over 22 years. The data base from which these regressions was derived spanned a total of 5 years of observations. It is also possible that the USLE may not be valid for Canadian conditions and the poor correlation is due to the fact that the experimental sites are located outside the area in which the USLE was developed.

In an attempt to account for the short observation period and to improve upon soil loss predictions from the fallow, correlations between 11 independent variables and the dependent variable, fallow soil loss were calculated. The objective was to determine the relationship between fallow soil losses and cultivation, rainfall energy times intensity relationships, and antecedent soil moisture content. Table 4.15 and 4.16 summarize the coefficient of determination values between each of measured variables and soil loss from the fallow treatment.

TABLE 4-15

Coefficients of Determination (R^2) Values of Variables Used in Determining Soil Losses From Fallow for Gretna Clay

	Rain	Crai	K.E.	CK.E	EI_{30}	EI_{20}	EI_{15}	EI_{10}	EI_5	Mcap	Meros
	mm		MJ			MJ mm ha^{-1} h^{-1}				%	
Crai	0.05										
K.E.	0.91	0.08									
CK.E.	0.04	0.96	0.07								
EI_{30}	0.61	0.12	0.80	0.12							
EI_{20}	0.71	0.05	0.85	0.05	0.88						
EI_{15}	0.64	0.11	0.79	0.11	0.96	0.88					
EI_{10}	0.64	0.10	0.77	0.10	0.92	0.86	1.00				
EI_5	0.64	0.10	0.73	0.10	0.86	0.83	0.96	0.98			
Mcap	0.01	0.12	0.05	0.12	0.07	0.04	0.03	0.02	0.01		
Meros	0.35	0.16	0.54	0.16	0.79	0.59	0.62	0.58	0.50	0.27	
Flw	**0.25**	**0.01**	**0.36**	**0.02**	**0.46**	**0.45**	**0.44**	**0.38**	**0.32**	**0.00**	**0.21**

All variables correspond to measurements taken for individual soil loss events.
Rain = Depth of rainfall: Crai = cumulative rainfall since last cultivation: K.E. = kinetic energy of erosive rainfall: CK.E. = cumulative K.E. since last cultivation: EI_X = product of the storms kinetic energy times the maximum intensity received during X minutes: Mcap = moisture capacity: Meros = modified erosivity index: Flw = soil loss from the fallow plot (t ha^{-1})

TABLE 4.16
Coefficients of determination (R^2) Values for Variables Used in Determining Soil Losses From Fallow for Leary Sandy Loam

	Rain	Crai	K.E.	CK.E	EI_{30}	EI_{20}	EI_{15}	EI_{10}	EI_5	Mcap	Meros
	mm		MJ			MJ mm ha^{-1} h^{-1}				%	
Crai	0.00										
K.E	0.92	0.00									
CK.E.	0.00	0.94	0.00								
EI_{30}	0.62	0.02	0.83	0.02							
EI_{20}	0.58	0.01	0.79	0.01	0.98						
EI_{15}	0.56	0.02	0.77	0.02	0.96	0.98					
EI_{10}	0.55	0.03	0.77	0.03	0.94	0.96	0.98				
EI_5	0.53	0.02	0.74	0.02	0.88	0.90	0.94	0.96			
Mcap	0.06	0.14	0.10	0.12	0.09	0.10	0.10	0.13	0.15		
Meros	0.62	0.03	0.81	0.03	0.98	0.96	0.95	0.94	0.90	0.12	
Flw	**0.09**	**0.07**	**0.18**	**0.14**	**0.21**	**0.27**	**0.21**	**0.18**	**0.21**	**0.03**	**0.18**

Variable definitions are the same as in table 4.12

Field observations revealed that following cultivation, fallow surface characteristics changed with successive rainfall events and the soil becomes progressively more erodible. Therefore, the cumulative rainfall since last cultivation (Crai) and the cumulative kinetic energy since last cultivation (CK.E.) were chosen as indicators of changing soil surface morphology with successive rainfall events.

Wischmeier and Smith (1958) found that the best single variable for predicting soil loss was the EI_{30} parameter. Elwell and Stocking (1975) found the EI_{15} parameter to be most useful. Since storms in the study area were found to occasionally produce very large quantities of rainfall in short time periods (see section 4.2.3), a number of EI_X parameters were tested: EI_{30}, EI_{20}, EI_{15}, EI_{10}, and EI_5.

Antecedent soil moisture levels were monitored weekly. Field data was collected and expressed as a gravimetric water content. From this, the moisture capacity (Mcap) variable was calculated. Mcap represents the proportion of pore space not filled with water prior to the erosive storm. It is calculated as follows:

$$Mcap = (S - M)*Bd$$

Where:

S = saturation moisture content. (% by weight)
M = gravimetric water content in the top 7.5 cm of the soil profile
Bd = the average bulk density of the soil for the experimental site.

Saturation moisture content (S) was calculated from soil physical property data as described by Shaykewich et al. (1991), Appendix A.

A new variable called the modified erosivity index (Meros) was introduced by Shaykewich et al. (1991) in an attempt to account for the effects of antecedent soil moisture levels within the USLE EI_{30} variable.

$Meros = Mcap * EI_{30}$

The coefficients of determination between soil loss and all variables tested were poor. Therefore, no single variable was a very good predictor of soil loss. Significantly, however, the EI_{30} and EI_{20} were the best single predictors of soil loss for the Gretna clay and Leary sandy loam sites, respectively. This suggests the USLE R values may be a good predictors of soil loss if enough data was collected

Three groups of inter-dependent variables exist within the 11 measured variables: 1) Rainfall energy is represented by the factors EI_{30}, EI_{20}, EI_{15}, EI_{10}, and EI_5; 2) surface roughness prior to an erosive event is related to Crai and CK.E.; 3) antecedent soil moisture is represented by Mcap. Since Meros is a product of the EI_{30} and Mcap, it was highly correlated to these variables, and therefore left out of the multiple regression analysis because R^2 values for this variable were low. From each of the three groups, the variable which best described soil loss from fallow was used in a series of successive multiple regressions to determine the improvement of soil loss prediction capability for each site. For the Gretna clay, successive regressions yielded the following equations:

$A = 1.063 + 0.0598*EI_{30}$ $\quad R^2 = 0.46$

$A= -9.626 + 0.0710*EI_{30} + 0.6186*\ CK.E.$ $\quad R^2 = 0.57$

$A = -2.520 + 0.0741\ EI_{30} + 0.5342*CK.E. - 0.4717*Mcap$ $\quad R^2 = 0.59$

Regression on Leary sandy loam yielded:

$A = 0.3716 + 0.0128EI_{20}$ $\quad R^2 = 0.27$

$A = 0.4717 + 0.0141*EI_{20} + 0.1946*CK.E.$ $\quad R^2 = 0.47$

$A = 0.2248 + 0.0125*EI_{20} + 0.2248*CK.E. + 0.02444*Mcap$ $\quad R^2 = 0.51$

Coefficients of determination are poor for all regressions attempted. More research is needed in order to better understand the factors which affect soil losses. However important trends do exist which may help to direct future research. Soil loss predictions on the Gretna clay were best when using the EI_{30} value. At the Leary sandy loam, the EI_{20} value was better. More work must be done so that an appropriate value for I_X may be determined for the study area.

By adding the CK.E. term to the regression, R^2 values were improved for both sites. This suggest that soil surface morphology is important factor governing soil losses, However, using cumulative kinetic energy since last cultivation (CK.E.) may not adequately describe changes to the soil surface. More research should be done so that the effects of changing soil surface morphology can be quantified.

Prediction capability of the models for both sites was only slightly improved using Mcap. This does not necessarily prove that antecedent soil moisture in not important in governing soil losses. The poor results using Mcap can be attributed to the fact that soil moisture data was collected on a weekly basis at the erosion sites. These measurements were intended to provide an estimate of the soil moisture content prior to a given rainfall erosion event. Unfortunately, small non-erosive rainfall events often occurred between the time that soil moisture sampling was performed and the time that an erosive rainfall events took place elevating soil moisture levels. Sometimes actual antecedent soil moisture levels were much lower than at the time of sampling. This occurred when hot weather and/or a few days occurred between sampling times and erosive rainfall events. In order to accurately gauge soil moisture levels prior to a given event, it would be necessary to take more frequent measurements of soil moisture or develop a model which predicts fluctuations in soil moisture levels based on frequent sampling times, variations in daily temperature, wind and precipitation.

4.7.2 Variability in soil erodibility.

Soil erodibility (K) was observed to be highly variable between storms. Field observations suggest that this was due to the effects of antecedent soil moisture levels and plot surface conditions. Multiple linear regressions of K verses Mcap and CK.E. yielded the following equations for Gretna clay:

$K = 0.0220 + 0.0039*CK.E.$ $R^2 = 0.21$

$K = 0.1807 - 0.0074*Mcap$ $R^2 = 0.33$

$K = 0.1197 + 0.0026*CK.E. - 0.0058*Mcap$ $R^2 = 0.38$

and for the Leary sandy loam:

$K = 0.0057 + 0.0012*CK.E.$ $R^2 = 0.33$

$K = 0.0089 + 0.00031*Mcap$ $R^2 = 0.00$

$K = - 0.0468 + 0.0014*CK.E. + 0.0018*Mcap$ $R^2 = 0.43$

This analysis produced poor results. However, CK.E. does explain 21 and 33% of the variation in observed K values on the Gretna clay and Leary sandy loam sites, respectively. Antecedent soil moisture influenced K values on the Gretna clay but not on the Leary sandy loam. The Leary soil was not statistically significantly affected by antecedent soil moisture levels, probably because the soil profile drained faster than the Gretna clay. Therefore, antecedent soil moisture levels were often relatively low at this site.

Due to problems associated with weekly moisture measurements at the sites, the significance of antecedent soil moisture levels may be masked by the poor data set. Multiple regressions using CK.E. and Mcap explained 38 and 43% of the observed variation in measured K values for the Gretna and Leary sandy loam sites, respectively.

The need for further research into the effects of soil surface conditions and soil moisture levels at the time of a soil loss event are needed to help quantify soil losses. In addition, improved methods of evaluating antecedent soil surface and soil moisture conditions are needed in order for more accurate models may be constructed.

5. SUMMARY AND CONCLUSIONS

Visual analysis of the data sets generated during the 1991 and 1992 growing seasons revealed clear trends in individual storm soil losses, soil erodibility and soil loss ratios between the treatments. These visual trends were repeated between successive cultivations and were influenced by cultivation, surface drainage characteristics, soil moisture levels and crop growth and development. The existence of consistent trends in the data sets suggests that modelling of the soil erosion process may be quite possible on a storm by storm basis.

By using the USLE as a base from which to understand the erosion process, an attempt was made to improve upon the short term prediction capabilities of the USLE. Individual storm soil losses, soil erodibility values and soil loss ratios were highly variable. Each was influenced by soil surface morphology and antecedent soil moisture levels.

Although, multiple regression analysis explained less than 60% of the observed variation in soil losses and less than 50% of the variation in measured soil erodibility, the analysis showed that variables related to soil surface morphology and antecedent soil moisture levels improved the prediction capability of the regression models. The variables in this study poorly described the changes in soil surface morphology and antecedent soil moisture levels. Better results may have been obtained through the use of parameters which more precisely characterized rainfall, soil surface morphology and antecedent soil moisture levels

Future research should focus on developing rain recording systems which are capable of measuring high intensity surges in violent storms. In addition, techniques capable of measuring soil roughness and drainage efficiency across the plots should be developed. This may be accomplished by developing a clod size index based on the number and size of clods. Drainage efficiency may be better quantified by measuring rill patterns and/or rill density. Micro relief measurements to characterize the surface of the plot may also be useful. Antecedent soil moisture levels need to reflect changes in soil water content between sampling dates and soil loss events. This may be accomplished by using evapotranspiration models for the cropped treatments and a soil evaporation model for the fallow treatment. Parameters measured at the experimental sites should be designed so as to minimize sampling disturbances to the soil surface.

Future attempts at developing new soil loss models or revising the USLE should focus on parameters which are easily measured. It is also imperative that soil loss models be developed using relatively short periods of observations so that model validation or improvements can be accomplished in reasonable time frames. Not only should a soil erosion model be capable of predicting soil losses but it should also include a soil renewal component based on soil specific pedogenic processes. In other words, the model should answer two questions, 1) how much soil is being lost, 2) and how fast is it being regenerated. Such a model would make cropping and management recommendations more compatible with sustainable resource management goals.

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Appendix A Physical Characteristics of Surface Soil at Soil Erosion Sites

Soil type	Particle Size Analysis			Particle Density	Organic Matter	Bulk Density	[z]Saturation	[z]Field Capacity	[*]Permanent Wilting
	sand	silt	clay						
	%			Mg m^{-3}	%	Mg m^{-3}	%		
Gretna clay	23.0	28.6	50.4	2.64	4.3	1.45	33.57	26.19	18.78
Leary sandy loam	74.5	14.5	11.1	2.62	0.9	1.55	28.67	11.40	5.34

[z] Moisture contents expressed as percentage of dry mass of soil. Saturation percentage calculated from bulk and particle densities. Field capacity and permanent wilting point determined by standard methods.

(source: Shaykewich et al. 1991)

Appendix B Rainfall Erosion Event Characteristics and Soil Losses for Gretna Clay 1988-1992

Date	Rain	Cumulative		Kinetic Energy	Rainfall Erosivity Index					Soil Losses			
		Rain	Kinetic Energy		EI_{30}	EI_{20}	EI_{15}	EI_{10}	EI_5	Fallow	Corn	Wheat	Alfalfa
month/ day	——mm——		———MJ———		————MJ mm ha^{-1} h^{-1}————					————t ha^{-1}————			
1988													
05/07	22.4	–	–	4.23	44.0	50.8	67.7	96.4	142.1	1.49	0.26	0.70	0.00
07/05	17.1	3.8	0.54	3.85	58.5	83.2	107.8	157.1	231.0	0.07	0.06	0.01	0.01
07/06	21.3	27.0	5.90	6.08	270.0	342.9	398.8	437.8	481.5	13.90	10.27	10.76	0.08
09/11	40.6	0.2	0.04	7.30	125.6	118.3	140.2	175.2	245.3	0.09	0.13	0.05	0.01
1989													
06/12	43.3	–	–	7.29	64.2	74.4	75.8	78.7	87.5	0.16	0.15	0.13	0.00
08/03	23.8	0.8	0.12	6.90	314.6	472.0	618.2	819.7	5547.6	5.98	0.57	0.57	0.00
08/25	10.8	18.4	3.67	2.64	40.1	60.2	73.9	82.4	107.7	0.00	0.25	0.00	0.00
09/10	60.4	41.8	8.85	10.36	66.3	68.4	68.4	74.6	124.3	5.97	0.14	0.13	0.00
1990													
05/14	38.2	–	–	5.96	45.3	50.1	52.5	57.2	57.2	0.06	0.06	0.04	0.00
05/20	16.2	–	–	3.70	48.8	71.0	91.8	119.9	124.3	11.50	7.91	0.77	0.00
05/30	86.0	0.0	0.00	17.67	1018.4	1527.3	2021.5	3032.8	5980.4	51.31	98.88	21.33	0.31
06/08	20.8	91.0	18.48	3.02	18.1	19.9	19.9	21.7	29.0	0.30	0.72	0.07	0.00
06/11	32.8	114.0	21.99	8.83	522.7	720.5	805.3	964.2	1356.5	100.29	58.60	67.80	0.42
06/17	18.6	128.6	33.53	3.90	54.1	77.2	95.4	123.8	173.4	6.84	8.24	0.91	0.00
06/19	18.4	147.2	37.43	3.68	31.2	38.7	47.1	60.9	76.2	9.37	8.54	5.30	0.00
07/02	28.2	168.2	41.52	6.83	139.0	185.9	232.2	308.8	407.3	13.94	4.83	0.64	0.00
07/06	15.0	7.8	1.43	3.57	87.1	124.2	148.5	167.1	179.9	0.28	3.51	4.99	0.00
08/22	22.8	2.6	0.32	5.74	211.2	254.9	266.3	310.0	427.1	0.03	0.25	0.00	0.00
1991													
05/30	36.2	23.4	4.90	7.72	154.4	199.2	247.0	277.9	315.0	0.07	0.07	0.12	0.00
06/13	38.6	67.2	14.01	10.23	622.0	914.6	1187.0	1731.6	3118.2	>12.00	22.14	>3.35	0.00
06/15	13.2	105.8	24.24	2.26	14.5	17.6	19.9	21.7	27.1	1.10	0.70	0.30	0.00
06/25	45.2	0.6	0.07	11.64	751.1	883.8	962.9	1269.0	2215.0	20.60	29.33	6.36	0.00
06/30	43.4	45.8	11.71	8.50	163.2	227.0	265.2	323.0	510.2	30.36	34.12	5.01	0.00
07/01	11.7	89.0	20.20	1.78	7.1	8.0	10.2	9.6	17.1	3.14	1.54	0.34	0.00
07/02	12.6	101.6	21.98	1.58	3.0	3.6	4.4	6.6	13.3	1.08	0.44	0.08	0.00
07/06	17.0	113.5	23.57	3.88	57.8	11.6	104.0	128.6	157.1	11.13	8.80	1.82	0.00
07/12	58.0	130.5	27.45	11.92	220.1	272.4	314.5	383.7	477.5	23.50	20.60	4.05	0.00
1992													
06/03	24.6	19.4	5.85	3.41	104.6	146.6	187.3	248.0	327.3	0.42	0.46	0.54	0.00
06/16	16.0	44.6	3.40	9.33	61.2	69.4	76.2	89.8	130.6	0.16	0.14	0.07	0.00
06/21	10.2	77.8	1.81	16.33	12.3	13.0	15.9	19.5	26.1	0.09	0.07	0.04	0.00
06/24	7.4	90.8	1.58	18.66	16.4	17.1	21.5	30.3	45.5	0.36	0.16	0.05	0.00
06/30	31.6	111.0	3.92	20.24	25.1	28.2	31.4	37.6	56.4	0.80	0.00	0.00	0.00
07/10	9.2	143.0	1.77	24.27	10.8	15.3	19.0	25.4	33.3	0.07	0.00	0.00	0.00
07/14	29.8	0.0	7.73	0.00	318.5	463.8	599.8	853.4	1539.8	9.25	7.02	0.04	0.00
07/15	3.4	29.8	0.75	7.73	5.1	7.2	9.6	11.7	18.0	0.93	0.41	0.00	0.00
07/18	17.2	37.2	4.08	9.16	107.7	149.3	186.0	259.5	479.8	14.17	>3.00	0.07	0.00
07/27	12.4	55.4	2.97	13.48	60.6	85.5	104.5	131.9	171.1	0.77	error	0.00	0.00
08/08	11.2	69.6	2.98	16.71	66.8	98.3	124.0	164.5	221.7	0.43	0.13	0.00	0.00

Appendix B.1 Rainfall Erosion Event Characteristics and Soil Losses for Leary Sandy Loam 1988-1992

Date	Rain	Cumulative		Kinetic Energy	Rainfall Erosivity Index					Soil Losses			
		Rain	Kinetic Energy		EI_{30}	EI_{20}	EI_{15}	EI_{10}	EI_5	Fallow	Corn	Wheat	Alfalfa
month\ day	---mm---		------MJ------		------------MJ mm ha^{-1} h^{-1}------------					------------t ha^{-1}------------			
							1988						
06/01	26.6	–	–	6.76	181.2	198.8	238.0	292.2	503.1	0.19	0.45	0.46	0.00
07/05	21.5	2.4	0.35	4.99	91.9	125.9	163.8	239.7	287.7	0.06	0.09	0.52	0.00
07/12	28.8	30.8	6.72	6.91	243.2	240.5	265.3	315.1	398.0	3.70	0.73	0.72	0.00
							1989						
07/14	7.4	0.0	0.00	1.90	28.1	41.0	53.1	72.9	104.8	0.05	0.04	0.08	0.02
08/03	37.2	12.4	2.85	10.00	396.0	528.1	656.1	744.1	888.1	4.27	1.38	0.45	0.12
08/17	21.4	0.0	0.00	5.10	71.2	104.1	130.7	163.6	210.3	0.49	0.37	0.21	0.00
09/10	45.2	42.1	9.02	7.48	41.9	44.9	47.9	53.9	71.8	0.49	0.12	0.03	0.00
							1990						
06/01	76.4	0.0	0.00	14.92	532.6	600.7	722.1	884.2	1136.9	0.45	5.62	2.71	0.03
06/08	30.4	77.8	15.14	5.04	62.5	84.7	100.8	114.9	121.0	0.47	4.21	0.91	0.00
06/11	12.6	108.2	20.18	3.17	44.3	61.2	79.9	114.6	179.9	1.07	8.86	3.34	0.00
06/18	36.6	112.2	20.64	8.08	210.1	278.8	315.0	371.9	522.4	6.10	2.11	0.65	0.00
06/19	11.6	148.8	28.72	3.04	68.1	100.3	126.4	171.4	233.4	4.15	32.81	9.62	0.00
07/02	33.2	168.2	32.92	8.21	238.2	308.5	375.6	425.9	587.7	5.89	error	14.11	0.00
07/06	28.0	0.0	0.00	7.33	343.0	435.4	439.8	466.2	492.5	7.51	error	16.19	0.00
07/28	14.4	34.0	12.45	3.81	97.6	144.1	189.0	224.1	301.8	2.39	4.39	2.90	0.00
08/01	25.8	48.4	19.16	6.71	198.6	293.8	300.5	362.2	579.6	17.94	8.20	6.22	0.00
08/22	15.8	0.2	0.04	3.75	94.4	125.9	143.9	188.9	242.9	0.00	1.70	1.32	0.00
09/17	20.4	25.4	5.51	3.61	28.9	36.8	43.3	52.0	60.7	0.00	0.11	0.06	0.00
							1991						
05/30	24.4	11.2	2.15	5.0	64.1	93.2	124.2	180.3	264.5	0.17	0.12	0.08	0.00
06/13	25.4	43.2	8.43	6.2	162.4	217.3	284.7	374.7	524.5	5.84	3.47	3.05	0.00
06/25	36.8	0.0	0.00	8.9	277.7	383.5	465.5	609.3	722.9	2.44	error	4.53	0.00
06/30	33.0	47.6	11.43	6.0	89.3	115.9	140.0	152.1	188.3	1.36	error	0.77	0.00
07/02	21.4	81.6	17.56	2.7	14.8	15.9	17.0	19.1	25.5	0.09	0.00	0.00	0.00
07/06	10.2	104.6	20.40	1.8	10.2	11.2	13.5	17.4	27.5	0.12	0.00	0.00	0.00
07/12	68.4	114.8	22.22	14.7	367.3	448.1	474.7	517.5	666.6	11.10	error	4.40	0.00
							1992						
06/21	17.4	39.6	7.35	3.50	61.6	88.2	103.6	121.8	142.8	0.11	error	0.22	0.00
06/24	11.8	59.2	11.23	3.06	60.4	88.,7	115.9	155.8	159.4	>0.48	1.26	>0.52	0.00
07/14	24.2	0.0	0.00	5.82	134.9	177.9	223.3	314.0	530.3	1.25	0.34	0.45	0.00
07/18	8.4	27.2	6.27	1.45	11.6	14.0	16.3	17.4	24.4	0.15	0.05	0.03	0.00
07/27	10.8	42.8	9.04	2.43	27.0	35.7	44.5	59.2	104.2	0.33	0.11	0.06	0.00
08/08	8.4	53.8	11.51	2.09	34.3	48.9	63.6	85.3	100.4	0.72	0.16	0.02	0.00
08/29	20.6	35.6	5.46	4.10	60.8	81.3	95.2	118.2	137.9	0.13	0.05	0.01	0.00

Appendix C Antecedent Soil Moisture Content Prior to Soil Loss Events for the Experimental Sites in 1991

Date		Antecedent Soil Moisture at Depth (cm)							
date of Sampling date	Soil loss event	Fallow		Alfalfa		Corn		Wheat	
		0-7	7-15	0-7	7-15	0-7	7-15	0-7	7-15
		% by mass							
		Gretna clay 1991							
May 24	May 30	18.49	25.13	14.95	18.17	23.30	26.30	23.59	27.79
June 12	June 13	21.59	26.16	14.20	14.05	20.98	26.22	19.36	25.26
June 12	June 15	21.59	26.16	14.20	14.05	20.98	26.22	19.36	25.26
June 20	June 25	14.80	17.76	13.95	15.68	24.49	26.48	18.53	25.53
June 26	June 30	26.93	23.36	25.88	23.32	26.51	25.34	25.94	26.25
June 26	July 1	26.93	23.36	25.88	23.32	26.51	25.34	25.94	26.25
June 26	July 2	26.93	23.36	25.88	23.32	26.51	25.34	25.94	26.25
July 3	July 6	32.83	29.85	30.68	27.63	33.47	26.12	31.98	26.39
July 9	July 12	25.23	25.43	27.10	27.52	22.55	25.16	26.00	24.36
		Leary sandy loam 1991							
May 24	May 30	8.80	13.87	5.40	8.50	7.93	12.28	7.90	12.49
June 12	June 13	7.65	13.59	6.83	7.28	10.14	13.07	9.07	13.64
June 20	June 25	6.23	13.44	6.70	6.50	6.23	13.44	5.83	11.36
June 26	June 30	10.85	14.76	19.33	15.49	18.68	17.08	15.19	16.78
June 26	July 2	10.85	14.76	19.33	15.49	18.68	17.08	15.19	16.78
July 3	July 6	18.24	17.86	19.33	15.49	18.68	17.08	15.19	16.78
July 9	July 12	10.66	15.87	12.58	13.46	11.44	15.60	8.75	10.93

Appendix C.1 Antecedent Soil Moisture Content Prior to Soil Loss Events for the Experimental Sites in 1992

Date		Antecedent Soil Moisture at Depth (cm)							
Sampling	Soil loss	Fallow		Corn		Wheat		Alfalfa	
		0-7	7-15	0-7	7-15	0-7	7-15	0-7	7-15
		% by mass							
		Gretna clay 1992							
May 27	June 3	23.92	25.52	22.36	26.37	23.19	27.07	17.90	18.67
June 10	June 16	20.98	26.27	17.41	17.03	22.58	25.66	20.56	24.80
June 17	June 21	30.55	30.18	29.77	26.64	30.91	27.84	31.38	28.74
June 24	June 24	24.88	25.25	25.13	20.58	26.50	26.67	25.84	25.77
June 24	June 30	24.88	25.25	25.13	20.58	26.50	26.67	25.84	25.77
July 8	July 10	24.89	26.39	24.73	23.82	23.99	27.34	22.53	21.37
July 8	July 14	24.89	26.39	24.73	23.82	23.99	27.34	22.53	21.37
July 15	July 15	30.39	23.49	28.70	27.32	31.26	26.19	29.82	25.67
July 15	July 18	30.39	23.49	28.70	27.32	31.26	26.19	29.82	25.67
July 23	July 27	25.55	25.46	26.51	24.37	26.09	25.36	34.56	22.87
Aug. 6	Aug. 8	22.59	25.54	15.81	16.26	18.83	26.01	15.97	16.49
		Leary sandy loam 1992							
June 17	June 21	13.69	15.38	14.27	12.90	14.04	15.19	13.04	14.88
June 24	June 24	11.86	14.06	16.48	13.47	12.44	14.22	11.36	13.34
July 8	July 14	10.16	14.25	13.10	12.99	9.92	14.21	8.17	15.23
July 15	July 18	14.41	16.92	15.15	12.59	14.33	16.21	12.58	15.26
July 23	July 27	11.41	11.53	12.60	13.11	14.13	15.27	13.07	18.26
Aug. 6	Aug. 8	6.88	11.75	6.52	8.18	5.65	9.76	5.79	7.51
Aug. 27	Aug. 29	--	--	--	--	--	--	--	--

Appendix D Peak Runoff Flow Rates for Soil Loss Events at the Experimental Sites

Date	Peak Flow Rates			
	Fallow	Corn	Wheat	Alfalfa
	l s^{-1}			
	Gretna clay 1991			
May 30	0.018	0.019	0.023	0.000
June 13	3.218	2.322	1.460	0.000
June 15	error	0.325	0.170	0.000
June 25	2.999	3.124	1.496	0.000
June 30	2.273	2.583	1.472	0.000
July 1	0.528	0.534	0.264	0.000
July 2	0.101	0.104	0.102	0.000
July 6	1.523	1.648	0.649	0.000
July 12	2.125	1.825	0.902	0.000
	Leary sandy loam 1991			
June 25	0.730	0.263	2.922	0.000
June 30	0.667	0.313	0.647	0.000
July 2	0.084	0.023	0.024	0.000
July 6	0.123	0.026	0.024	0.000
July 12	2.527	1.269	2.063	0.000
	Gretna clay 1992			
June 3	0.222	0.218	0.234	0.000
June 16	0.222	0.078	0.038	0.000
June 21	0.055	0.022	error	0.000
June 24	0.329	0.078	0.027	0.000
June 30	0.101	0.00	0.000	0.000
July 10	0.031	0.000	0.000	0.000
July 14	1.492	1.257	error	0.000
July 15	0.612	0.126	0.000	0.000
July 18	3.469	4.060	error	0.000
July 27	0.365	0.112	error	0.000
Aug. 8	0.116	0.019	0.00	0.000
	Leary sandy loam 1992			
June 21	0.050	0.023	0.493	0.000
June 24	0.847	0.557	2.063	0.000
July 14	1.213	0.043	2.896	0.000
July 18	0.021	error	0.020	0.000
July 27	error	error	error	0.000
Aug. 8	0.602	0.125	0.402	0.000
Aug 29	0.138	0.247	0.124	0.000

Appendix E Biomass and Seed Yields for Water Erosion Sites

Date	Treatment	Biomass	Seed yield
		------Kg ha^{-1}------	
	Gretna clay 1991		
May 27	alfalfa	3578	
Sept. 5	wheat	8493	880
Sept 12	corn	6615	
	Leary sandy loam 1991		
May 27	alfalfa	4166	
Aug. 30	alfalfa	2240	
Aug. 13	^{z}wheat	4933	3132
Sept. 12	^{z}corn	13092	
	Gretna clay 1992		
June 24	alfalfa	3484	
Aug. 18	alfalfa	2620	
Sept. 30	wheat	11600	4535
Aug. 27	corn	8741	
	Leary sandy loam 1992		
June 24	alfalfa	4110	
Aug. 18	alfalfa	1702	
	^{z}wheat	no sample	
Aug. 27	^{z}corn	9932	

^{z}plots damaged by wild life. Yield data may be too low.