University of Alberta

Measurement and Simulation of Water Erosion

By

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A thesis submitted to the Faculty of Graduate Studies and Research in partial fulfillment of the requirements for the degree of Master of Science

in

Water and Land Resources

Department of Renewable Resources

Edmonton, Alberta

Spring 2000

0-612-60168-4

University of Alberta

Library Release Form

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Title of Thesis: Measurement and Simulation of Water Erosion

Degree: Master of Science

Year this Degree Granted: 2000

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Date: April 14, 2000

University of Alberta

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research for acceptance, a thesis entitled Measurement and Simulation of Erosion submitted by Hendrikus Joel Puurveen in partial fulfillment of the requirements for the degree of Master of Science in Water and Land Resources.

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ABSTRACT

Two adjacent runoff plots were instrumented and monitored at Breton, Alberta from summer 1995 until spring 1997 to quantify runoff volume and sediment yields due to snowmelt and rainfall. The data collected were used to evaluate two simulation models, EPIC (Environmental Policy Integrated Climate) and WEPP (Water Erosion Prediction Project), in their ability to predict runoff and sediment yields. On average, snowmelt runoff accounted for 72% of annual runoff during the two study years. In 1995, nine rainfall events generated 19.4 mm of runoff while, in 1996, eight events totaled 20.8 mm of runoff. On average, snowmelt sediment yield comprised 56% of the 1.77 Mg ha^{-1} of soil eroded in 1995 - 1996, and 45% of the 8.38 Mg ha^{-1} of soil eroded in 1996 - 1997. EPIC correctly estimated snowmelt and rainfall runoff, but overestimated rainfall sediment yield in 1995. WEPP was unable to match observed springmelt or rainfall runoff.

ACKOWLEDGEMENTS

To be honest, this acknowledgement would likely not have been written if it wasn't for the encouragement of many people. After hearing "How's the thesis coming?" for five years, I am curious to hear how people will start a conversation with me now. So, if you were one of those who encouraged me to finish, I thank you, and here it is!

I dedicate this to my parents, who for the first two decades of my life taught me to do my best in all that I do. To my biggest role model, my father, for teaching me to be a good steward of the land. Your faith and beliefs are sincere, your wisdom exceeds that of "the wise old owl" and your work ethic puts us siblings to shame.

If any one person has guided my career in the last decade, it has been Cesar Izaurralde. A sincere "Thank-you, Cesar". You showed confidence in my abilities since day 1, and I have learned many things from you. I, and many others, really miss your presence here in Edmonton.

A big thanks to Jeff Thurston, for all your help and intellectual (or otherwise) conversations. I follow in your footsteps by choice...

Thanks to the guys at Alberta Agriculture, C & D Branch, for the help and cooperation in this project; namely, Andy, Ralph, Sid and Douwe. I hope to work with you again in the future. I appreciated the funding through CAESA.

Finally, to the most important people in my life, many thanks to my better half Georgina, for being patient and understanding while completing this Chapter in my life. And to my daughter Farell, let's go do something fun.

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1. LITERATURE REVIEW

1.1. Measuring Erosion

Climate, topography, soil properties, and management are essential characteristics determining the extent and rate of erosion. Erosion is a complex process because the multitudes of factors that intervene in it contribute not only through their pure effects but also through their interactions. Numerous researchers throughout Canada have conducted erosion studies by altering certain factors (i.e., vegetation) while characterizing others that cannot be controlled (i.e., climate).

Water erosion has long been a common event in the Peace River region of Alberta and British Columbia. Already in 1917, settlers witnessed extensive erosion on cultivated fields after a May snowfall followed by a rapid thaw. Albright (1939) identified water erosion as a continuing problem and suggested the need for soil conservation measures. In 1981 and 1984 Chanasyk and Woytowich (1986; 1987) established Wischmeier-type plots near La Glace, in the Peace River region of Alberta, to study snowmelt and rainfall-induced erosion. After measuring runoff and sediment yields due to rainfall and snowmelt, they concluded that from 90 to 95% of the total annual sediment yield had occurred during the spring snowmelt period (Chanasyk and Woytowich 1984). In 1987, they also concluded that although fallow plots had yielded the least runoff (about 500 m^3 ha^{-1}) their mean sediment yield had been one of the highest (about 0.8 Mg ha^{-1}) among the cropping and management practices studied (Chanasyk and Woytowich 1987).

In 1982, other erosion plots were established near Fort St. John, British Columbia in the northern half of the Peace River region. The objective was to determine the effect of two crop rotations on seasonal and annual runoff and soil loss (van Vliet and Hall 1991). Over a six-year period, cumulative runoff and soil losses were significantly greater in the rotation that had two fallow cycles (229 mm and 4.9 Mg ha^{-1}) than in the one with only with one fallow cycle (172 mm and 1.0 Mg ha^{-1}). In 1987, van Vliet et al. (1993) established a similar erosion study near Dawson Creek, in the southern half of the Peace River region of British Columbia. Over a 4-year period, these workers evaluated the seasonal effects of various tillage treatments on runoff and soil loss from erosion plots. With snowfall 45% below normal, soil losses from rainfall accounted for 75% of the total-annual soil loss. Treatments with intensive tillage had significantly higher rainfall runoff and soil loss from snowmelt than those with reduced tillage.

Throughout the rest of Alberta, relatively few studies have documented water erosion and runoff. Water erosion rates from experimental plots at St. Albert were reported by Toogood (1963). Over a 10-year period, their objective was to measure soil losses from plots consisting of fallow after wheat, wheat after fallow and continuous wheat. Annual soil losses were greatest for fallow after wheat (2.0 Mg ha^{-1}) and smallest for continuous wheat (0.05 Mg ha^{-1}).

Beke et al. (1989; 1990) used a sprinkler irrigation system to simulate rainfall in a two-year erosion study near Lethbridge. They used twelve 6 x 12 m plots to evaluate the effect of cropping and tillage practices on the particle size distribution of eroded sediment and on the plant nutrient concentrations in sediment and runoff water. Treatments consisted of bare fallow, perennial forage, barley sown on rows down the slope, and barley sown on the contour. Soil losses were highest for the fallow treatment, varying from 2.0 to 0.2 Mg ha^{-1}, and lowest for the perennial forage treatment, varying from 0.05 to 0.07 Mg ha^{-1}.

Howitt (1991) estimated soil redistribution on several sites in east central Alberta using soil erosion pans, a rill meter, ^{137}Cs techniques and landscape analysis. Soil erosion pans were installed at various slope positions at the beginning of the study to determine springmelt interrill erosion. Rill erosion was calculated by measuring the length of all rills on a basin and using the rill meter to determine rill surface area. Soil redistribution from upper to lower slope positions by erosion and tillage was estimated using ^{137}Cs techniques, based upon the assumption of a 40-year Cesium fallout period. He estimated total soil loss from eroded knolls over this period to be 107 kg m^{-2}, which represented a rate of about 27 Mg ha^{-1} per year.

Nolan et al. (1992) used a portable rainfall simulator to measure soil loss and runoff in undisturbed field conditions. Rainfall simulators were developed as a field tool to obtain site specific, repeatable measurements of soil loss (Tossell et al. 1987). Using intensities of 140 mm h^{-1}, water was delivered with a cone-pattern nozzle at a height of 0.8-1.2 m over a 1.0-m^2 plot. At two sites in the Peace River region, they found treatments under no tillage experienced soil losses 4 to 22 times lower those under conventional tillage. Results from rainfall simulations on Black and Brown soils under summer fallow showed a 2 to 16 times reduction in soil loss when cultivation was minimized.

Between June 1988 and April 1991, Naeth and Chanasyk (1996) quantified the effects of short duration and continuous grazing systems on runoff and sediment yield from sloped areas of the fescue-grasslands foothills of Alberta. Runoff and sediment were collected from at upper and mid-slope positions using 1-m^2 runoff frames. On average, snowmelt accounted for 70% of the total runoff, with increased runoff on the heavily grazed areas. Only a few summer storms caused runoff due to low rainfall and dry antecedent soil moisture conditions. Sediment yields from the frames were very low for both rainfall and snowmelt events (highest sediment yield measured 0.00003 Mg ha^{-1}) likely because overland flow from above the frame was excluded.

Beginning in 1992, Harms and Chanasyk (1998) quantified surface runoff for both rainfall and snowmelt events in two reclaimed surface-mined watersheds. Watershed runoff was measured using a 61-cm H-flume located at the outlet of each watershed, and hillslope overland flow was measured using replicated 1-m^2 runoff frames located on two slope aspects and at two slope gradients. In 1993 and 1994, snowmelt was the greatest contributor to runoff, accounting for 86% and 100%, respectively, of the annual watershed runoff. Runoff from the hillslope frames was generally variable, and occurred for both rainfall events and snowmelt. Annual rainfall frame runoff exceeded annual snowmelt frame runoff on one of the two watersheds.

1.2. Modeling Erosion

Erosion prediction became possible through the analysis of data collected from erosion studies. The majority of these original erosion equations were the result of early research conducted in the United States, which were later adapted to suit conditions elsewhere. Already in 1940, A. Zingg (1940) published an erosion equation that calculated sheet and rill erosion as a function of slope length and steepness. During the same time period, W. Ellison (1947) was conducting similar research on fundamental water erosion processes. Further studies on the Zingg's equation resulted in the addition of the effects of cropping, management and climatic erosivity (Smith and Whitt 1957), and to the introduction of the soil-loss tolerance concept.

1.2.1. USLE

The first widely used erosion equation was developed and published by Wischmeier and Smith (1978). Named the universal soil loss equation (USLE), it permitted the quantitative evaluation of rainfall erosion for a wide range of climatic, soil, slope, and cropping conditions (Hausenbuiller 1985). The equation is:

$$A = R * K * LS * C * P \quad [1]$$

where A is the predicted average soil loss (t acre^{-1} y^{-1}), R is the rainfall index ([hundreds of ft-tons] inch acre^{-1} h^{-1} y^{-1}), K is the soil erodibility measured under standard unit plot conditions (t h [hundreds of ft-tons]$^{-1}$ inch^{-1}), LS is a dimensionless factor representing the effect on erosion of slope length and steepness , C is a dimensionless factor for cover and management, and P is a dimensionless factor for conservation support practices. Derived from thousands of plot-years of data from under both natural and simulated rainfall (Wischmeier and Smith 1978), this empirically based equation computes rill and sheet erosion using values representing five major factors affecting erosion. The first three factors are site-specific and express the inherent potential for a soil to erode under a given set of rainfall, soil and slope conditions. The last two factors take into account the potential for land use and conservation practices to protect the soil against erosion.

The USLE was developed initially as a tool to assist soil conservationists in choosing practices that would control erosion adequately on croplands (Renard et al. 1991). Adequate erosion control was defined as an USLE estimated annual value of erosion less than the calculated annual soil loss tolerance (Foster 1991). However, the USLE was applied to many conditions. In the United States, the USLE has been used for estimating erosion on cropland in national inventories (U.S. Department of Agriculture 1982), on rangeland (Simanton et al. 1980), forest land (Dissmeyer and Foster 1985), urban construction area (Crafton 1987), recreation sites (Kuss and Morgan 1984), highway embarkments (Farmer and Fletcher 1976), mine tailings (King 1977; McKenzie and Studlick 1979), and coal piles (Fogel et al. 1979).

In Canada, research was conducted to adapt the USLE to simulate erosion under local conditions. In Canada, R values were calculated for Alberta (Tajek et al. 1985), Saskatchewan (Kachanoski and de Jong 1985) and the Maritime provinces (Gordon and Madramootoo 1989), K values calculated for forest type strata (Van Kesteren 1994), and K and C factors for cropping systems in the P.E.I. (Parsons et al. 1994). In addition, the USLE has been used to estimate soil loss on cultivated fields (de Jong et al. 1986), watersheds (Mellerowicz et al. 1994) and erosion plots (Kirby and Mehuys 1987; Salehi et al. 1991), for soil conservation practices selection (Arbour et al. 1990), and to evaluate effectiveness of surficial erosion control materials during road development (Armstrong and Wall 1993).

Despite being widely used, the USLE has been criticized for its limitations. These limitations included: a) a rainfall-erosion (R) factor based on a limited number of weather stations, with no compensation for runoff from frozen and partially thawed soils;

b) a soil erodibility (K) factor that did not account for seasonal changes; c) a slope length –steepness (LS) factor that did not fit well for data from steep slopes, designed only for simple slope applications, and the inability to account for soil deposition; d) cropping and management (CP) factors specific for cropland; and e) the model predicts soil loss on an annual basis, not on an event basis (Farmer and Fletcher 1976; Renard et al. 1991; Moore and Wilson 1992; Renard et al. 1994).

The USLE has been modified numerous times based on further research conducted on the individual factors within the USLE. For example, runoff variables replaced the rainfall erosivity variables (R factor) in the Modified Universal Soil Loss Equation, allowing for event-based predictions of sediment yield (Williams 1975). The Onstad-Foster modification of the USLE used a combination of rainfall erosivity and runoff variables to estimate this factor (Onstad and Foster 1975). In the late 1980's, an effort was made to revise the USLE. Based on additional knowledge of theory describing fundamental hydrologic and erosion processes, and the analysis of new erosion data, the revised Universal Soil Loss Equation (RUSLE) was developed (Renard et al. 1991). Many of the changes in RUSLE were improvements to the apparent limitations found in each factor of the USLE. In addition, the increased availability and speed of the microcomputer allowed for the development of RUSLE as a computer program rather than in "paper" form. This allowed for easy calculation of factors that were interrelated and changing with time (Renard et al. 1994).

During the 1970's and 1980's, increased knowledge of the fundamental processes of erosion not only resulted in changes to the USLE, but also resulted in the development of processed-based mathematical models that had numerous components. Erosion prediction represented only one component of these models. Several of these models were designed to address the concerns of pollution from nonpoint-sources, and included ANSWERS (Beasley et al. 1980) and CREAMS (Knisel 1980). In 1981, the need to determine the relationship between soil erosion and crop productivity resulted in the research and development of the Erosion-Productivity Impact Calculator (EPIC) model.

1.2.2. EPIC

EPIC is a physically based model developed in the United States which simulates on a daily basis the major aspects of an erosion/productivity relationship, including hydrology, weather, erosion, nutrients, plant growth, soil temperature, tillage, economics, and plant environment control (Sharpley and Williams 1990). Given inputs of climatic conditions, landscape characteristics, soil properties and management, EPIC continuously simulates erosion, plant growth and related processes for a time interval specified by the user. In addition, EPIC has an economic component used to assess the cost of erosion and for determining optimal management strategies. Since its inception, the role of EPIC has changed such that it is now known as the Environmental Policy Integrated Climate model.

Because of its many components, the validation and use of EPIC has not been limited to the simulation of erosion. EPIC has been used in the United States to predict runoff and soil loss (Bingner et al. 1989; Chung et al. 1999), determine the effects of erosion on crop productivity (Williams et al. 1985) and economics (Colacicco et al. 1989), and to simulate crop yields (Parsons et al. 1995). EPIC has also been used as an analysis tool for rangeland (Gebhardt 1985), tillage (Lee et al. 1993), and irrigation management (Ellis et al. 1993), climate change (Stockle et al. 1992; Izaurralde et al. 1999), cropping sustainability (Foltz et al. 1995), pesticide fate (Sabbagh et al. 1992), and nutrient mobility (Edwards et al. 1994; Sugiharto et al. 1994).

EPIC has been used in Canada to estimate erosion due to wind (Potter et al. 1998), estimate runoff and soil loss due to water (Izaurralde et al. 1994; Jedrych et al. 1995; Puurveen et al. 1997), predict grain yields (Moulin and Beckie 1993; Toure et al. 1995; Roloff et al. 1998), estimate groundwater recharge (Laroche et al. 1999), develop crop input parameters (Kiniry et al. 1995) and used as one of several computer models to evaluate government policy effects on soil erosion (Izaurralde et al. 1996).

EPIC uses factor-based erosion prediction technology. As such, it has similar limitations to that of the USLE. A move towards the development of process-based erosion prediction technology began in the early 1980's. By 1985, an initiative by U.S. federal agencies resulted in the inception of the Water Erosion Prediction Project (WEPP), designed to replace the USLE with improved erosion technology (Laflen et al. 1991).

1.2.3. WEPP

WEPP is a process-based, continuous simulation, distributed parameter erosion model that can be applied to small watersheds and hillslope profiles within those watersheds. WEPP is composed of many submodels, including climate generation, winter processes, irrigation, hydrology, soils, plant growth, residue decomposition, hydraulics of overland flow and erosion (Flanagan and Livingston 1995). While WEPP can be run in a single storm mode, it is used primarily as a continuous simulation model with a daily time step. For every day, plant and soil characteristics are updated and used in the consideration of runoff when rainfall occurs.

Erosion in WEPP is simulated as a process of rill and interrill detatchment and transport. Rill erosion is defined as the detachment of soil by flowing water. It is estimated as a linear function of excess hydraulic shear. Interrill erosion is the detachment and transport by raindrops and very shallow flows. It is estimated as a function of slope and rainfall intensity as modified by crop canopy and surface cover (Laflen et al. 1991).

WEPP uses a steady state sediment routing equation to describe sediment transport in channels and rills:

$$\frac{dG}{dx} = D_r + D_i \qquad [2]$$

where G is sediment rate per unit width of rill channel (M L^{-1} T^{-1}), x is distance in the direction of rill flow (L), and D_r and D_i are rill and interrill net detachment or deposition rates (M L^{-2} T^{-1}). Depending on the energy of flow, sediment is either transported or deposited in the rill. Spatial and temporal distribution of soil loss is estimated through the calculation of soil transport for segments or entire slopes and by integrating losses over days, months, or years (Izaurralde et al. 1994).

The first hillslope profile version of WEPP was completed in August 1989 (Lane and Nearing 1989). Further research and development resulted in the release of the hillslope and watershed versions in 1995 (Flanagan and Livingston 1995). Updates continue to be released as changes are made to the model. These changes are the result of research conducted for and with the model.

Since its original documentation in 1989, WEPP has been used extensively in the United States. This includes the evaluation of erosion equations (Huang and Bradford 1993; Cochrane and Flanagan 1996; Zhang et al. 1998) and the validation of WEPP runoff and soil loss predictions from research on runoff plots (Zhang et al. 1996; Baffaut et al. 1998), different cropping and tillage systems (Ghidey and Alberts 1996), rangeland (Wilcox et al. 1992), forests (Elliot and Hall 1997), frozen/thawing soils (McCool et al. 1998) and irrigation (Kottwitz et al. 1995). In addition, WEPP has been used for the determination of best management practices for tillage systems (Williams and Nicks 1993), the influence of climate change (Hawkins et al. 1991) and in conjunction with geographic information systems (Savabi et al. 1995).

Relatively few studies have documented the use of WEPP in Canada. WEPP has been used to simulate rainfall and snowmelt runoff (Hayhoe et al. 1993; Izaurralde et al. 1994). WEPP interrill erosion equations were evaluated in a study with the objectives of determining the effects of management on clay dispersibility (Curtin et al. 1994). Soil erodibility parameters have been determined for selected soils in Alberta (Jedrych et al. 1995; Wright et al. in press).

1.3. Study Objectives

The main objective of this study was to compare observed and predicted runoff and sediment yield values from a Luvisolic soil in central Alberta. This was accomplished by analyzing runoff data collected from two adjacent hillslopes with Luvisolic soil and a 5% slope, with consideration to the meteorological and soil conditions that existed during the course of the study. Climatic, landscape, management and soils data were compiled for prediction of runoff and sediment yield using two erosion simulation models, the Environmental Policy Integrated Climate model (EPIC) and the Water Erosion Prediction Project (WEPP). Information is presented in four chapters, each with individual objectives:

The objective of Chapter 2 is to quantify snowmelt and rainfall runoff and sediment yield, with consideration to the existing climatic and soil conditions, on two hillslopes over a two-year period.

Chapter 3 discusses the simulation of snowmelt and rainfall runoff and sediment yield, using quantified climatic, landscape, management and soil data as input, with EPIC over the two-year period.

Chapter 4 discusses the simulation of snowmelt and rainfall runoff and sediment yield, using quantified climatic, landscape, management and soil data as input, with WEPP over the two-year period.

Chapter 5 is a synthesis of the results and conclusions reported in Chapters 2 - 4 and provides some comparisons between EPIC and WEPP simulation results.

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2. RUNOFF QUANTITY AND SEDIMENT YIELD FROM TWO FALLOWED HILLSLOPES

2.1. Introduction

Water erosion has long persisted as a major threat to soil productivity throughout regions within Canada (Coote 1984; Sparrow 1984). Although numerous studies have quantified the extent of erosion, the objectives set for each study have varied among researchers. The lack of quantitative information on water erosion has hindered the development of soil conservation planning (van Vliet et al. 1993) and the validation and use of computer models for erosion simulation (Puurveen et al. 1997). Therefore, field studies are required utilizing methods that lead not only to the quantification of erosion but also to the establishment of the soil and climatic conditions that lead to its development.

The majority of erosion studies in Alberta were conducted on erosion plots to evaluate the influence of different crops and soil management on erosion. A 10-year study by Toogood (1963) quantified erosion on plots under various combinations of wheat (*Triticum aestivum* L.) and fallow. Chanasyk and Woytowich (1987) quantified erosion between 1981 and 1986 on plots under a fallow-canola (*Brassica rapa*)-barley (*Hordeum vulgare* L.) rotation, with fescue (*Festuca rubra* L.) representing continuous cover crops. In 1982, erosion plots were established to quantify soil erosion under a fallow-canola-barley rotation, and a fescue-fescue-fallow-canola-canola-barley rotation (van Vliet and Hall 1992). Nolan et al. (1992) conducted field experiments with a rainfall simulator using 1-m^2 microplots to quantify soil erosion under different conservation management and residue levels. Beke et al. (1990) used sprinkler irrigation to quantify erosion on plots under fallow, barley seeded parallel and perpendicular to the slope, and forage. Naeth and Chanasyk (1996) quantified erosion on grasslands under various grazing intensities.

While these experiments were conducted on size-limited plots, others have been larger in scale. Howitt (1991) estimated past erosion in a basin using ^{137}Cs techniques, and MacAlpine et al. (1992) measured runoff from six farm watersheds throughout Alberta. Similarly in scale, Harms and Chanasyk (1998) quantified erosion on two watersheds that were reclaimed after stripmining.

Despite the vast amount of data collected by past researchers on erosion, input data required for computer simulation of their erosion results were often missing. There remained a need for plot-specific, measured, input data with corresponding measurements of erosion that would be conducive for validation of computer simulation modeling of erosion (Puurveen et al. 1997).

The primary objective of this study was to quantify snowmelt and rainfall runoff and sediment yields on two fallowed hillslopes at Breton, Alberta. The experiment was conducted on an Orthic Gray Luvisol, representative of Luvisolic soils dominant in the region. The hillslopes were maintained under fallow with chemical and cultivation methods for the duration of the study to represent the worst-case erosion scenario in management of these soils.

2.2. Methodology

2.2.1. Location of Study Site and Delineation of Experimental Units

A water-erosion study was conducted during 1994 – 1997 on two adjacent 28 x 84 m hillslopes located on a 5% slope with a southerly aspect at the University of Alberta Breton Plots (53°07' N Lat., 114°29' W Long.) near Breton, Alberta. The two hillslopes were surrounded by a series of long-term agronomic experiments (Figure 2.1). The site was selected because it represented well the characteristics of Luvisolic soils and as such, it contributed to a series of similar studies conducted on different soil zones across Alberta (Alberta Agriculture, Conservation and Development Branch, [Jedrych et al.

1995]). Slope, combined with a fine-textured Breton loam soil and relatively high precipitation, make the area highly susceptible to water erosion.

Rather than using standard-sized (4 x 22 m) Wischmeier plots (Wischmeier and Smith 1978), the entire hillslope was used for the study. This was determined to be better suited for rill development, a large component of the more recent process-based water erosion simulation models. On the other hand, the relatively large size of the hillslopes increased the amount of spatial variability within and between hillslopes versus plots of smaller dimension. For example, there was some unquantified variability in soil type (Figure 2.1). Researchers have shown that there was a large amount of unexplained variability in erosion studies despite uniform management and only minor amounts of observed variability. This makes the effects of factors having relatively minor effects on runoff and soil loss difficult to detect statistically (Wendt et al. 1986).

In the fall of 1994, plot borders were lined with lawn edging, mounded with soil, and seeded to fescue to keep external runoff from entering the plots. Flumes, similar to that described by Kinnell (1987), were installed near the base of each hillslope, and orientated according to visual signs of past erosion (Figure 2.2). Plot borders were angled from the corners of the flume to the sides of the hillslope such that all runoff was channeled into the flume. The distance from the top of the hillslope to the flume was approximately 64 m. Pits were dug to a depth of approximately 2-m to accommodate the flumes, and were drained with two 25-m lengths of 152-mm unperforated tile drainage pipes at the bottom of the pits, leading to a nearby roadside ditch. Unfortunately, the drainage capacities of the two pipes were insufficient during high intensity rainfall and high runoff snowmelt events, resulting in flow back-up in the pits. In addition, the pipes gradually filled with sediment, reducing their capacity. In the fall of 1996, the tile drain was dug up and the channel left open for increased drainage capacity.

2.2.2. Soil Characteristics

The soil series of the study area is a Breton loam, an Orthic Gray Luvisol developed on glacial till. In Alberta, Luvisolic soils extend over approximately 15 million hectares and represent approximately 30% of the provincial landbase (Shields and Lindsay 1990). The soils in the forested regions of Alberta are dominantly Luvisolic soils. When cleared and cultivated, the surficial LFH leaf litter layer high in organic matter undergoes rapid decomposition. The now-exposed Ap horizon, formerly the mineral Ae horizon, is generally lighter in color and lower in clay content from the translocation of clay to the lower Bt horizon. In addition, this Ap horizon has a low water-holding capacity, low organic matter, low supplies of several plant nutrients and is mildly acidic. The Bt horizon is enriched in clay, forming a layer that is dark in color, blocky in structure, low in saturated hydraulic conductivity and acidic (Bentley et al. 1971). Fine texture, little organic matter and low infiltration rates are typical properties of these soils, making the soil highly erodible.

Surficial soil samples were taken in the spring of 1995 and texture and organic C content determined at the Provincial Soil and Feed Testing Lab, Edmonton. The infiltration rate of 3 mm h^{-1} was determined using a double ring infiltrometer (Bertrand 1965). These data were combined with previously documented Breton Plots soils data (Juma et al. 1992; Izaurralde et al. 1993) to form a comprehensive soils dataset (Table 2.1).

2.2.3. Plot Management

Two years prior to the study, the hillslopes were fallowed using a combination of tillage and herbicide application for weed control. As a result of fallowing, crop residues and weed populations were greatly reduced by 1995. Continuous fallow was selected as the management of the hillslopes to represent the worst-case scenario for erosion control and to evaluate the water erosion potential for the study site.

In 1995, the hillslopes were cultivated (up and downslope) on June 8 and October 30 using a field cultivator equipped with spring-tooth harrows. Cultivation depth was about 75 mm. Hillslopes were sprayed with RoundUp™ on August 22. In 1996, the hillslopes were cultivated on May 23 and August 13 using a rotary cultivator, and harrowed using diamond-tooth harrows. On June 27, the hillslopes were sprayed with RoundUp™.

2.2.4. Meteorology

The existing, on-site meteorological station used a CR7 datalogger (Campbell Scientific Inc., Logan, Utah) to continuously record hourly values for air temperature, relative humidity, solar radiation and wind speed and direction. The datalogger was programmed such that rainfall precipitation was measured on a one-minute time interval during rainfall events. Climatic data were downloaded remotely via a computer modem.

In September 1996, the meteorological station was damaged, so air temperature and precipitation data for the months of September to November were purchased from Environment Canada for a location approximately 8 km north of the Town of Breton. In addition, November to March snowfall data for winter 1995 and 1996 were obtained from Environment Canada for this location.

2.2.5. Snow Depth and Water Equivalents

Snow depth measurements were taken manually throughout the hillslopes with a ruler throughout the winter. In addition to these measurements, a 5-cm hollow aluminum tube was used to collect the snow, and the samples brought to the lab for determination of the water equivalent. Between 10 and 15 snow depth measurements and three snowwater equivalent samples were taken per hillslope prior to the 1996 snowmelt. Six snow depth and snowwater equivalent samples were taken per hillslope prior to the 1997 snowmelt. Measurements and samples were taken at upper, mid and lower slope positions. These measurements were taken on November 17, 1995; February 23, March 13 and November 29, 1996; and February 24 and March 24, 1997.

2.2.6. Flume Calibration

Flumes equipped with stilling wells are calibrated when the relationship between the stage of water in the stilling well and the corresponding flow rate is known. On August 29, 1996 an attempt was made to determine this relationship in the field. A large water truck equipped with a water pump was used, with a flow meter built into the water line. The maximum flow rate that could be attained with the water pump was approximately 100 L min^{-1}. Without the pump, and with a full tank of water, flow-rates of approximately 30 L min^{-1} were attained. Flow rates between these values were attained by restricting water flow via a valve connected to the water line. Using various flow rates, the water was poured into one side of the flume and the flow rate recorded. The corresponding flume stage was recorded by instantaneously reading the potentiometer value from the datalogger.

The data from this calibration were difficult to interpret for several reasons. Firstly, a constant flow rate from the water tank was never attained, especially when the water pump was on. Secondly, because it was only possible to pour the water into one side of the flume (with the outlet in the center of the flume), water levels at the flume outlet constantly fluctuated when water flowed to the other side of the flume instead of going directly out the flume outlet. As a result, fluctuations in the potentiometer readings for water stage were also noted.

A second attempt was made at calibrating the flumes using 1997 snowmelt runoff data. When snowmelt first began, flow rates were relatively low and their change throughout the day gradual, and sediment concentrations minimal. Manual flow rate determinations, measured water levels in the stilling wells, and potentiometer readings were tabulated on a half hourly basis. As snowmelt progressed from day to day, both flow rates and sediment concentrations increased. During the later days of snowmelt, sediment concentrations were so high that sediment deposited in the flume outlet, elevating the water levels in the flume by an unknown amount. As a result, calculations of flow rate based on water stage were believed to have been overestimated using this method.

Prior to being used in this study, the flumes were used in a runoff study conducted by the University of Manitoba. Three of their calibration equations were randomly selected, and an average flow rate was calculated (n = 3). The equations used were:

$$y = 0.003126+0.01383(x*0.3)+0.00183((x*0.3)^2)+0.0000684((x*0.3)^3) \quad [1]$$

$$y = 0.004187+0.01948(x*0.3)+0.0000289((x*0.3)^2)+0.0001292((x*0.3)^3) \quad [2]$$

$$y = 0.001994+0.00329(x*0.3)+0.00241((x*0.3)^2)+0.0000090((x*0.3)^3) \quad [3]$$

where y is the flow rate (L sec^{-1}) and x is the stage of the water in the flume (mm). These equations, in conjunction with observed flow rates, were used to determine runoff volume (Figure 2.3).

2.2.7. Runoff Quantity and Sediment Yield

The two flume stilling wells were equipped with a modified Stevens water level recorder. Ink pens were replaced with ten-turn potentiometers for recording water stage in the flume stilling wells. The potentiometers were linked to a Campbell Scientific CR10 datalogger, which was programmed to take a reading on a 10-min time interval. Data were stored on a Campbell Scientific SM7 storage module, and downloaded onto a PC computer using Campbell Scientific PC208 software.

Each flume was equipped with a Coshocton wheel, a water-driven wheel which turns and collects 1% of the runoff from the flume. A hose was attached to the Coshocton wheel outlet and drained into an open 240-L trough installed at the bottom of the flume pit. The remainder of the runoff drained through the tile drain or open channel.

After rainfall events, the sample in the trough was stirred until the settled sediment was equally suspended, and 1-L subsamples were taken. Total trough volume was then determined by filling pails of known volume. The subsamples were taken to the lab, evaporated and the weight of sediment determined using an analytical balance. The Coshocton wheel was removed during snowmelt events.

During snowmelt runoff events, runoff "grab" samples were collected throughout the day. Few samples were taken during the 1996 snowmelt because of flow back-up in the pits. For the 1997 snowmelt, grab samples were taken every 15 to 30 min, depending on the rate of change in flow on a given day. Samples were retained every 0.5 to 1 h when sediment concentrations increased. Runoff rate was calculated by measuring with a stopwatch the time required to fill various sized containers. The volume collected divided by the time required to fill the container gave the flow rate.

Runoff volumes were estimated using two methods. The first method (A) was based on the measurement of the water stage (mm) in the stilling well by the 10-turn potentiometer. These data were converted to flow rate (L s^{-1}) via the three calibration equations, plotted verses time (s), integrated and averaged to give daily total runoff (L). This method was used with all the rainfall data, most of the 1996 snowmelt data and a fraction of the 1997 snowmelt data. The second method (B) uses the manual measurement of the flow rate, where the measured flow rate was plotted verses time and integrated to give daily total runoff. This method was used with most of the 1997 snowmelt data. For the snowmelt data, manual flow rates were not determined at night time when flow had subsided, so the termination of the recession limbs on the hydrographs was estimated based on air temperature and water stage readings (if available).

Sediment yields were estimated based on samples taken during snowmelt runoff, and samples taken after rainfall runoff. For snowmelt runoff, when only 2 – 3 samples were taken, an average daily sediment concentration (g L^{-1}) was determined and multiplied by the daily runoff quantity (L) to give total daily sediment (g). This method was used for most of the 1996 snowmelt runoff and for the first 3 days of 1997 snowmelt runoff. For the rest of the 1997 snowmelt, when sediment samples were taken every 0.5 to 1 h throughout the daytime, sediment yield was estimated by multiplying sediment concentration (g L^{-1}) by the flow rate (L s^{-1}) at the time of collection to give sediment yield per unit time (g s^{-1}). These values were plotted over the daily runoff period and integrated to give total daily sediment (kg).

For rainfall runoff, average sediment concentrations were determined from the samples taken from the 240-L trough after the rainfall event. The concentrations were multiplied by the total rainfall event runoff to give a total sediment yield for the rainfall event.

In an attempt to keep the float in the stilling well from freezing when temperatures dropped below 0°C, winter windshield washer fluid was added to the stilling wells after daily observations. This was generally unsuccessful as continuing runoff during the night diluted the fluid. Propane heaters were also used which proved to be more successful.

2.3. Results

2.3.1. Meteorology

Based on precipitation records from 1951 – 1980, on average Breton receives 547 mm of precipitation annually, with 405 mm as rain and 132 mm as snow (Environment Canada 1982). The months of June, July and August receive 50% of the annual rainfall, while the majority of snowfall occurs during December and January. The mean annual air temperature at Breton is 2.1°C, where the warmest month of the year is July with an average maximum temperature of 21.2°C and an average minimum of 8.8°C, and the coldest month of the year is January with an average daily maximum temperature of -8.6°C and an average minimum of -19.5°C (Juma et al. 1992).

The Breton Plots received 368.1 mm of rainfall in 1995 and 480.5 mm of rainfall in 1996 from the beginning of April to the end of October. In 1995, July and August precipitation were above the long-term-normals (LTN) by about 20%, while the rest of the months were below the LTN (Figure 2.4). Rainfall in 1996 was above the LTN for April, June, August and September, almost equal in May, and lower in July and October.

The LTN for days with precipitation > 1mm are 13, 12 and 12 for June, July and August, respectively (Environment Canada 1982). Except for the dry June in 1995 (eight days precipitation > 1 mm), days of precipitation for these months in 1995 and 1996 were within one-day deviations of the LTN.

Daily snowfall (cm) was recorded near the Town of Breton during winter 1995 and 1996, converted to snowwater equivalent (mm) based on an assumed snow density of 0.1 g cm^{-3}, and compared on a monthly basis to the LTN (Figure 2.5). November snowfall was 3 and 4 times greater than the LTN for 1995 and 1996, respectively. Snowfall during winter 1995 – 1996 was 128% of the LTN for November 1995 through March 1996. December 1995 and February 1996 were well below the LTN during this period. Snowfall during winter 1996 – 1997 was 157% of the LTN for November 1996 through March 1997. During this period, December 1996 to February 1997 were months with snowfall below the LTN.

2.3.2. Snow Depth and Water Equivalents

Snow depth and snowwater equivalents were measured prior to the 1996 and 1997 snowmelt (Table 2.2). Small variations in snow depth within and between hillslopes were likely the result of snow drifting, where uniformity of the snow surface was achieved on a non-uniform soil surface. Microdepressions accumulated more snow than ridges that formed from fall tillage of the previous year. Drifting also resulted in accumulation of snow in and in front of the flumes. Prior to snowmelt, this snow was removed. Snow depth decreased between the February and March sampling dates for both years likely because of ripening of the snowpack (average daily air temperatures were > 0°C on 1, 10 - 12 March, 1996, and 17 – 24 March, 1997). For both years, snow depth was similar between hillslopes.

The average snowwater equivalent for both hillslopes in late February was 56.3 mm in 1996 and 79.2 mm in 1997. Again, March values were lower likely from ripening of the snowpack. For most measurements, the snowwater equivalent was similar between hillslopes. The exception was the March 25, 1997 measurement, where the east hillslope appeared to have similar snow depth to the west, but the snowwater equivalent was almost twice as high. This was likely the result of ice in the sample, as the average density of the samples were 0.28 versus 0.17 g cm^{-3} for the west hillslope.

2.3.3. Snowmelt

Snowmelt was defined as the period of time beginning with the first observation of snowmelt runoff into the flume and ending with the cessation of runoff from snow. Snowmelt was first observed on March 13, 1996, however, runoff may have began on March 12. This is based on the March 13 observation of an unquantified amount of ice in the east flume pit. Runoff data from the flume does not support this observation because the floats were frozen in the stilling wells. Snowmelt was not continuous as a cold front was present from March 20 to April 2 (Figure 2.6), bringing with it about 8 mm of additional water (measurement from melt water in a raingauge on April 3). Snowmelt commenced on April 3 and ended April 5, 1996.

In 1997, snowmelt began on March 25, but a cold front arrived on March 26 resulted in an additional 13 mm of water (measurement from melt water in a raingauge on March 27) and < 0°C temperatures until March 29 (Figure 2.7). After two days of runoff, < 0°C temperatures from April 1 to April 10 delayed further snowmelt until April 11, and subsequent snowmelt was continuous until April 16.

2.3.4. Snowmelt Runoff Quantity and Sediment Yield

Snowmelt from March 13 to April 5, 1996 was the first measured snowmelt for the hillslopes. Drainage from the east flume pit was inadequate during peak flow periods resulting in flow back-up in the pit. Pumps were used to keep water levels from flooding the pit, with moderate success. Runoff stage readings may have been affected during these times, however, no manual flow rates could be taken to verify these readings. Runoff stage readings were not recorded for the afternoon of March 14, all of March 15 and the morning of March 16 due to a technical problem with the datalogger. Hydrographs were constructed for this period based on a few measured flow rates and stage height measurements. The pits were opened in the fall of 1996, after which no flooding occurred.

Total runoff volume for the 1996 snowmelt was estimated to be 92.9 mm for the east hillslope and 40.4 mm for the west hillslope (Table 2.3). The greatest daily flow rates of 4.4 L s^{-1} were observed on March 15 from the east hillslope, while flows of 2 L s^{-1} were measured on April 5 from the west hillslope. Runoff volumes from the east flume were 2 to 3 times greater than those from the west flume on a day-to-day basis except for the last day of snowmelt, where the reverse condition occurred.

Runoff from the east hillslope was likely overestimated in the first seven days of snowmelt, as the snowwater equivalent measured on March 13 was 56.2 mm prior to any additional precipitation (Table 2.2). The overestimation is likely the result of water back-up in the flume pit, elevating water stage readings and manual stage measurements in the east flume. In comparison, water did not back-up in the west flume, resulting in an estimation of runoff volume that is more indicative of the measured snowwater equivalent of 53.3 mm. The runoff coefficient for the west hillslope was 0.66 based on a runoff volume of 40.4 mm and total water (snowwater equivalent and precipitation) of 61.3 mm.

Total sediment yield for the 1996 snowmelt was estimated to be 1280 and 702 kg ha^{-1} for the east and west hillslopes, respectively (Table 2.3). On April 5, sediment from the east hillslope was 33% of the total snowmelt sediment, and 83% of the total for the west hillslope. Maximum sediment concentrations for the 1996 snowmelt were 16 and 8 g L^{-1} for the east and west hillslopes, respectively, on that day.

Total runoff volume for the 1997 snowmelt was estimated to be 46.7 mm for the east hillslope and 34.8 mm for the west hillslope (Table 2.3). Similar to 1996 snowmelt, daily runoff volumes from the east hillslope were greater than the west hillslope except for the last day of snowmelt. The greatest measured flow rates of near 2 L s^{-1} occurred on April 13 from the east hillslope, while flows of near 2 L s^{-1} occurred on April 15 from the west hillslope. The runoff coefficients were 0.54 and 0.61 for the east and west hillslopes, respectively.

Total sediment yield for the 1997 snowmelt was estimated to be 4163.0 and 3352.4 kg ha^{-1} for the east and west hillslopes, respectively. On April 15, sediment from the east hillslope was 46% of the total snowmelt sediment, and 94% of the total for the west hillslope. Maximum sediment concentrations for the 1997 snowmelt were 31 and 41 g L^{-1} for the east and west hillslopes, respectively, on this day.

2.3.5. Rainfall Runoff Quantity and Sediment Yield

Generally, runoff resulted from rainfall events with high total precipitation or events with low total precipitation of a short duration. No runoff was recorded in May of 1995 or 1996 because rainfall events were low in precipitation and long in duration. Appendix 1.1 and 1.2 highlight the rainfall events for 1995 and 1996 that resulted in runoff.

Runoff resulted from nine rainfall events in 1995 and eight rainfall events in 1996. Although total rainfall was considerably lower in 1995 than 1996, the amount of rainfall resulting in runoff was similar between 1995 and 1996. In 1995, 180.0 mm of rainfall resulted in 15.7 mm of runoff from the east hillslope and 22.5 mm of runoff from the west hillslope (Table 2.5). In 1996, 213.2 mm of rainfall resulted in 22.0 mm of runoff from the east hillslope and 19.3 mm of runoff from the west hillslope.

In 1995, five rainfall events in August resulted in 64% and 57% of the total rainfall runoff for the east and west hillslopes, respectively. Those events accounted for 40% of the total precipitation that resulted in runoff. In 1996, one rainfall event in August resulted in 58% and 63% of the total rainfall runoff for the east and west hillslopes, respectively. This event accounted for 36% of the total precipitation that resulted in runoff.

Despite similarities in runoff volumes between 1995 and 1996, sediment yields were vastly different between years. In 1995, total sediment yield as a result of rainfall runoff totaled 632 and 928 kg ha^{-1} for the east and west hillslopes, respectively (Table 2.4). In 1996, total sediment yield as a result of rainfall runoff totaled 5582 and 2027 kg ha^{-1} for the east and west hillslopes, respectively.

In 1995 and 1996, rainfall runoff events in August resulted in considerable soil loss. On August 21, 1995, sediment in the runoff amounted to 56% and 38% of the total seasonal sediment yield resulting from rainfall for the east and west hillslopes, respectively. The August 2 to 3, 1996 runoff event produced 55% and 62% of the total seasonal sediment yield for the east and west hillslopes, respectively.

Sediment yields were different between years and hillslopes because of differences in the measured sediment concentration. The average sediment concentration from rainfall runoff in 1995 was 3.3 and 4.1 g L^{-1} for the east and west hillslopes, respectively. In comparison, the average sediment concentration from rainfall runoff in

1996 was 30.5 and 12.1 g L^{-1} for the east and west hillslopes, respectively. In 1995, the highest recorded sediment concentrations were on average 10 g L^{-1} on August 21 (16.4 mm precipitation) for both hillslopes (Figure 2.8). In comparison, the July 15 to 16, 1996 rainfall event of 13.8 mm produced an average sediment concentration of near 104 g L^{-1} for the east hillslope and near 40 g L^{-1} for the west hillslope (Figure 2.9).

High sediment concentrations from rainfall are possible, but the high sediment concentrations measured in this experiment reflect one of the flume set-up flaws. Highest sediment concentrations were measured when there was flow back-up in the flume pits. The runoff collection troughs at the bottom of the flume pits were covered but not sealed, so it is unlikely that all water and sediment in the trough originated from the Coshocton wheel (Figure 2.2). In fact, the troughs were located at the lowest point in the flume pit, so settling of sediment into the trough during flow back-up was probable. This would elevate sediment concentrations in the grab sample.

Taking a grab sample from collected runoff after a runoff event is a common method for determining sediment yield. However, Zobisch et al. (1996) evaluated this method with five field staff collecting a known sediment yield and found sampling errors ranging from 4 to 83%. These errors stemmed from differences in the way the suspended sediment was stirred just before sampling and from the way the sample was retrieved. Generally, insufficient stirring and sampling near the bottom of the collection container resulted in overestimation of sediment yield. Conversely, snowmelt sediment yields were based on runoff taken directly from the flume outlet, greatly reducing sampling errors.

Snowmelt sediment concentrations also support the observation of overestimated rainfall sediment concentrations. The highest average daily sediment concentration recorded during snowmelt was near 20 g L^{-1}, with a maximum sediment concentration of near 40 g L^{-1}. Table 2.5 shows adjusted sediment yields when using 20 g L^{-1} as the average daily sediment yields for events that had flow back-up in the flume pits.

2.3.6. Total Runoff Quantity and Sediment Yield

On a seasonal basis, snowmelt runoff contributed more to annual runoff than did rainfall runoff (Figure 2.10). From May 1995 through April 1996, snowmelt accounted for 86% and 64% of the total runoff for the east and west hillslopes, respectively. From May 1996 to April 1997, snowmelt accounted for 68% and 64% of the total runoff for the east and west hillslopes, respectively. For both years, above normal precipitation in August resulted in a considerable increase in the rainfall runoff values.

Total runoff from the west hillslope was 58% and 79% of runoff from the east hillslope for 1995-1996 and 1996-1997, respectively. However, correction of the overestimation of the 1996 snowmelt runoff from the east hillslope would increase the agreement between the east and west hillslopes for 1995-1996.

Sediment yields were 24% and 32% less in 1995-1996 than 1996-1997 for the east and west hillslopes, respectively (Figure 2.11). Sediment yields were greater for snowmelt than for rainfall events, except for the west hillslope for 1995-1996. In 1995, runoff was greater for the west hillslope than the east hillslope, resulting in greater sediment yield. In 1996-1997, sediment yields from the east hillslope exceeded the commonly used soil loss tolerance value of 6 Mg ha^{-1} y^{-1} (American Society of Agronomy 1979).

2.4 Discussion and Conclusions

Runoff and sediment yields were measured on two hillslopes for two years. For 1995 and 1996, runoff was measured based on the change in height of a float in the stilling well of each flume, where the change in height was converted to flow rate based on three calibration equations. There was agreement between the predicted flow rates, as calculated by the equations, and measured flow rates, as determined from manual measurements taken during snowmelt runoff events (Figure 2.3). Because manual measurements were not taken during rainfall events, it was assumed that the equations would also predict flow rates for these events based on this agreement. For seven of the eight days of snowmelt in 1997, manual measurements of runoff and sediment yield were used to quantify erosion.

Annually, the number of rainfall runoff events varied from nine in 1995 to eight in 1996. There was no rainfall runoff during May, September, October and November for both years. The daily rainfall for runoff events varied between 4.6 and 62.2 mm. During June, July and August, most rainfall events > 5 mm produced runoff. For rainfall runoff events, maximum 15-min rainfall intensities were generally greater than 10 mm h^{-1}. Average 15-min rainfall intensities were 8.1 mm h^{-1} in 1995 and 5.8 mm h^{-1} in 1996. Others (Wischmeier and Smith 1978; van Vliet and Hall 1992) have observed that low-intensity, long-duration storms generally did not produce soil loss.

From May 1995 to April 1996, between 7 – 11% of rainfall and 66% of snowfall became runoff. From May 1996 to April 1997, between 9 – 10% of rainfall and 54 – 61% of snowfall became in runoff. Others have observed similar trends of low runoff from rainfall and high runoff from snowmelt. On fallow plots in the Peace River Region of British Columbia on Solonetzic soil, van Vliet and Hall (1992) found that between 4 – 5% of rainfall and 24 – 34% of snowfall became runoff. On fallow plots near La Glace, Alberta on Solonetzic soil, Chanasyk and Woytowich (1987) found that 60 – 93% of snowfall became runoff.

Sediment yields were calculated from sediment concentrations of samples taken during the runoff event (1996 and 1997 snowmelt) and after the runoff event (1995 and 1996 rainfall events). Sediment yields were adjusted for several rainfall events because of the likely overestimation of sediment concentration using manual sampling methods after runoff events. This overestimation may also have been the result of deposition in the collection trough during flow back-up in the flume pits.

In 1995, 16 and 23 mm of rainfall runoff produced soil losses of 630 and 930 kg ha^{-1}, respectively. In 1996, 12 and 13 mm of rainfall runoff produced soil losses of 3889 and 1734 kg ha^{-1} respectively. For snowmelt, 40.4 mm of runoff produced 702 kg ha^{-1} sediment in 1996, and 46.7 and 34.8 mm of runoff produced 4163 and 3352 kg ha^{-1} sediment, respectively, in 1997. Others also measured high sediment losses from runoff on fallow plots. In 1983 and 1987, van Vliet and Hall (1992) measured 16 and 21 mm of rainfall runoff which resulted in 2909 and 2305 kg ha^{-1} of sediment from fallow plots following fescue and barley, respectively. Runoff from springmelt in the same years were 30 and 37 mm, producing 783 and 398 kg ha^{-1} of sediment. In 1985 and 1986, Chanasyk and Woytowich (1987) observed 41.3 and 62 mm of runoff, resulting in sediment yields of 730 and 855 kg ha^{-1}, respectively, from fallow plots following barley.

Results of this study demonstrated the extent of runoff and soil loss on fallow fields with erodible soil in central Alberta. Several trends were observed in this study. This study revealed that the majority of snowfall became runoff. The majority of annual runoff was the result of snowmelt. Large soil losses on fallow fields from rainfall during the growing season were also demonstrated. Storms with high intensity and precipitation generally resulted in runoff. Sediment yields resulting from rainfall-runoff events could exceed those from snowmelt, despite lower runoff quantities. Results also suggested that annual soil loss in 1995-1996 did not exceed the tolerable soil loss of 6 Mg ha^{-1} y^{-1}. In contrast, average annual soil loss in 1996-1997 for both hillslopes exceeded tolerable soil loss by 0.6 Mg ha^{-1}.

2.5. References

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Table 2.1. Soil properties of a Breton Loam.

Lower horizon depth (m)	0.18	0.33	0.76	1.12	1.50
Bulk density (Mg m^{-3})	1.30	1.40	1.50	1.50	1.50
Sand (%)	42	34	32	31	35
Silt %	41	37	35	36	38
pH (H_2O)	6.1	5.3	5.2	5.0	5.4
Sum of Bases (cmol(+) kg^{-1})	12.8	14.4	14.7	14.7	16.0
Organic matter (%)	1.6	0.3	0.5	0.3	0.1
Calcium carbonates (%)	0	0	0	0	3

Table 2.2. Snow depth and snowwater equivalent for 1996 and 1997 on two hillslopes at Breton.

	Hillslope	Snow Depth			Snowwater Equivalent		
			cm			mm	
		n^z	Mean	SD^y	n^z	Mean	SD^y
17-Nov-95	East	14	13.7	1.0	3	22.2	1.0
	West	15	13.3	1.8	2	22.0	2.1
23-Feb-96	East	10	20.2	2.7	3	53.8	5.4
	West	10	20.0	1.9	3	58.8	6.5
13-Mar-96	East	13	15.5	3.3	3	56.2	10.4
	West	13	17.2	3.7	3	53.3	10.3
8-Nov-96	East	6	6.1	0.4	6	5.3	1.0
	West	6	6.1	0.4	6	7.0	1.7
29-Nov-96	East	6	28.4	1.9	6	48.6	4.7
	West	6	26.9	0.9	6	43.5	2.6
24-Feb-97	East	6	38.0	2.0	6	80.5	7.3
	West	6	40.2	1.6	6	77.9	7.1
25-Mar-97	East	2	26	1.4	2	73.0	1.8
	West	2	26	2.8	2	43.9	3.3

^{z}n = Number of observations
^{y}SD = Standard deviation

Table 2.3. Snowmelt runoff volume and sediment yield on two hillslopes at Breton for Spring 1996 and 1997.

Date	Data Source[z]	Runoff Volume (mm) East	Runoff Volume (mm) West	Sediment Yield (kg ha^{-1}) East	Sediment Yield (kg ha^{-1}) West
1996					
13-Mar	A	2.8	1.0	3	2
14-Mar	A,B	18.1	4.3	19	8
15-Mar	B	30.6	6.4	92	13
16-Mar	A,B	9.3	3.9	47	12
17-Mar	A	9.1	4.9	73	21
18-Mar	A	3.4	4.2	96	23
19-Mar	A	1.4	3.3	100	26
04-Apr	A,B	13.2	3.9	432	15
05-Apr	A,B	5.0	8.5	420	584
1996 Total		92.9	40.4	1282	704
1997					
25-Mar	B	0.1	0.0	0	0
30-Mar	B	1.2	0.4	3	1
31-Mar	B	2.2	1.1	4	2
11-Apr	B	2.9	1.0	3	1
12-Apr	B	12.3	7.1	38	17
13-Apr	B	16.9	10.7	1513	56
14-Apr	A	3.6	0.6	689	110
15-Apr	B	7.5	13.9	1914	3166
1997 Total		46.7	34.8	4164	3353

[z]Data Source: A = stilling well stage; B = measured flow rates.

Table 2.4. Rainfall runoff volume and sediment yield on two hillslopes at Breton for 1995 and 1996.

Date	Precipitation (mm)	Runoff Volume (mm)		Sediment Yield ($kg\ ha^{-1}$)	
		East	West	East	West
1995					
24 Jun	8.8	0.4	0.4	nr[z]	nr
1-3 Jul	33.8	0.2	1.3	4	27
4 Jul	19.6	4.1	5.4	41	54
29 Jul	31.8	1.0	2.5	53	249
7-8 Aug	34.2	1.4	2.6	35	55
11-13 Aug	15.4	0.8	2.0	26	70
15 Aug	6.4	1.2	1.5	15	12
19 Aug	13.6	3.4	3.5	106	111
21 Aug	16.4	3.2	3.3	352	351
1995 Total	180.0	15.7	22.5	632	929
1996					
18-19 Jun	83.8	1.7	2.5	33	45
1 Jul	10.2	1.6	1.4	1001	228
9 Jul	12.0	0.8	0.1	44	3
15-16 Jul	13.8	2.3	1.5	2370	601
18 Jul	6.0	1.7	1.2	624	217
20-21 Jul	5.6	0.2	0.0	7	2
24 Jul	6.2	0.9	0.5	89	42
2-3 Aug	75.6	12.8	12.1	3067	890
1996 Total	213.2	22.0	19.3	7235	2028

[z]nr - not recorded.

Table 2.5. Corrected sediment yields for rainfall runoff on two hillslopes at Breton for 1996.

Date	Sediment Concentration (g L^{-1})		Sediment Yield (kg ha^{-1})	
	East	West	East	West
1996				
18-19 Jun	2.0	1.8	33	45
1 Jul	20.0	16.2	336	228
9 Jul	5.3	2.7	44	3
15-16 Jul	20.0	20.0	459	307
18 Jul	20.0	18.2	356	217
20-21 Jul	2.8	3.1	7	2
24 Jul	9.8	8.0	89	42
2-3 Aug	20.0	7.3	2565	890
1996 Total			3889	1734

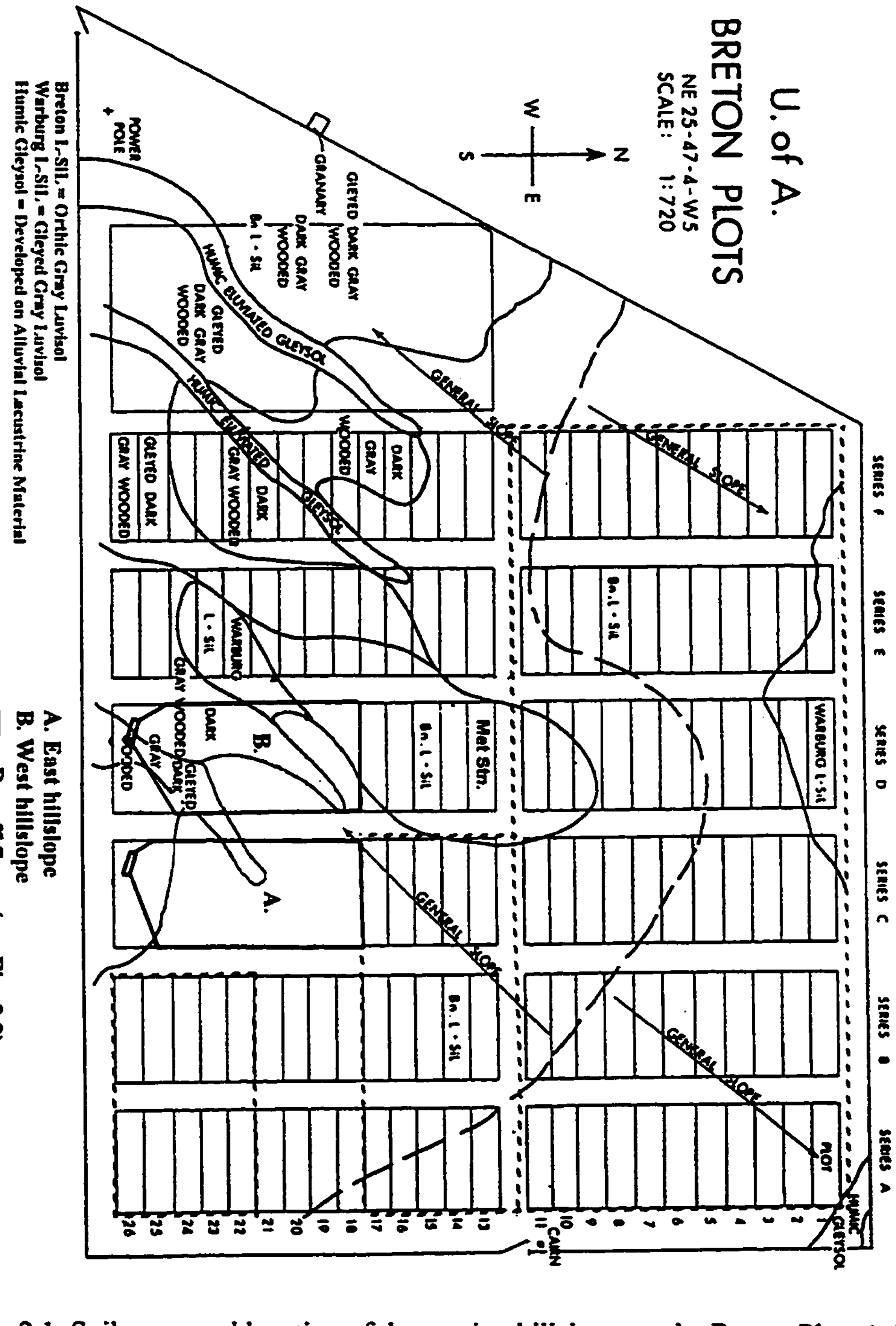

Figure 2.1. Soils map and location of the erosion hillslopes at the Breton Plots (adapted from Robertson 1992)

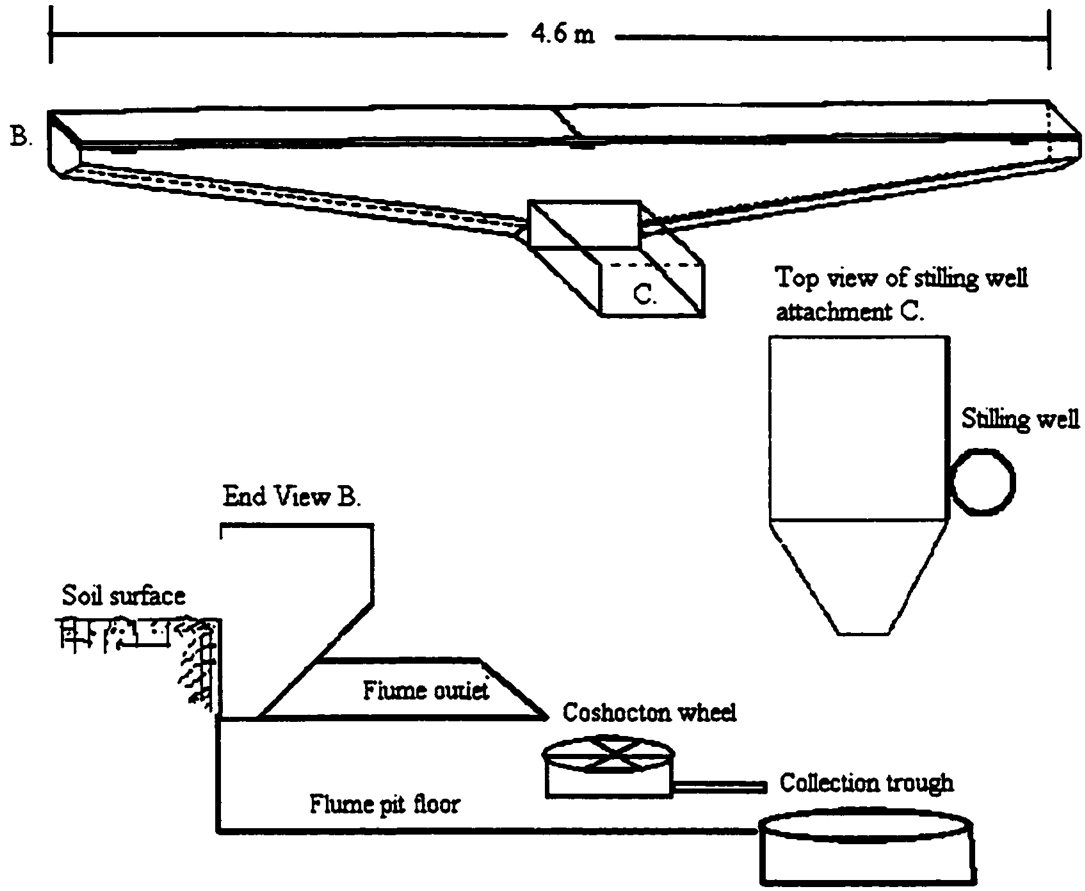

Figure 2.2. Schematic diagram of the runoff flume.

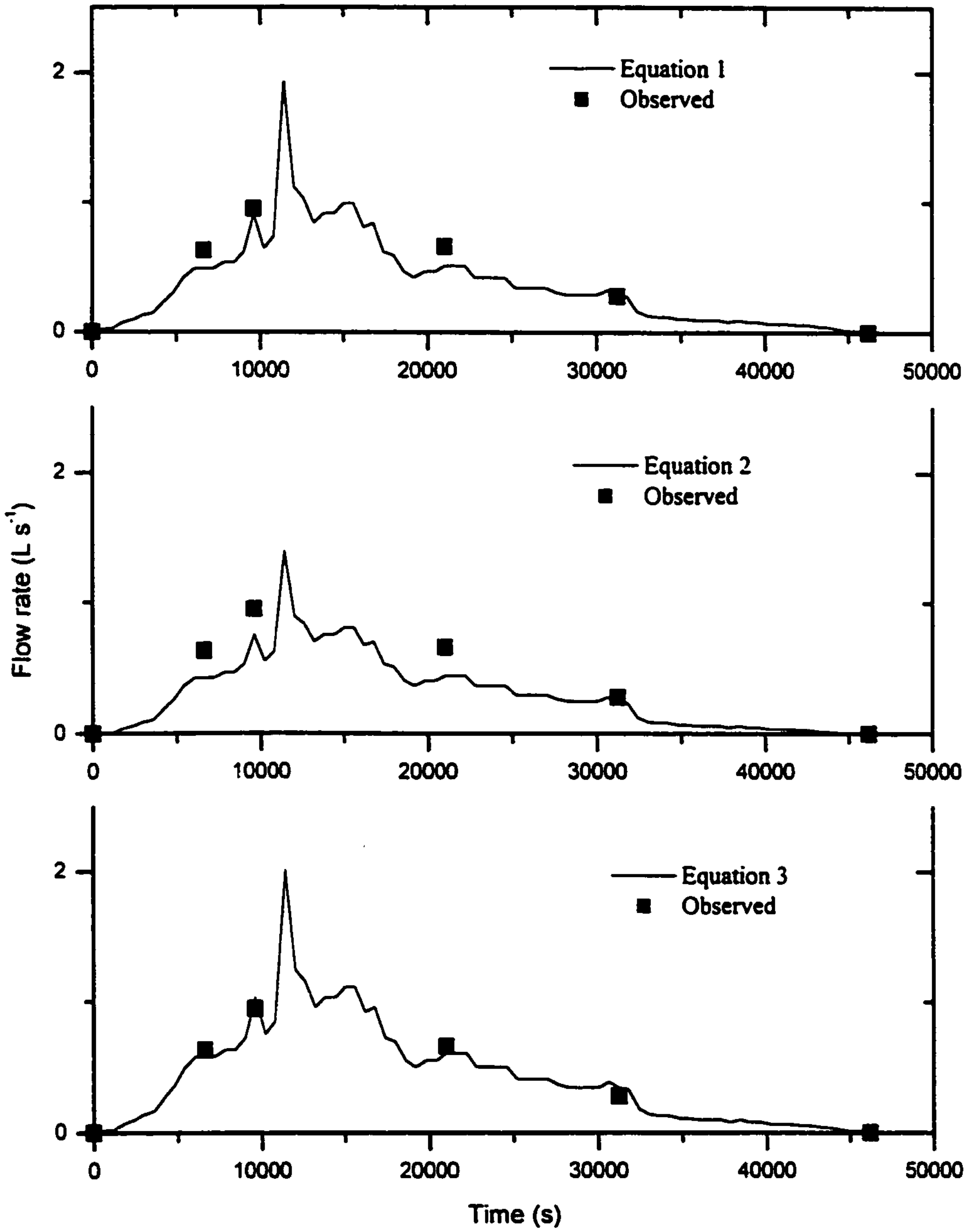

Figure 2.3. Comparisons between observed and predicted flow rates from the west flume on April 5, 1996.

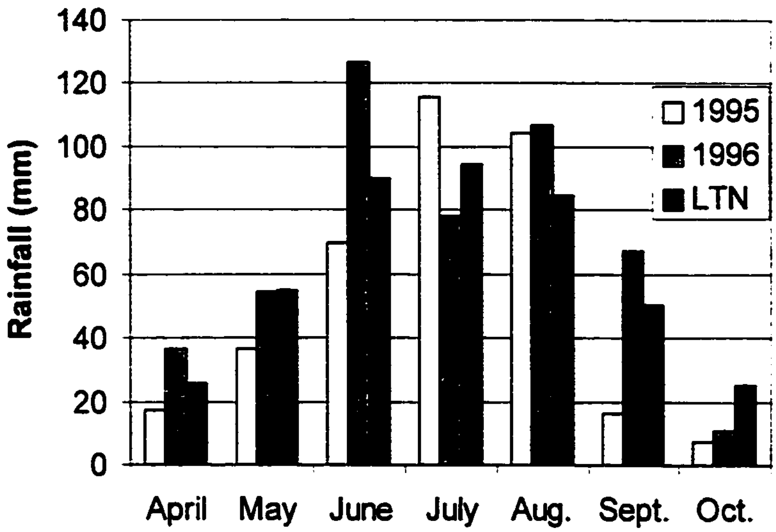

Figure 2.4. Monthly rainfall at the Breton Plots for 1995 and 1996 and long-term normals (LTN) from the Town of Breton (1951 - 1980).

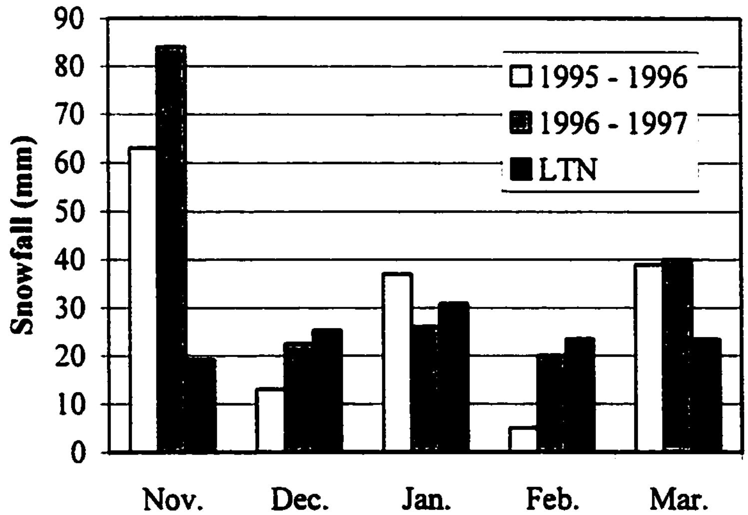

Figure 2.5. Monthly snowfall for 1995 - 1997 and long-term normals (LTN [1951-1980]) of snowfall from the Town of Breton.

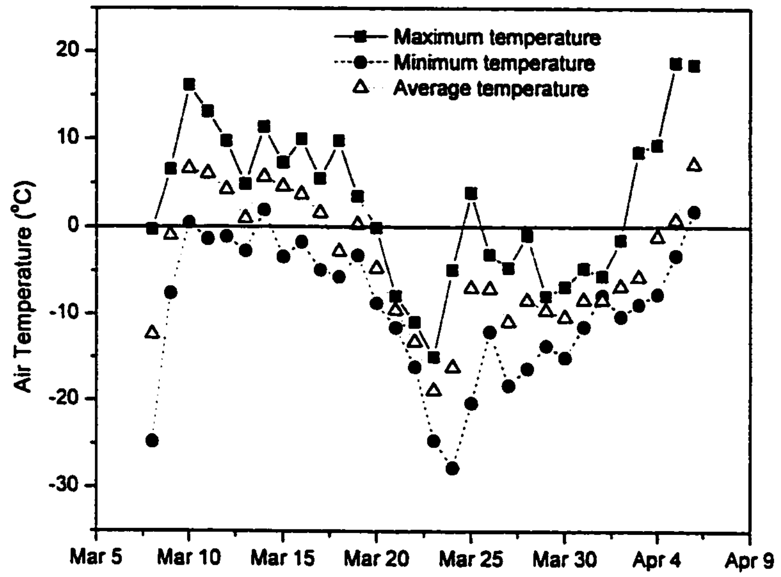

Figure 2.6. Daily maximum, average and minimum air temperatures from March 8 to April 6, 1996, at Breton.

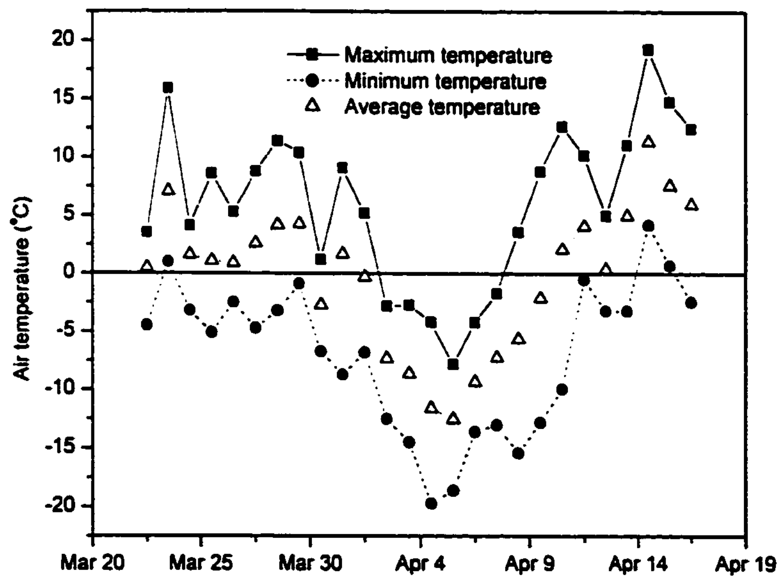

Figure 2.7. Daily maximum, average and minimum air temperatures from March 23 to April 17, 1997, at Breton.

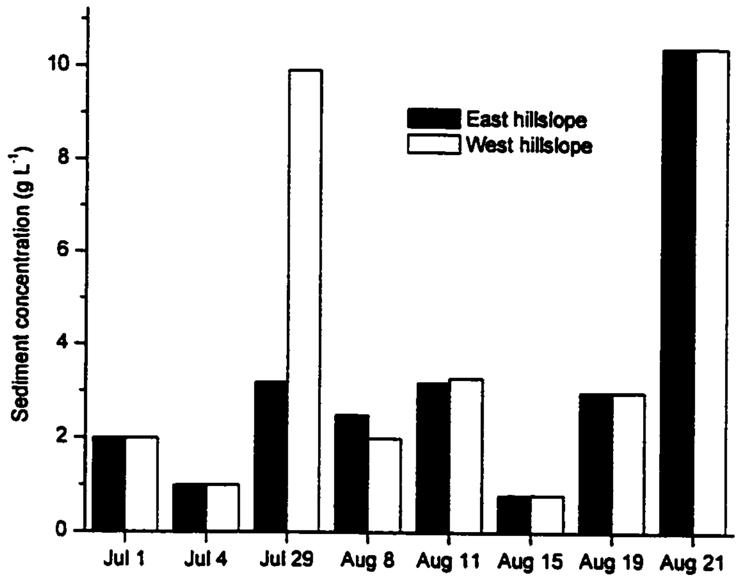

Figure 2.8. Average daily sediment concentrations for rainfall-runoff events at Breton, 1995.

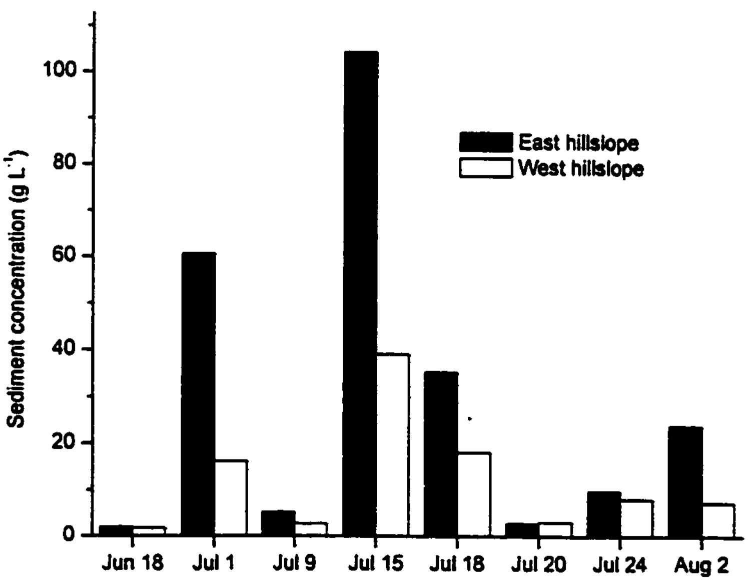

Figure 2.9. Average daily sediment concentrations for rainfall-runoff events at Breton, 1996.

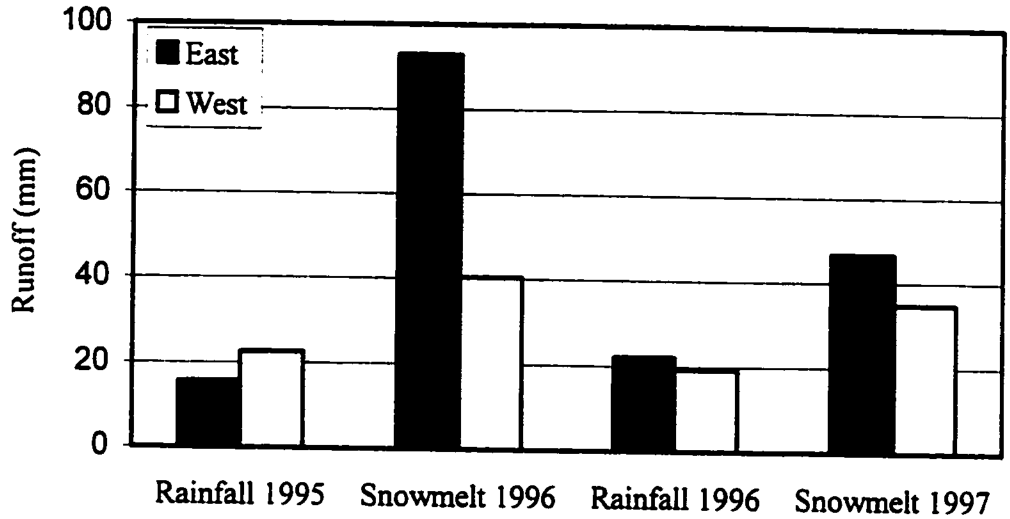

Figure 2.10. Seasonal rainfall and snowmelt runoff volume from two hillslopes at Breton during 1995 to 1997.

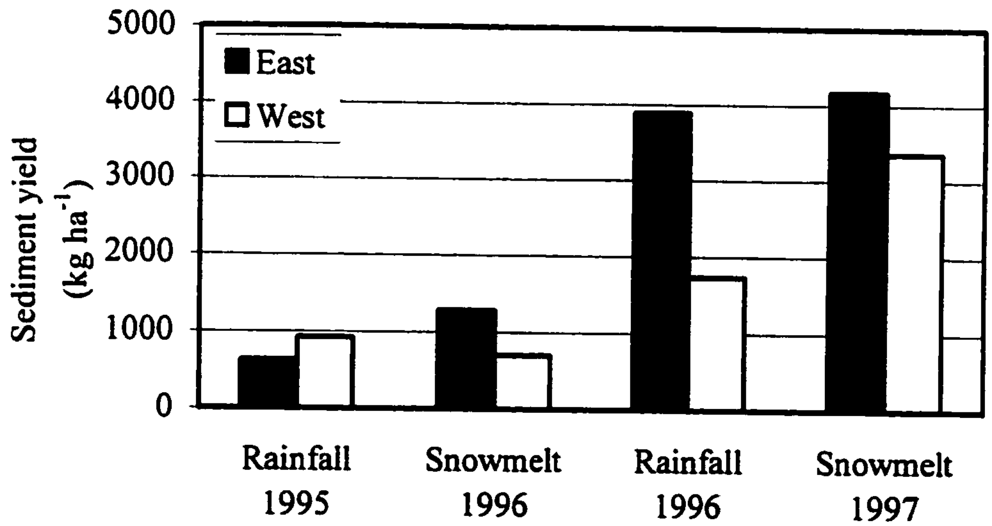

Figure 2.11. Seasonal rainfall and snowmelt sediment yield from two hillslopes at Breton during 1995 to 1997.

3. EPIC SIMULATION OF RUNOFF AND SEDIMENT YIELD FROM TWO FALLOWED HILLSLOPES

3.1. Introduction

Water erosion has long persisted as a major threat to the sustainability of agriculture in many regions throughout Canada (Sparrow 1984). In Alberta, numerous erosion studies have quantified the amount of erosion (Toogood 1963; Chanasyk and Woytowich 1987; van Vliet and Hall 1992; Harms 1998). Further estimates of water erosion obtained with a rainfall simulator were reported by Nolan et al. (1992). Artificially eroded plot studies were conducted to determine the relationship between erosion and productivity (Larney et al. 1995). Numerous computer simulation models have been created to simulate erosion and related processes (Singh 1995). Erosion prediction technology has been used as a tool for soil conservation planning and government policy evaluation (Foster 1991; Izaurralde et al. 1996).

One such model is the Environmental Policy Integrated Climate (EPIC) model, a comprehensive computer model developed in the United States to determine the relationship between productivity and erosion (Sharpley and Williams 1990). With the input of climate, landscape, soil, vegetation and management, the model can simulate changes in soil properties and crop yields as a result of wind and water erosion. EPIC has been used in Canada to estimate erosion due to wind (Potter et al. 1998), estimate runoff and soil loss due to water (Izaurralde et al. 1994; Jedrych et al. 1995; Puurveen et al. 1997), predict grain yields (Moulin and Beckie 1993; Toure et al. 1995; Roloff et al. 1998), develop crop input parameters (Kiniry et al. 1995) and to evaluate government policy effects on water and wind erosion (Izaurralde et al. 1996). The continued development and use of the EPIC model increases the need to determine the accuracy of its predictions.

Puurveen et al. (1997) used EPIC (version 4160) to simulate runoff from snowmelt events and its associated sediment yield. Most of the inputs to the model were extracted from a report by Chanasyk and Woytowich (1987), who measured snowmelt from field plots during 1985 and 1986 in the Peace River Region of Alberta. Remaining inputs were compiled from different sources. EPIC overestimated runoff volume by 25% in 1985 but underestimated it by 7% in 1986 using the runoff curve number method for estimation of runoff. Estimations of sediment yield using the Moderate Rate Equation (MUSS) were generally within the same order of magnitude as the observed values. A need for plot-specific, measured, input data for computer simulation of erosion were recognized by the researchers. The objective of this study was to compare measured and EPIC-simulated (version 8120) water erosion soil losses for a location in central Alberta, Canada.

3.2. The Runoff and Snowmelt Subroutines in EPIC

EPIC simulates surface runoff volumes and peak runoff rates using daily precipitation data. The USDA Soil Conservation Service (1972) method is one method used to estimate runoff, using the equation:

$$Q = \frac{(I - 0.2s)^2}{I + 0.8s} \qquad [1]$$

where Q is daily surface runoff (mm), I is daily rainfall (mm), and s is a surface retention parameter (mm). As defined in Schwab et al. (1981), s is the maximum potential difference between rainfall and runoff, starting at the time the precipitation event begins. s varies among soils, land use, management and slope, and with time because of changes in soil water content. The variable s is calculated as:

$$s = 254\left(\frac{100}{CN_2} - 1\right) \qquad [2]$$

where CN_2 is the curve number for moisture condition 2, varying from 0 to 100 according to tables prepared by the USDA Soil Conservation Service (1972) for various conditions: i.e. condition 1 (CN_1) is for dry conditions, condition 2 is an average value, and condition

3 (CN_3) is for wet conditions prior to the storm. The constant, 254, is a conversion factor to give s in millimeters.

Changes in soil water content cause the retention parameter (s) to change according to:

$$s = s_1(1 - \frac{FFC}{FFC + \exp[w_1 - w_2(FFC)]}) \qquad [3]$$

where s_1 is the value of s associated with the condition 1 curve number, and w_1 and w_2 are shape parameters. Values for w_1 and w_2 are obtained from the simultaneous solution of this equation assuming that $s = s_2$ when FFC=0.6 and $s = s_3$ when FFC=0.5. s_2 and s_3 are the values of s associated with condition 2 and condition 3 curve numbers, respectively. FFC is the fraction of field capacity, the difference between the soil water content in the root zone and the wilting point water content (Ψ_m = -1500 kPa), divided by the difference between the field capacity water content (Ψ_m = -33 kPa) and the wilting point water content.

In EPIC, the soil profile can be divided into a maximum of ten layers (Sharpley and Williams 1990). The first layer is always set to be 1 cm thick for initialization of boundary conditions. Subsequent layers are set according to the horizons in the soil profile. When erosion occurs, the second layer thickness is reduced by the amount of the eroded thickness, and the top layer properties are adjusted according to the distance the first layer is moved into the second layer.

EPIC estimates runoff from frozen soils when the temperature of the second soil layer is less than 0°C. The retention parameter (s) is replaced by the retention parameter for frozen ground (s_f) using the equation:

$$s_f = 0.1s \qquad [4]$$

With this equation, runoff for frozen soils is significantly increased, yet allowing for infiltration when the soil is dry.

Recently, the Green and Ampt infiltration equation was offered as a second method for estimating runoff volume (Williams unpublished). The original Green and Ampt equation was modified to take advantage of the curve number method's link to soil properties and management, using the equation:

$$f = SATK \cdot \left(\frac{s}{FT + 1} \right) \qquad [5]$$

where f is the infiltration rate (mm h^{-1}), SATK is the soil saturated conductivity (mm h^{-1}), s is the curve number retention parameter at the beginning of the storm (mm), and FT is the accumulated infiltration (mm). Runoff volume for a storm is calculated by summing the incremental estimates:

$$Q = \sum (dt \cdot (r - f)) \qquad [6]$$

where dt is the time interval (h) and r is the rainfall rate (mm h^{-1}). Rainfall rates are generated from exponential distributions taken from the weather generator CLIGEN (Nicks et al. 1995). In addition, CLIGEN also simulates storm duration (h), peak rainfall rate (mm h^{-1}) and time to peak of the storm (h). Additional details can be found in Nicks et al. (1995). If peak rainfall rates are known, they can be input into the climate input file rather than estimated by EPIC.

A modification of the Rational formula (USDA Soil Conservation Service 1972) is used to estimate the peak runoff rate:

$$qp = \frac{(\rho)(r)(A)}{360} \qquad [7]$$

where q_p is the peak runoff rate (m^3 s^{-1}), ρ is a runoff coefficient (equal to Q/I) that describes the watershed infiltration characteristics, r is the rainfall intensity (mm h^{-1}) for the watershed's time of concentration, and A is the drainage area (ha). The constant, 360, is a conversion factor to give q_p in m^3 s^{-1}. Factors involved in estimating the watershed's time of concentration include Manning's roughness factor (SN), slope length (SL), and slope gradient (S) (Sharpley and Williams 1990).

In EPIC, snow may be melted on days when the temperature of the second soil layer exceeds 0.0°C. The rate of snowmelt is a function of the snow pack temperature using the equations:

$$SML = T(1.52+0.54SPT), \quad \text{if} \quad 0.0 \leq SML < SNO \qquad [8]$$

where SML is snowmelt (mm), T is the mean daily air temperature (°C), SPT (°C) is the snow pack temperature and SNO (mm) is the water content of the snow. The snow pack temperature is estimated with the equation:

$$SPT = \min(T_s, T(2)) \qquad [9]$$

where T_s is the temperature at the top of the snow pack and T(2) is the temperature at the center of soil layer 2. In an accounting procedure, snowmelt is calculated until the snowpack is depleted. Melted snowfall is treated the same as rainfall for estimating runoff volume (i.e., SML becomes I in Eqn. 1), except that the peak runoff rate is distributed uniformly over a 24-h duration, with the rainfall energy set to zero (Williams 1995).

The EPIC soil temperature model assumes a close relationship between bare soil surface temperature and air temperature (Potter and Williams 1994). Daily estimates of bare soil surface temperature are influenced by precipitation and previous day soil temperature. The amount of cover (i.e., crop biomass, residue, or snow) present on any given day delays the predicted bare soil temperature according to the equation:

$$TG_i = (BCV)(TGB_{i-1}) + (1 - BCV)(TGB_i) \qquad [10]$$

where TG_i is the final estimate of soil surface temperature (°C) on day *i*, TGB_i is the final estimate of bare soil surface temperature (°C) on day *i*, and BCV is a lagging factor for simulating residue and snow cover effects on soil surface temperature. BCV takes the value of 0 in the case of bare soil and approaches 0.95 as cover increases:

$$BCV = \max\left[\frac{CV}{CV + \exp(5.3396 - 2.3915CV)}, \frac{SNO}{SNO + \exp(2.303 - 0.2197SNO)}\right] \qquad [11]$$

where CV ($Mg\ ha^{-1}$) is total aboveground biomass (harvested crop + residue) and SNO (mm) is the water content of the snow cover. Large quantities of biomass or snow increase the value of BCV and thus the influence of this factor on the temperature (Eqn. 10).

Changes in soil temperature are simulated on a daily basis for each soil layer according to the equation:

$$T_{l,i} = T_{l,i-1}\text{LAG} + (1.0 - \text{LAG})\,[(\overline{T} - \text{TG}_i)\,\text{FZ}_l + \text{TG}_i \qquad [12]$$

where T is the soil temperature of soil layer l on day i (°C), LAG is a coefficient (range = 0 - 1) which allows for proper weighting of the previous day's temperature, $\overline{T}$ is the long-term average annual air temperature at the site, TG_i is the soil surface temperature on day i, and FZ is a depth factor which governs temperature changes between the soil temperature and the constant temperature depth (Potter and Williams 1994). The depth factor regulates soil temperature changes between the soil surface and the damping depth: i.e., temperatures of soil layers closer to the surface are more sensitive to soil surface temperatures. The soil temperature of the second soil layer is important for the calculation of the retention parameter for frozen soils (Eqn. 4). Additional details can be obtained from Sharpley and Williams (1990).

Sediment yield was simulated using the Moderate Rate Equation (MUSS), based on the Universal Soil Loss Equation (USLE), but designed to account for small watershed hydrology with no channel erosion (Williams 1995):

$$Y = 0.79(Qq_p)^{0.65}\text{A}^{0.009}(\text{K})(\text{CE})(\text{PE})(\text{LS})(\text{ROKF}) \qquad [13]$$

where Y is the sediment yield ($Mg\ ha^{-1}$), Q is the runoff volume (mm), q_p is the peak runoff rate ($mm\ h^{-1}$), A is the watershed area (ha), K is the soil erodibility factor, CE is the crop management factor, PE is the control practice factor, LS is the topography factor (slope length and steepness), and ROKF is the coarse fragment factor. The equations used in determining these factors are presented by Sharpley and Williams (1990).

Five potential-evapotranspiration equations are offered in EPIC: (i) Penman, (ii) Penman-Monteith, (iii) Priestley, (iv) Hargreaves, and (v) Baier-Robertson. The Penman-Monteith equation which is based on solar radiation, air temperature, wind speed, relative humidity, and elevation was selected for the simulations. This was the equation that was used in a prior study (Puurveen et al. 1997), where runoff and sediment yields were adequately simulated using data collected at La Glace, Alberta.

3.3. The Input Datasets and Model Runs

The major inputs to EPIC are a climate data file, a soil data file, a cropping/management data file, and a miscellaneous data file. Input data required to initialize model runs were obtained during the runoff study presented in Chapter 2.

3.3.1. Climate Data File

In order to simulate erosion at any given time in the past, EPIC requires daily inputs of solar radiation, maximum and minimum daily air temperature, total daily precipitation, relative humidity and daily average wind velocity at a 10-m height. The on-site meteorological station collected these data for most days, however, missing temperature and precipitation data were obtained from near the Town of Breton (5 km west, 8 km north of the study site, elev. = 843 m) for September to November, 1995, when the on-site station was being repaired. The accuracy of these Town data versus the Breton Plots data were not critical as no runoff occurred during this period.

In EPIC, the snowwater equivalent is simulated daily according to snowfall precipitation in the climate data file. Although daily snow depth was measured by a snow depth sensor at the meteorological station, its accuracy and the corresponding snowwater equivalent were not known. Therefore, snowfall precipitation in the climate data file was adjusted prior to the actual snowmelt period to reflect the observed snowwater equivalent at that time. The observed snowwater equivalents were based on manual measurements taken prior to snowmelt for each year.

3.3.2. Soil Data File

Soil properties inputted in the EPIC soil data file include horizon thickness, bulk density, texture, moisture characteristics, pH, sum of bases, organic carbon, cation exchange capacity and saturated hydraulic conductivity (Table 3.1). Section 2.2.3. describes how these data were obtained. Remaining soil parameters were left at a value of 0 to allow for EPIC estimation. Generally, these parameters were insensitive to runoff and sediment prediction (Sharpley and Williams 1990). The hydrologic soil group input parameter (hsg), which replaced the runoff curve number input parameter (CN_2) in previous EPIC versions, was set to describe the soil as belonging to Hydrologic Soil Group C (slow infiltration due to a restrictive soil layer).

3.3.3. Cropping/Management Data File

Plot management operations and the dates on which they occurred were presented in Section 2.2.2. Tillage implements and their pre-defined parameter values were selected from existing tillage parameter files based on actual tillage properties.

3.3.4. Miscellaneous Data File

A "miscellaneous" data file is used to store numerous parameters required by EPIC including those for model initialization, slope length and steepness, and long-term climatic normals for climate generation and wind erosion submodels. The subsequent discussion will describe some of the parameters that were used for model initialization.

The Green and Ampt method for estimation of runoff was used, with peak 15-min rainfall intensity for rainfall events input in the climate input file (Appendix 1.1 and 1.2), and daily rainfall exponentially distributed. The runoff curve number was estimated by EPIC throughout the simulation based on the designation of the Hydrologic Soil Group and simulated changes in soil moisture. Manning's roughness factor η (SN) was assigned a value of 0.01 based on a fallow condition with no residue (Engman 1983). This value remained constant throughout the simulation. The erosion control practice factor (PE) was set to 1 signifying no contouring or terracing.

Landscape parameters used in EPIC include slope length (SL) and slope gradient (S). The hillslopes were about 64 m long on an area with a 5% slope (Section 2.2.1). The southerly aspect of the hillslopes was not an input in EPIC.

The simulation was started 1 January 1995 and ended 1 January 1998. Although the study ended after snowmelt 1997, simulation of the remainder of 1997 was necessary as EPIC required cropping inputs somewhere in the simulation. Therefore, a crop was hypothetically grown in 1997. This had no effect on model output as the period of interest was between May, 1995 to April, 1997. Daily output for variables of interest such as runoff (*Q*) and sediment yield (*MUSS*) were tabulated and compared to those presented in Chapter 2.3.

Observed values for runoff volume and sediment yield represent an average of the two hillslopes. Standard errors (n=2) were calculated to express the variability between the two hillslopes. On an event basis, the relative difference (RD) was calculated as the difference between the average observed value and the simulated value, where a positive RD value represented an underestimated simulated value and a negative RD value represented an overestimated simulated value for runoff volume or sediment yield.

Total seasonal observed and simulated values of runoff and sediment yield were compared using the Root Mean Square Error (RMSE) method:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}(O_i - S_i)^2}{N}} \qquad [12]$$

where O_i and S_i are observed and simulated values, respectively, and N is the number of observations. This method is commonly recommended for analysis of model performance (Smith et al. 1996). The smaller the RMSE, the closer the simulated values are to the observed values.

3.4. Results

3.4.1. Runoff and Erosion due to Snowmelt Events

For the purpose of this study, snowmelt was defined as a reduction in the snowwater equivalent. With respect to EPIC simulations, snowmelt may be simulated without the simulation of runoff because of infiltration. Runoff was defined as the water leaving the hillslope area.

In 1996, snowmelt runoff began 13 March and ended 5 April. Within this period, 20 March to 3 April were days of no measurable runoff. In 1996, EPIC simulated snowmelt and runoff on 10 and 11 March, but no further runoff was simulated until 5 April (Table 3.2). Snowmelt was not simulated between 12 and 19 March, days on which runoff was observed, possibly because maximum air temperatures were lower than on 10 and 11 March and simulated soil temperatures were below –8°C (Figure 3.1). While snowmelt runoff was observed to finish on 4 and 5 April, snowmelt runoff was simulated from 5 April until 8 April. This period was likely extended from that observed because of the overestimation of the remaining snowwater equivalent in early April.

In 1997, snowmelt runoff began 25 March and ended 15 April. Within this period, 26 March to 29 March and 1 April to 10 April were days of no runoff. EPIC simulated snowmelt without runoff on 25 and 30 March, and runoff on 31 March. While subsequent runoff was observed beginning 11 April and ending 15 April, EPIC lagged in the simulation of runoff until 15 April and ended on 16 April with a runoff estimate of 35.9 mm.

The average observed and simulated values for runoff and sediment yield during the 1996 and 1997 snowmelt periods are presented in Figure 3.2 and 3.3. Based on the average runoff from the two hillslopes, total simulated snowmelt runoff was underestimated in 1996 (RMSE = 36.8 mm). However, the simulated snowmelt runoff was only 0.5 mm greater than that observed from the west hillslope. For 1997 snowmelt, total runoff was correctly estimated (RMSE = 6.0 mm). There were nine days of snowmelt runoff in 1996 and eight days of snowmelt runoff in 1997. Simulated snowmelt runoff was limited to six days in 1996 and three days in 1997.

Predictions of total snowmelt sediment yield using the MUSS equation were underestimated in 1996 and 1997 based on the comparison to the average of both hillslopes (RMSE = 416 and 6245 kg ha^{-1}, repectively). However, the model predicted 694 kg ha^{-1} of sediment in 1996, which agreed with that observed from the west hillslope (RD = 10 kg ha^{-1}). The 1997 prediction of total sediment yield was underestimated by 284%, despite the accurate prediction of runoff volume (RD = 0.3 mm). In comparison to total sediment yields in 1996, EPIC simulated the trend of increased sediment yield in 1997, despite lower observed and simulated runoff volumes in 1997. Generally, EPIC simulated the observed trend of increased sediment yield as snowmelt progressed.

Since actual soil temperatures were not monitored, a direct comparison to simulated soil temperatures cannot be made. However, several qualitative statements can be made based on the observations of soil conditions and sediment yields during the snowmelt periods of 1996 and 1997. Simulated soil temperatures at 9-cm depth were > 0°C beginning 12 April, 1996 and 19 April, 1997 (Figure 3.1). Based on field observations, soil temperatures at 9-cm depth were likely > 0°C around 5 April, 1996 and 13 April, 1997. However, simulated soil temperature may be in error from the overestimation of the snowwater equivalent in early April, for both years.

3.4.2. Runoff and Erosion due to Rainfall Events

For the purpose of this study, a rainfall event was defined as the period of time during which rainfall was present. Rainfall events were separated by a period of no rainfall during which runoff and sediment from a previous event were sampled. Runoff resulted from nine rainfall events in 1995. EPIC simulated runoff from eight rainfall events in 1995 (Table 3.3). Two rainfall events in June resulted in EPIC simulations of runoff when no runoff was observed. Runoff was simulated likely from the high precipitation amounts and maximum 15-min rainfall intensities (Table 3.4). The 5-6 June rainfall event totaled 28.2 mm of rainfall, with a maximum 15-min rainfall intensity of 21.6 mm h^{-1} on 6 June. EPIC simulated 2.9 mm of runoff from this event on 6 June. The 18 June rainfall event totaled 12.6 mm with a maximum rainfall intensity of 15 mm h^{-1}. EPIC simulated 0.5 mm of runoff from this event. EPIC did not simulate runoff from three rainfall runoff events in August. Runoff was likely not simulated because of low peak rainfall intensities.

Runoff resulted from eight rainfall events in 1996, of which EPIC simulated runoff from four of these rainfall events (Table 3.2). EPIC overestimated runoff for the 18-19 June and 1 July events (RD = -8.8 and -0.3 mm, respectively), and underestimated runoff for the 15-16 July and 2-3 August events (RD = 1.2 and 4.3 mm, respectively). For the 18-19 June event, EPIC simulated a runoff to precipitation (Q/P) ratio of 13% (Table 3.4), whereas the observed Q/P ratio from this event was only 3% (RD = -8.8 mm). For the 2-3 August rainfall event, EPIC simulated a Q/P of 11% while 17% was measured as runoff (RD = 4.3 mm). Of the four rainfall runoff events missed by EPIC, three produced runoff < 1 mm. The remaining missed event, 18 July, had a Q/P ratio of 25%. This rainfall amount of this storm was only 6 mm, however the duration of the storm was 1.25 h with a relatively high maximum 15-min rainfall intensity of 13.6 mm h^{-1}.

On an annual basis, EPIC was able to simulate the amount of rainfall runoff for both years (Figure 3.2). In 1995, the average observed rainfall runoff was 19.4 mm versus 16.6 mm simulated by EPIC (RMSE = 4.2 mm). In 1996, the average observed rainfall runoff was 20.8 mm versus 21.6 mm of simulated by EPIC (RMSE = 1.7 mm).

Predictions of sediment yield using the MUSS equation were generally overestimated for high runoff events and underestimated for low runoff events. In 1995, the highest sediment yield of 351 kg ha^{-1} occurred on 21 August (Table 3.3). EPIC did not predict runoff from this event. The highest simulated sediment yield of 1135 kg ha^{-1} occurred on 29 July, however EPIC overestimated runoff by 42%. The overestimation of sediment was not always the result of the overestimation of runoff. For the 4 July rainfall event, EPIC underestimated runoff by 56%, however simulated sediment yields were overestimated by an order of magnitude (RD = -647 kg ha^{-1}).

In 1996, sediment yields were greater than in 1995 (Figure 3.3), as were the variabilities in sediment yields between the hillslopes (Table 3.3). EPIC simulated sediment yield from three of the four runoff events simulated. The highest average sediment yield of 1978 kg ha^{-1} occurred on 2-3 August. EPIC correctly estimated the sediment yield from this event (RD = 501 kg ha^{-1}), despite underestimating the runoff volume (RD = 4.3 mm), as the observed variability between the east and west hillslope was the greatest (SE = 770 kg ha^{-1}). The highest simulated sediment yield of 3144 kg ha^{-1} occurred on 18-19 June, however the observed sediment yield was only 39 kg ha^{-1}. This overestimation was largely due to the overestimation of runoff (RD = -8.8 mm). Generally, large sediment yields resulted from small runoff events in 1996. EPIC was able to reproduce this trend for the 1 July event, but was unable to reproduce this for the 15-16 July and 18 July events.

3.5. General Discussion and Conclusions

A test of EPIC was conducted to determine its ability to simulate water erosion under conditions existing on two adjacent and similar hillslopes in central Alberta with measured precipitation, runoff quantity and sediment yield. The model was initialized as accurately as possible using obtained and reported climate, landscape, soil and management data. Subsequent simulation of the processes related to erosion therefore depended solely on the initialized conditions and internal model algorithm. The simulation results suggested that EPIC adequately identified the snowmelt period, however was unable to simulate snowmelt runoff on a day to day basis. This may have been the result of underestimating the increase in soil temperature during the later days of snowmelt. EPIC overestimated the termination of snowmelt runoff by three days in 1996, and one day in 1997. Snowmelt runoff was correctly estimated in 1996 (RMSE = 36.8 mm) and 1997 (RMSE = 6.0 mm) when considering the variability within the observed data. The trends in rainfall runoff were generally simulated by EPIC, although the model was unable to simulate several low runoff, and in the case of 18 July, 1996, high sediment yielding events. Total seasonal sediment yields were correctly estimated from snowmelt events in 1996 (RMSE = 416 kg ha^{-1}) and rainfall events in 1996 (RMSE = 2658 kg ha^{-1}), underestimated from snowmelt events in 1997 (RMSE = 6245 kg ha^{-1}), and overestimated from rainfall events in 1995 (RMSE = 3102 kg ha^{-1}).

In related studies, McCool et al. (1995) found difficulties in the EPIC simulation of erosion in the Palouse Region of eastern Washington, an area dominated by winter processes of snowfall and soil freezing and thawing. They showed that runoff estimations for winter non-snowmelt events were improved by using winter runoff index values (RI) calculated using Curve Number (CN) relationships. These RI values were generally greater than the CN value, and found to be highly variable. Puurveen et al. (1997) used EPIC for the simulation of erosion in the Peace River Region of Alberta, where snowmelt may account for over half of annual runoff and soil loss. They showed that EPIC simulations using the CN method for estimation of runoff adequately estimated snowmelt runoff volumes, although the model was unable to reproduce the reported cropping treatment effects on erosion. With respect to these findings, the incorporation of the Green and Ampt method for estimation of runoff appears to be a valuable addition to the EPIC model, as this study demonstrates this method's ability to simulate realistic snowmelt runoff values for location in central Alberta at approximately 53°N.

Overall, EPIC performed very well on an annual basis using the Green and Ampt method of estimation of runoff, with peak rainfall intensities input. Evaluation on a daily basis, however, was variable. The lack of measured soil temperatures prevented a more thorough examination of the accuracy with which EPIC simulated soil temperatures during the snowmelt period.

3.6. References

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Table 3.1. Soil properties of a Breton Loam used in the EPIC simulation.

Lower horizon depth (m)	0.18	0.33	0.76	1.12	1.50
Bulk density (Mg m^{-3})	1.30	1.40	1.50	1.50	1.50
Wilting point (m m^{-1})	0.07	0.13	0.17	0.13	0.13
Field capacity (m m^{-1})	0.20	0.22	0.30	0.32	0.21
Sand (%)	42	34	32	31	35
Silt %	41	37	35	36	38
pH (H_2O)	6.1	5.3	5.2	5.0	5.4
Sum of bases (cmol(+) kg^{-1})	12.8	14.4	14.7	14.7	16.0
Organic carbon (%)	1.0	0.2	0.3	0.2	0.0
CEC (cmol(+) kg^{-1})	20.4	18.0	21.0	21.0	20.0
Saturated cond. (mm h^{-1})	3	10	10	1	1

Table 3.2. Observed and simulated daily runoff and sediment yield from snowmelt at Breton, Alberta, using EPIC 8120 and beginning the simulation 1 Jan., 1995, using the Green & Ampt method for estimation of runoff.

Date	Runoff				Sediment yield			
	Ob[z]	SE[y]	Sim[x]	RD[w]	Ob	SE	Sim[v]	RD
	mm				kg ha^{-1}			
1996								
10 Mar	0.0	0.0	7.3	-7.3	0	0	0	0
11 Mar	0.0	0.0	3.0	-3.0	0	0	0	0
13 Mar	1.9	0.6	0.0	1.9	2	0	0	2
14 Mar	11.2	4.9	0.0	11.2	13	4	0	13
15 Mar	18.5	8.6	0.0	18.5	52	28	0	52
16 Mar	6.6	1.9	0.0	6.6	29	12	0	29
17 Mar	7.0	1.5	0.0	7.0	47	18	0	47
18 Mar	3.8	0.3	0.0	3.8	59	26	0	59
19 Mar	2.4	0.7	0.0	2.4	63	26	0	63
4 Apr	8.6	3.3	0.0	8.6	224	147	0	224
5 Apr	6.8	1.2	3.4	3.4	502	58	43	459
6 Apr	0.0	0.0	16.6	-16.6	0	0	430	-430
7 Apr	0.0	0.0	7.9	-7.9	0	0	175	-175
8 Apr	0.0	0.0	2.7	-2.7	0	0	46	-46
1997								
25 Mar	0.1	0.0	0.0	0.1	0	0	0	0
30 Mar	0.8	0.3	0.0	0.8	2	1	0	2
31 Mar	1.7	0.4	2.4	0.7	3	1	36	-33
11 Apr	2.0	0.7	0.0	2.0	2	1	0	2
12 Apr	9.7	1.8	0.0	9.7	27	8	0	27
13 Apr	13.8	2.2	0.0	13.8	784	515	0	784
14 Apr	2.1	1.1	0.0	2.1	399	205	0	399
15 Apr	10.7	2.3	2.2	8.5	2540	443	32	2508
16 Apr	0.0	0.0	35.9	-35.9	0	0	1257	-1257

[z]Average observed of two hillslopes.

[y]SE = Standard Error of the mean of observed treatments= $SD/\sqrt{n}$.

[x]Simulated.

[w]Relative difference.

[v]Sediment yield is simulated using the MUSS (Moderate Rate) equation.

Table 3.3. Observed and simulated daily runoff and sediment yield from rainfall events at Breton, Alberta, using EPIC 8120 and beginning the simulation 1 Jan., 1995, using the Green & Ampt method for estimation of runoff, with peak rainfall intensity input.

Date	Runoff				Sediment yield			
	Ob[z]	SE[y]	Sim[x]	RD[w]	Ob	SE	Sim[v]	RD
	mm				kg ha^{-1}			
1995								
5-6 Jun	0.0	0.0	2.9	-2.9	0	0	263	-263
18 Jun	0.0	0.0	0.5	-0.5	0	0	0	0
24 Jun	0.4	0.0	0.9	-0.5	-	-	0	-
1-3 Jul	0.8	0.4	3.1	-2.3	15	8	1031	-1016
4 Jul	4.8	0.5	2.1	2.7	48	5	695	-647
29 Jul	1.8	0.5	3.1	-1.3	151	69	1135	-984
7-8 Aug	2.0	0.4	0.6	1.4	45	7	0	45
11-13 Aug	1.4	0.4	0.0	1.4	48	16	0	48
15 Aug	1.4	0.1	0.0	1.4	14	1	0	14
19 Aug	3.5	0.0	3.4	0.1	108	2	755	-647
21 Aug	3.3	0.0	0.0	3.3	351	0	0	351
1996								
18-19 Jun	2.1	0.3	10.9	-8.8	39	4	3144	-3105
1 Jul	1.5	0.1	1.8	-0.3	614	273	547	67
9 Jul	0.5	0.2	0.0	0.5	24	14	0	24
15-16 Jul	1.9	0.3	0.7	1.2	1485	625	0	1485
18 Jul	1.5	0.2	0.0	1.5	420	144	0	420
20-21 Jul	0.1	0.1	0.0	0.1	5	2	0	5
24 Jul	0.7	0.1	0.0	0.7	65	17	0	65
2-3 Aug	12.5	0.2	8.2	4.3	1978	770	1477	501

[z]Average observed of two hillslopes.

[y]SE = Standard Error of the mean of observed treatments= $SD/\sqrt{n}$.

[x]Simulated.

[w]Relative difference.

[v]Sediment yield is simulated using the MUSS (Moderate Rate) equation.

Table 3.4. Rainfall precipitation, duration, maximum 15-minute intensity and comparison of observed runoff to precipitation ratios (OQ/P) and sediment yield (OSY) to EPIC-simulated runoff to precipitation ratios (SQ/P) and sediment yield (SSY) for two hillslopes located at Breton, Alberta.

Date	Precip.	Duration	Max. Int.	OQ/P[z]	SQ/P	OSY[z]	SSY[y]
	mm	h	mm h^{-1}	%	%	kg ha^{-1}	kg ha^{-1}
1995							
5-6 Jun	28.2	8.50	21.6	0.0	10.0	0	263
18 Jun	12.6	3.25	15.0	0.0	4.0	0	0
24 Jun	8.8	1.00	28.0	4.5	10.2	-	0
1-3 Jul	33.8	11.50	31.2	2.4	9.2	15	1031
4 Jul	19.6	4.75	16.5	24.5	10.7	48	695
29 Jul	30.2	11.00	12.0	6.0	10.3	151	1135
7-8 Aug	34.2	25.50	8.8	5.8	2.0	45	0
11-13 Aug	15.4	11.75	8.8	9.1	0.0	48	0
15 Aug	6.4	1.25	12.0	21.9	0.0	14	0
19 Aug	13.6	1.75	39.2	25.7	25.0	108	755
21 Aug	16.4	3.00	14.4	20.1	0.0	351	0
1996							
18-19 Jun	83.8	35.00	10.4	2.5	13.0	39	3144
1 Jul	10.2	1.25	24.0	14.7	17.6	614	547
9 Jul	12.0	6.25	4.0	4.2	0.0	24	0
15-16 Jul	13.8	6.00	20.8	13.8	5.1	1485	0
18 Jul	6.0	1.25	13.6	25.0	0.0	420	0
20-21 Jul	4.8	4.50	2.4	2.1	0.0	5	0
24 Jul	6.2	0.50	19.2	11.3	0.0	65	0
2-3 Aug	75.6	16.00	22.4	16.5	10.8	1978	1477

[z]Average observed of two hillslopes.

[y]Sediment yield is simulated using the MUSS (Moderate Rate) equation.

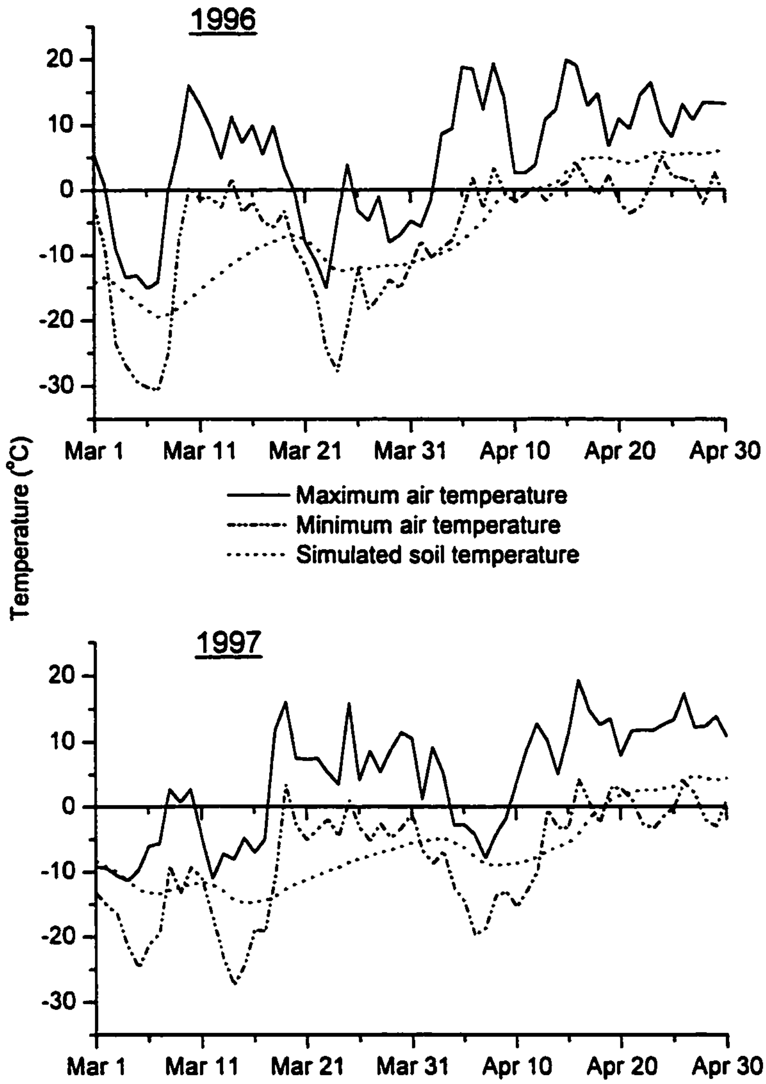

Figure 3.1. Recorded daily air temperature and EPIC-simulated soil temperature at 9-cm depth prior to and during snowmelt for 1996 and 1997 at Breton, Alberta.

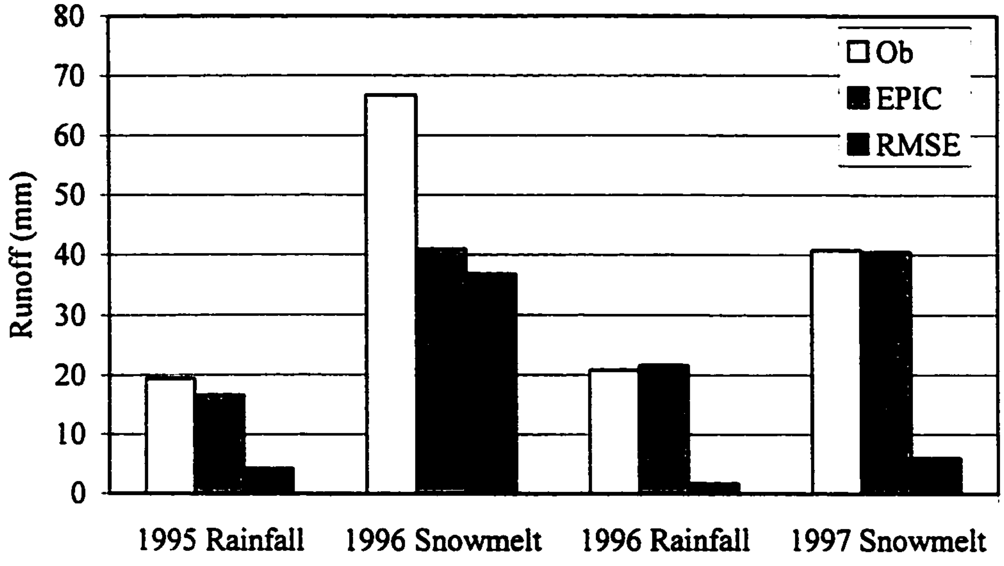

Figure 3.2. Average observed, EPIC-simulated and Root Mean Square Error of seasonal runoff at Breton, Alberta during 1995 to 1997.

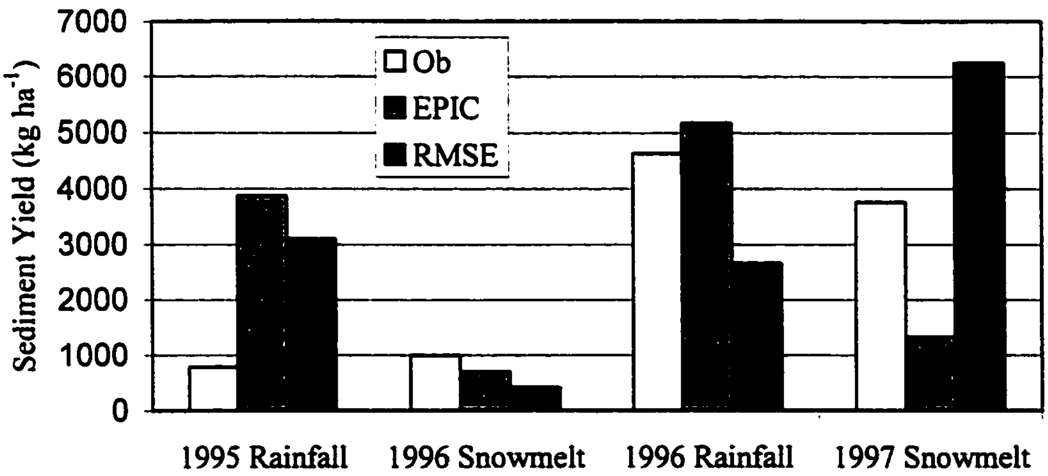

Figure 3.3. Average observed, EPIC-simulated and Root Mean Square Error of seasonal sediment yield at Breton, Alberta during 1995 to 1997.

4. WEPP SIMULATION OF RUNOFF AND SEDIMENT YIELD FROM TWO FALLOWED HILLSLOPES

4.1. Introduction

Erosion prediction is widely used and has become a powerful tool for soil conservation planning and government policy evaluation (Laflen et al. 1991; Izaurralde et al. 1996). In the past, most erosion predictions used some form of the factor-based Universal Soil Loss Equation (USLE) developed by Wischmeier and Smith (1968), with varied success (Laflen et al. 1991). Concurrent with the development of factor-based erosion prediction equations was research on fundamental erosion processes, where researchers described in detail the processes associated with rainfall and runoff erosion (Foster 1991). However, development of process-based erosion equations were hindered by an incomplete knowledge base and the inaccessibility of computers required for driving the process-based erosion prediction models. In the last two decades, vast improvements in computer technology have mirrored the development of computer erosion prediction technology. In 1985, the U.S. Department of Agriculture (USDA), Agricultural Research Service (ARS), and several other agencies began a cooperative project to develop new generation, process-based technology for predicting erosion by water. This project, the Water Erosion Prediction Project (WEPP), was designed to replace the USLE once fully developed and implemented (Ghidey and Alberts 1996).

WEPP is a distributed parameter, continuous simulation model developed in the United States to predict erosion from a hillslope or watershed based on specific requirements and knowledge of fundamental hydrologic and erosion processes (Laflen et al. 1991). With the input of climate, slope, soil and crop/management data, the model can simulate time-integrated and spatial estimates of runoff, erosion, sediment delivery and sediment enrichment. WEPP has been successfully used to simulate soil loss in the United States (Ghidey and Alberts 1996; Zhang et al. 1996). However, it is unclear whether the erodibility equations used in WEPP are suitable for the younger soils of Alberta under a cooler climate (Wright et al. in press).

Relatively few studies have documented the use of WEPP to simulate water erosion and runoff in Alberta. Hayhoe et al. (1993) were unable to simulate snowmelt runoff using data from the Peace River region because of WEPP's apparent inability to estimate snow depth, soil frost depth and frequency of freeze-thaw cycles. Izaurralde et al. (1994) documented WEPP simulations that were based on existing runoff data, but the results were variable. They concluded that improved erosion estimates would be obtained by using erodibility parameters specifically determined for Alberta soil conditions. Wright et al. (in press) discussed the methods and results of determining these erodibility parameters. The objective of this study was to determine the influence of measured and estimated erodibility parameters on WEPP (version 99.5) predictions of runoff and erosion at a location in central Alberta, Canada.

4.2. Erosion and Winter Hydrology Subroutines in WEPP

4.2.1. Hillslope Erosion Processes

WEPP simulates soil erosion as a process of rill and interrill detachment and transport. Description of components involved in each process is beyond the scope of this study; however, the fundamental equations used in the erosion component of the model will be briefly discussed. Additional details can be obtained from Flanagan and Livingston (1995).

To describe the movement of sediment in a rill, WEPP uses a steady state sediment continuity equation (Foster et al. 1995):

$$\frac{dG}{dx} = D_f + D_i \qquad [1]$$

where G is sediment load (kg s^{-1} m^{-2}), x is distance downslope (m), D_f is rill erosion rate (kg s^{-1} m^{-2}), and D_i is interrill erosion rate (kg s^{-1} m^{-2}). Interrill sediment delivery, D_i, is the delivery rate of sediment to concentrated flow channels, or rills. The D_i term is considered to be independent of x, and is always positive. The rill erosion rate, D_f is positive for net detachment or negative for net deposition.

Interrill sediment delivery is the detachment and transport of soil particles by raindrops and shallow overland flow (Laflen et al. 1991). Interrill sediment delivery is calculated using the equation (Foster et al. 1995; Zhang et al. 1998):

$$D_i = K_{iadj} I_e \sigma_{ir} SDR_{RR} S_f \qquad [2]$$

where D_i is interrill detachment rate (kg s^{-1} m^{-2}), K_{iadj} is adjusted interrill erodibility (kg s m^{-4}), I_e is effective rainfall intensity (m s^{-1}), σ_{ir} is interrill runoff rate (m s^{-1}), SDR_{RR} is a sediment delivery ratio, and S_f is the slope adjustment factor (Elliot et al. 1989).

Rill erosion is the removal of soil particles by concentrated flowing water. The net rill detachment capacity (D_f) of water is calculated when hydraulic shear exceeds the critical shear stress of the soil and when sediment load is less than sediment transport capacity (Foster et al. 1995) using the equation:

$$D_f = D_c\left(1 - \frac{G}{T_c}\right) \qquad [3]$$

where D_c is detachment capacity by rill flow (kg s^{-1} m^{-2}), G is sediment load (kg s^{-1} m^{-1}) and T_c is sediment transport capacity in the rill (kg s^{-1} m^{-1}). The rill detachment capacity, D_c, is calculated when hydraulic shear stress (τ_f, Pa) exceeds the critical shear stress required for detachment to occur (τ_c, Pa) using the equation:

$$D_c = K_r(\tau_f - \tau_c) \qquad [4]$$

where K_r is a rill erodibility parameter (s m^{-1}). Rill erodibility and critical shear stress are simulated on a daily basis within WEPP to account for various temporally changing factors, including incorporated residue, roots, sealing and crusting, and freezing and thawing.

Hydraulic shear stress (τ) represents the energy available for detaching soil particles within the rill and can be calculated using the equation:

$$\tau = \gamma R S_f \qquad [5]$$

where γ is the specific weight of water (N m^{-3}), R is the hydraulic radius (m) and S_f is the friction slope (m m^{-1}). Hydraulic radius (R) is calculated using the equation:

$$R = \frac{A}{P} \qquad [6]$$

where A is the rill cross sectional area (m^2) and P is the wetted perimeter (m).

The system is said to be in equilibrium with net detachment equal to net deposition when the transport capacity is reached for a given flow condition. By changing the flow condition, the system favors either detachment or deposition (Cochrane and Flanagan 1996).

4.2.2. Winter Hydrology

On an hourly basis, the WEPP winter hydrology subroutines simulate snow accumulation and density, snowmelt, and soil freeze and thawing. Winter subroutines are called when a snowpack is present, frost is present in the soil and average daily temperature is less than 0°C. Because the climate input file is on a daily basis, WEPP calculates hourly values based on these daily values for precipitation, temperature and radiation before simulating snow accumulation, snowmelt, and soil freeze and thaw.

The snowmelt rate equation used in WEPP is a modification of a generalized basin snowmelt equation by Hendrick et al. (1971), and is expressed as:

$$hrmelt = 0.0254(amelt - bmelt + cmelt + dmelt) \qquad [7]$$

where *hrmelt* is the hourly melt water, 0.0254 is a conversion factor from inches to meters, *amelt* represents hourly radiation and canopy cover, *bmelt* represents the amount of long wave radiation coming down on a snowpack due to cloud cover, *cmelt* represents the effects of wind, and *dmelt* represents the hourly air temperature and any heat input from rainfall.

In WEPP, snowmelt is dependent on hourly simulated temperature, radiation, vapor transfer and precipitation. A number of assumptions are made when calculating snowmelt: a) any precipitation that is simulated to occur on an hour when the maximum daily temperature is < 0°C is snowfall; b) no snowmelt will occur if the maximum daily temperature is < -3°C; c) the snowpack will not melt until the snowpack density is ≥ 350 kg m^{-3}; d) the surface soil temperature equals 0°C during the melt period; e) the temperature of a cloud base is approximately the same as the surface air temperature; and f) the albedo of melting snow is approximately 0.5 (Flanagan and Livingston 1995). Fresh snow is assumed to have a density of 100 kg m^{-3}.

The soil frost subroutine in WEPP predicts hourly frost and thaw development based on daily inputs of maximum and minimum air temperature and snow depth. Based upon simple heat flow theory, the frost subroutine assumes that heat flow in a frozen or unfrozen soil or soil-snow system is unidirectional and that the average 24-h temperature of the system surface-air interface is approximated by the average daily air temperature. The hourly surface temperature is computed by a surface energy balance routine (Flerschinger 1987) that modifies hourly air temperature by accounting for wind speed, solar radiation, cloud cover and atmospheric emissivity. Over a 24-h period, the subroutine iteratively balances the heat lost through the snow-soil zone with heat flow through the unfrozen soil to the freezing front.

4.3. The Input Datasets and Model Runs

The major inputs to WEPP are a climate data file, a slope data file, a soil data file and a cropping/management file. All input files were edited to reflect the conditions that existed at the study site prior to, and during, the course of the study.

4.3.1. Climate Data File

Climatic input data required to initialize model runs were obtained during the runoff study presented in Chapter 2. In order to simulate erosion at any given time in the past, WEPP requires daily inputs of rainfall amount, duration, maximum intensity, time to peak intensity, maximum and minimum air temperature, solar radiation, wind speed, wind direction, and dew point temperature. Except for dew point temperature, the on-site meteorological station collected these data for most days. Missing temperature and precipitation data was obtained from near the Town of Breton (5 km west, and 8 km north of the study site) for September to November, 1995, when the on-site station was being repaired. The accuracy of this data were not critical as no runoff occurred during this period. Dew point temperature (T_d, °C) was calculated using the equation:

$$T_d = \frac{b}{\left[\frac{a}{\log RH + \left(\frac{aT}{b+T}\right) - 2}\right] - 1} \qquad [8]$$

where T is air temperature (°C), RH is relative humidity (%), a is 7.5 and b is 237.3 (Tetens 1930). For air temperature (T), daily average air temperature was used in the calculation.

Precipitation dynamics were calculated based on 1-min output readings from a tipping raingauge during precipitation events (Appendix 1.1 and 1.2). Similar to U.S. National Weather Service methodology, daily storm duration (h) was calculated by adding all 15-min time intervals with precipitation, removing all inter-storm periods with zero rainfall from the total. The time to peak was calculated from the beginning of the first precipitation interval to the end of the 15-min interval containing the peak intensity. The time to peak is the ratio of time to rainfall peak (h) over the rainfall duration (h). Peak rainfall intensity is the ratio of maximum 15-min rainfall intensity (mm h^{-1}) over the average rainfall intensity (mm h^{-1}).

Snowfall precipitation in the daily meteorological input data set was that recorded near the Town of Breton. As snow depth and snow density are simulated in WEPP, values were not adjusted prior to snowmelt to reflect observed values during the study period. Rather, these values are compared in the results. In WEPP, the snow depth and snow density is simulated hourly as previously discussed. Snow depth and snowwater equivalents were measured throughout the winter and were presented in Table 2.3.

For initialization of the model for simulation beginning 1 January 1995, frost depth was set to 0.5 m and snow depth set to 0.3 m. The actual initialization values were not known.

4.3.2. Slope Data File

Landscape geometry parameters used in WEPP include slope orientation, slope length and slope steepness at points down the slope profile. The plots were 64 m long on an area with a 5% slope and a southerly aspect. Only one Overland Flow Element (OFE) was used in the simulation, reflecting homogeneous soils, cropping and management over the whole plot area.

4.3.3. Soil Data File

Soil properties are input to the WEPP model through the soil input file. Properties for each soil layer (Table 4.1) include soil layer thickness (mm), sand content (%), clay content (%), organic matter content by volume (%), cation exchange capacity (meq 100 g^{-1}), and percentage of rock fragments by volume (%). Soil properties for the first layer were those determined by Wright et al. (*in press*) while subsequent layer properties were described by Izaurralde et al. (1993).

Soil hydrological parameters include baseline effective hydraulic conductivity (K_b), baseline interrill erodibility parameter (K_i), baseline rill erodibility parameter (K_r) and baseline critical shear stress parameter (τ_c). The baseline effective hydraulic conductivity is a key WEPP parameter used in the Green and Ampt determination of infiltration. The value of K_b is different than that of saturated conductivity, although the parameters are related. A value of zero (0.0) was entered to allow the model to generate an initial conductivity value (mm h^{-1}) based on the equation:

$$K_b = -0.46 + 0.05 * SAND^{1.25} + 9.44 * CEC^{-0.69} \qquad [9]$$

where SAND is the percentage of sand and CEC (meq 100 g^{-1}) is the cation exchange capacity of the soil. With this parameter, WEPP will run in two modes by either: a) using a K_b value that is adjusted daily to account for the effects of climate, tillage, residue, crusting, and macroporosity; or b) using a constant input value of K_b which is representative of both the soil and the management practice modeled (Flanagan and Livingston 1995). For these simulations, internal adjustment of K_b (mode "a") was allowed during simulation.

The WEPP model was run using two different sets of values for K_i, K_r and τ_c in the soil input data file (Table 4.2). The first simulation consisted of a soil input data file with soil erodibility input parameters based on WEPP prediction equations (Flanagan and Livingston 1995):

$$K_i = 2728000 + 192100 * VFS \quad [10]$$

$$K_r = 0.00197 + 0.00030 * VFS + 0.03868e^{-1.84*ORGMAT} \quad [11]$$

$$\tau_c = 2.67 + 0.065 * CLAY - 0.058 * VFS \quad [12]$$

where VFS is percent very fine sand, ORGMAT is percent organic matter and CLAY is percent clay. These equations were the result of experiments conducted on 36 soils in the United States. These values were designated as "estimated" in Table 4.2. The second simulation consisted of a soil input data file with mean soil erodibility input values that were calculated after rill and interrill erosion experiments conducted on the Breton loam soil (Wright et al. *in press*). These values were designated as "measured" in Table 4.2. Throughout the simulations, algorithms within WEPP make adjustments to the interrill erodibility parameter (K_{iadj}) to account for root biomass, freezing and thawing, canopy cover, residue cover, and sealing and crusting. Similarly, different relationships are used for adjustment of the rill erodibility parameter (K_{radj}) and critical shear stress parameter (τ_{cadj}). Additional details of these adjustments can be found in Flanagan and Livingston (1995).

4.3.4. Cropping and Management Data File

Plot management operations and the dates on which they occurred were presented in Section 2.2.2. Tillage implements and their pre-defined parameter values were selected from existing tillage parameter files based on actual tillage properties.

The simulation was started 1 January 1995 and ended 31 December 1997. Daily output for variables of interest such as runoff (mm) and maximum detachment (kg m^{-2}) were tabulated and compared to that presented in Section 2.3. Variables used in winter subroutines were also outputted to observe the functionality of hourly simulated snowmelt and thaw depth.

Observed values for actual runoff volume and sediment yield represent an average of the two hillslopes. Standard errors were calculated to express the variability between the two hillslopes. On an event basis, the relative difference (RD) was calculated as the difference between the average observed value and the simulated value, where a positive RD value represented an underestimated simulated value and a negative RD value represented an overestimated simulated value for runoff volume and sediment yield.

Total seasonal observed and simulated values of runoff and sediment yield were compared using the Root Mean Square Error (RMSE) method:

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{N}(O_i - S_i)^2}{N}} \qquad [13]$$

where O_i and S_i are event-based observed and simulated values, respectively, and N is the number of observations. This method is commonly recommended for analysis of model performance (Smith et al. 1996). The smaller the RMSE, the closer the simulated values are to the observed values.

4.4. Results

4.4.1. Runoff and Erosion due to Snowmelt Events

In 1996, snowmelt runoff began 13 March and ended 5 April. There was no runoff within the period 19 March – 3 April. In 1997, snowmelt began 25 March and ended 15 April. No runoff was observed during the period 26 March – 29 March and again during 1 April – 10 April. WEPP-simulated winter runoff was identical whether soil erodibility parameters had been estimated or measured. For both simulations, snowmelt was simulated at numerous times throughout the winters. For both simulations, snowmelt was simulated at numerous times throughout the winters. However, WEPP only predicted one snowmelt day with runoff totaling 4.4 mm on April 5, 1996 (Table 4.3). This runoff was the result of precipitation received between 19 March and 3 April, not from the observed snowpack that had accumulated over the winter. From January through March, 1996, WEPP simulated three periods when the snowpack was absent due to snowmelt. Unlike 1995 - 1996, WEPP simulated a continuous snowpack in 1996 - 1997 until the completion of snowmelt on 27 March. However, snowmelt was again predicted throughout the winter except during the period when runoff was measured. The RMSE for total snowmelt runoff was 67.6 mm and 41.2 mm for 1995 - 1996 and 1996 - 1997, respectively, for both simulations.

Predictions of snowmelt sediment yield for the 5 April 1996 event varied according to the soil erodibility equation used (Table 4.4). With the estimated soil erodibility values, WEPP did not simulate any soil detachment (RD = 502 kg ha^{-1}). In comparison, WEPP simulated a soil loss of 600 kg ha^{-1} when used with the measured soil erodibility parameters (RD = 98 kg ha^{-1}). This agrees more closely to the observed total snowmelt soil loss of 991 kg ha^{-1}, however, runoff volumes were considerably lower (66.7 mm observed, 4.4 mm simulated). In 1997 sediment loss as a result of snowmelt was not simulated by WEPP (RD = 3758 kg ha^{-1}).

The output of the simulated daily water balance showed that on days of snowmelt but no runoff, snowmelt was largely increasing the total soil water, with small losses to soil evaporation and deep percolation. Soil evaporation is evaporation from the snow cover, or from the soil when calculated soil evaporation (m d^{-1}) exceeds the water content of the snow cover. Deep percolation is percolation below the root zone, and is considered lost from the WEPP water balance (Flanagan and Livingston 1995). For example, on 5 April 1996, WEPP predicted 27.7 mm of snowmelt, of which 4.4 mm became runoff, 3.9 mm evaporated, 0.3 mm deep percolated and 19.1 mm infiltrated (increased total soil water). This generally was the case throughout the winter, despite thaw depth being 0 mm. The runoff in this example was the exception.

Snow depth, snow density and thaw depth were simulated by WEPP on an hourly basis. Because of the erroneous simulation of mid-winter snowmelts, WEPP did poorly in estimating snow depth and snowwater equivalent during the winter of 1995 – 1996 (Table 4.5). However, the simulation of the snowwater equivalent was comparable to that observed during the winter of 1996 – 1997. Thaw depth was always simulated to be 0 mm when snow was present. However, during the winter periods in which WEPP simulated the absence of snow, thaw depth increased hourly to a simulated maximum and returned to 0 mm the next subsequent hour (generally the first hour of the next day). The number of freeze-thaw cycles simulated by WEPP does not appear to be realistic.

While the simulations predicted snowmelt runoff and sediment yield, they only predicted 6% of the snowmelt runoff events that occurred on a daily basis. Because of the small number of snowmelt runoff events simulated, it is difficult to determine which set of parameters resulted in a closer simulation of erosion for the Luvisolic soil at Breton, Alberta. A better simulation of snowmelt runoff on an event basis may aid in the determination of the suitable set of soil erodibility equations for the Breton soil.

4.4.2. Runoff and Erosion due to Rainfall Events

For the purpose of this study, a rainfall event was defined as the period of time during which rainfall, or potential rainfall was present. Rainfall events were separated by a period of no rainfall during which runoff and sediment from a previous event were sampled. Runoff resulted from nine rainfall events in 1995 and eight rainfall events in 1996 (Appendix 1.1 and 1.2). For both simulations, WEPP simulated identical runoff from two rainfall events in 1995 and one rainfall event in 1996 (Table 4.3). In 1995, the rainfall event on 4 July of 19.6 mm resulted in predicted runoff of 3.3 mm (RD = 2.4 mm). Runoff may have been predicted because of the high simulation of total soil water from three consecutive days of rainfall for a total of 33.8 mm prior to this rainfall, as well as to relatively short duration (4.75 h) of the storm. In comparison, no runoff was simulated for the 29 July rainfall of 30.2 mm because of lower antecedent moisture conditions and the storm's long duration (11 h). A second rainfall runoff event was simulated on 19 August 1995 (runoff = 0.5 mm; RD = 3.0 mm). Runoff may have been predicted because of the storm's short duration (1.75 h) and high peak rainfall intensity (39.2 mm h^{-1}), the highest measured during the study. Generally, WEPP increased total soil water by 70 - 80% of the precipitation amount for all observed runoff events rather than simulating runoff. Annual simulated runoff was 4% of that observed for summer rainfall events (RMSE = 18.6 mm).

In 1996, WEPP predicted runoff of 7.4 mm from the 3 August rainfall event of 58.4 mm. Observed runoff for this event was 12.5 mm (RD = 5.1 mm). Unlike the 1995 storm, this storm was of long duration and moderate intensity. Again, all the other rainstorms in 1996 resulted in the simulation of infiltration rather than runoff. No trend was observed between predicted runoff and observed rainfall characteristics. The RMSE for annual rainfall runoff in 1996 was 13.3 mm, suggesting a similar estimation of runoff to that for 1995.

Predictions of rainfall sediment yield differed depending on the soil erodibility parameters used (Table 4.4). The estimated soil erodibility parameters resulted in lower sediment yield predictions than the measured parameters, with runoff volumes the same. In 1995, the two simulated runoff events resulted in prediction of no sediment using the estimated parameters versus 900 kg ha^{-1} using the measured parameters. An even greater difference between the soil erodibility parameters was observed in the 1996 rainstorm prediction than in 1995. Sediment yield was simulated to be 100 kg ha^{-1} using the estimated parameters versus 6200 kg ha^{-1} using the measured parameters. This difference was the result of the soil erodibility parameters as all other input values were identical.

In 1995, sediment yields from the 4 July and 19 August events were underestimated using estimated soil erodibility parameters (RD = 48 and 108 kg ha^{-1}, respectively), and overestimated using measured soil erodibility parameters (RD = -452 and -292 kg ha^{-1}, respectively). Consequently, annual rainfall sediment yield was underestimated by 100% for estimated simulations (RMSE = 795 kg ha^{-1}), but only overestimated by 15% for measured simulations (RMSE = 191 kg ha^{-1}). In 1996, sediment yield on an event basis was underestimated using the estimated soil erodibility parameters (RD = 1878 kg ha^{-1}) and overestimated using the measured soil erodibility parameters (RD = -4222 kg ha^{-1}). On an annual basis, however, predictions using the measured soil erodibility parameters were closer to observed sediment yields than that using the estimated parameters (RMSE = 3039 and 5226 kg ha^{-1}, respectively).

While both simulations predicted rainfall runoff and sediment yield, they only simulated 22% and 13% of the runoff events that occurred in 1995 and 1996, respectively. Because of the small number of rainfall runoff events simulated, it is difficult to determine which set of parameters results in a closer simulation of erosion for the Breton soil. A better simulation of rainfall runoff on an event basis may aid in the determination of the suitable set of soil erodibility equations for the Breton soil.

4.5. Discussion and Conclusions

A test of estimated and measured soil erodibility parameters in WEPP was conducted to determine its ability to simulate water erosion under conditions existing on two similar hillslopes in central Alberta where measurements of runoff quantity and sediment yield were made. The simulation of runoff was identical for both model runs as the soil erodibility parameters K_i, K_r and τ_c are used in the estimation of soil loss rather than runoff. WEPP simulated rainfall runoff on two days out of nine rainfall runoff events in 1995, and one day out of eight rainfall runoff events in 1996. WEPP simulated snowmelt on one of the nine days that runoff was measured in the field in 1996, and zero of the eight days that runoff was measured in the field in 1997. Both simulations underestimated the runoff quantity that was observed on those days. Sediment yields were all underestimated using the estimated soil erodibility parameters. In contrast, sediment yields were all overestimated using the measured soil erodibility parameters, although only slightly for the 5 April, 1995 snowmelt event.

The lack of runoff estimation makes it difficult to conclusively state which set of soil erodibility parameters resulted in better erosion simulation. Because infiltration played such a large role on the water balance during days of precipitation, runoff predictions would likely be improved by inputting an initial value for the baseline effective hydraulic conductivity parameter (K_b) rather than allowing for WEPP prediction of this parameter. Van der Zeep and Stone (1991) showed that model performance increased when K_b was calibrated rather than estimated based on soil properties on a rangeland watershed. However, Risse et al. (1993) concluded that even with calibration of K_b, runoff was still overestimated from small events and underestimated from large events for fallow runoff plots at seven locations, suggesting a flaw in the Green and Ampt equation, the WEPP model, and/or the available data.

Excessive infiltration during snowmelt and runoff also suggests that WEPP is not accounting for the characteristic flow-restricting soil layer within a Luvisolic soil. The percolation component of WEPP uses storage routing techniques similar to that described by Arnold et al. (1990). In this component, the saturated hydraulic conductivity of each soil layer is calculated in WEPP based on soil texture, organic matter content and porosity. A saturated or nearly saturated lower layer may reduce flow through an upper soil layer. Unfortunately, daily changes of soil moisture throughout the soil profile are not output in WEPP. Therefore, it is difficult to determine whether WEPP can simulate a flow-restricting soil layer based on just the input of texture and organic matter content for each soil layer.

Similar to that observed by Hayhoe et al. (1993), this study demonstrates that the need to adapt the winter component of WEPP to northern latitudes still exists. WEPP was unable to simulate the observed snow depth because of its tendency to simulate snowmelt on days and hours when snowmelt does not occur. Also, WEPP appeared to simulate unrealistic amounts of infiltration when the soil was frozen. Further study is required on the calibration of the baseline effective hydraulic conductivity parameter for Luvisolic soils in Alberta before a conclusive analysis of the measured versus predicted soil erodibility parameters can be completed.

4.6. References

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Table 4.1. Input Breton soil properties used in WEPP simulations.

Layer thickness (mm)	180	150	430	510	50	50
Sand content (%)	36	34	32	31	35	32
Clay content (%)	17	29	33	33	27	28
Organic matter (%)	1.6	0.3	0.5	0.3	0.1	0.0
CEC (meq 100 g^{-1})	20	18	21	21	20	18
Rock fragments (%)	5	5	5	1	1	1

Table 4.2. Input values of the WEPP estimated and measured soil erodibility parameters for a Breton soil.

Interrill Erodibility (kg s m^{-4})	Estimated[z]	4380060
	Measured[y]	2989929
Rill Erodibility (s m^{-1})	Estimated[z]	0.00478
	Measured[x]	0.00424
Critical Shear (Pa)	Estimated[z]	3.28
	Measured[x]	0.94

[z]Based on equations 10 – 12, where CLAY is 17%, VFS is 8.6% and ORGMAT is 1%.

[y]Averaged values based on measurements obtained using a Guelph Rainfall Simulator on disturbed soil in the laboratory (Wright et al. in press).

[x]Averaged values based on measurements from four created rills on fallow soil at Breton (Wright et al. in press).

Table 4.3. Observed and simulated runoff at Breton, Alberta, using WEPP 99.5 and beginning the simulation Jan. 1, 1995, with soil erodibility parameters (e)stimated and (m)easured.

Date	Runoff					
	Ob[z]	SE[y]	Sim(e)[x]	RD(e)[w]	Sim(m)	RD(m)[w]
	mm					
1995 Rainfall Events						
4 Jul-95	4.8	0.5	0.3	4.5	0.3	4.5
19 Aug-95	3.5	0.0	0.5	3.0	0.5	3.0
Events total	19.4	2.4	0.8	18.6	0.8	18.6
1995 – 1996 Snowmelt Events						
5 Apr-96	6.8	1.2	4.4	2.4	4.4	2.4
Events total	66.7	18.6	4.4	62.3	4.4	62.3
1996 Rainfall Events						
2-3 Aug-96	12.5	0.2	7.4	5.1	7.4	5.1
Events total	20.8	1.0	7.4	13.4	7.4	13.4
1996 -1997 Snowmelt Events						
Events total	40.8	4.2	0	40.8	0	40.8

[z]Average observed of two hillslopes.

[y]SE = Standard Error of the mean of observed treatments= $SD/\sqrt{n}$.

[x]Simulated.

[w]Relative difference.

Table 4.4. Observed and simulated sediment yield at Breton, Alberta, using WEPP 99.5 and beginning the simulation Jan. 1, 1995, with soil erodibility parameters (e)stimated and (m)easured.

Date	Sediment Yield					
	Ob[z]	SE[y]	Sim(e)[x]	RD[w]	Sim(m)	RD[w]
	kg ha^{-1}					
1995 Rainfall Events						
4 Jul-95	48	5	0	48	500	-452
19 Aug-95	108	2	0	108	400	-292
Events total	780	105	0	780	900	-120
1995 – 1996 Snowmelt Events						
5 Apr-96	502	58	0	502	600	-98
Events total	991	204	0	991	600	391
1996 Rainfall Events						
2-3 Aug-96	1978	770	100	1878	6200	-4222
Events total	4630	1257	100	4530	6200	-1570
1996 -1997 Snowmelt Events						
Events total	3758	287	0	3758	0	3758

[z]Average observed of two hillslopes.

[y]SE = Standard Error of the mean of observed treatments= $SD/\sqrt{n}$.

[x]Simulated.

[w]Relative difference.

Table 4.5. Observed and WEPP-simulated snow depth and snowwater equivalent.

Date	Snow Depth		Snowwater Equivalent	
	Observed[z]	Simulated	Observed[z]	Simulated
	mm			
17 Nov-95	135	60	22	21
23 Feb-96	201	0	56	0
13 Mar-96	164	0	55	0
8 Nov-96	61	27	6	7
29 Nov-96	277	401	46	64
24 Feb-97	391	231	79	81
25 Mar-97	260	116	59	40

[z]Average observed of two hillslopes.

5. SYNTHESIS

5.1. Introduction

Erosion is a complex process because the numerous factors that intervene in it contribute not only through their pure effects but also through their interactions. Numerous studies have been conducted in Alberta to quantify the extent of erosion, while characterizing specific factors contributing to the erosion process. The characterization of these factors generally varied among researchers depending on the study objectives. The objectives of this study included the quantification of runoff and sediment yield due to snowmelt and rainfall under a given set of weather patterns, landscape conditions, soil properties and management factors. Factors such as air temperature, slope steepness, cultivation frequency and soil texture were characterized using a combination of available data and data measured during the course of this study.

5.2. Observed Runoff and Sediment Yields

This study compared the quantity of snowmelt and rainfall runoff and sediment yield from two adjacent, similar hillslopes (identified as east and west hillslopes) maintained in a fallow condition at the University of Alberta Breton Plots, near Breton, Alberta, from mid 1995 to mid 1997 (Chapter 2). Snowmelt runoff comprised the majority of annual runoff volume discharged from the hillslopes, accounting for 68% of the total in 1995 – 1996 (using the west hillslope snowmelt runoff volume) and 66% in 1996 – 1997. In spring 1996, nine days of snowmelt produced on average 66.7 mm of runoff (SE = 18.6 mm). In spring 1997, eight days of snowmelt produced on average 40.8 mm of runoff (SE = 4.2 mm).

Runoff resulted from nine rainfall events in 1995 and eight rainfall events in 1996. Although total rainfall between April and October was 31% lower in 1995 than 1996, the amount of rainfall resulting in runoff was similar between 1995 and 1996. In

1995, 180.0 mm of rainfall resulted in an average of 19.4 mm of runoff. In 1996, 213.2 mm of rainfall resulted in an average of 20.8 mm of runoff.

In 1997, the average sediment yield during snowmelt was 26% greater than that recorded in 1996, although the 1996 average runoff volumes had been 61% greater than those in 1997. For both years, sediment yields generally increased during the later days of snowmelt, despite fluctuation in runoff volume on those days. Despite similarities in rainfall runoff volumes between 1995 and 1996, sediment yields were vastly different between years. In 1995, total average sediment yield of 780 kg ha^{-1} was 17% of that in 1996. However, this difference would not be as great when accounting for elevated sediment from flow back-up in 1996 (see Section 2.3.5).

Although the hillslopes were similar in size, slope, and soil type, were managed identically, and were subjected to apparently identical meteorological conditions, there was variability in runoff and sediment yield between the hillslopes. The variability in runoff and sediment yield was an indication of unexplained variability in the factors contributing to the erosion process. Based on the deviations between the measured runoff and sediment yield from these hillslopes, these data were suitable for designating acceptable limits for simulation of runoff and sediment yield.

5.3. Computer Simulation of Erosion

Simulation models of erosion are intellectual constructs designed to represent our understanding of erosion processes as controlled by climate, land and management factors. These computer models can be used in either retrospective (e.g. past erosion events) or prospective mode (e.g. climate change). The retrospective mode is generally used in model evaluation.

There are several advantages and disadvantages to using computer simulation models versus conducting erosion measurements in the field. Erosion simulations are advantageous because: a) they are less costly, less time consuming, and less labour intensive, and b) they can simulate different combinations of climate, landscape, management or soil conditions. The disadvantages of erosion simulations are: a) their spatial scale of application is generally limited; b) their limited ability to accounting for spatial variability; c) the model inputs are generally data intensive and sometimes not readily available; and d) although the algorithms are intended to be of general applicability (universal), they need to be tested rigorously to ensure they are able to reproduce local conditions. With proper validation using Alberta conditions, erosion simulation models are and will be acceptable tools for assessing the impact of erosion under conditions that exist in Alberta.

5.3.1. Comparison of EPIC and WEPP

Two such computer models that simulate erosion are the Environmental Policy Integrated Climate (EPIC) model and the Water Erosion Prediction Project (WEPP) model. EPIC is a comprehensive computer model developed in the United States to determine the relationship between soil productivity and erosion (Sharpley and Williams 1990). With the input of climate, landscape, soil, vegetation and management, the model can simulate changes in soil properties and crop yields as a result of wind and water erosion. WEPP is a distributed parameter, continuous simulation model developed in the United States to predict erosion from a hillslope or watershed based on specific requirements and knowledge of fundamental hydrologic and erosion processes (Laflen et al. 1991). With the input of climate, slope, soil and crop/management data, the model can simulate time-integrated and spatial estimates of runoff, erosion, sediment delivery and sediment enrichment. Although EPIC and WEPP have several fundamental differences (Table 5.1), both models can be applied towards simulation of erosion from two fallowed hillslopes in Alberta at latitude 53°N.

5.3.2. Comparison of EPIC and WEPP Simulations of Erosion

A study was conducted to evaluate the ability of EPIC (Chapter 3) and WEPP (Chapter 4) to simulate erosion based on data collected during 1995 to 1997 from two hillslopes at the Breton Plots. Input files for both models were initialized to reflect the conditions that existed at the study site prior to, and during, the course of the study. The following model comparisons will be made using the WEPP results obtained with the measured soil erodibility parameters (see Chapter 4).

Using EPIC, snowmelt runoff was correctly estimated in 1996 and 1997 (Figure 5.1), however, the model was unable to simulate runoff on a day-to-day basis. WEPP was unable to simulate the observed snowmelt runoff in 1996 or 1997. The results were similar to previous findings, where EPIC simulation using the Curve Number method for estimation of runoff provided adequate estimations of snowmelt runoff (Puurveen et al. 1997), while WEPP had difficulties in simulating snowmelt (Hayhoe et al. 1993).

Total sediment yields were correctly estimated using EPIC for snowmelt events in 1996, however, they were underestimated for snowmelt events in 1997 (Figure 5.2). WEPP overestimated sediment loss due to snowmelt in 1996.

Of the nine rainfall runoff events observed in 1995, EPIC simulated runoff from six of these events (in addition to two rainfall events when runoff was not observed), while WEPP simulated runoff for two rainfall runoff events. Total rainfall runoff was correctly simulated by EPIC for 1995, but underestimated by WEPP. Of the eight rainfall runoff events observed in 1996, EPIC simulated four of these events, while WEPP simulated one. Similar to 1995, EPIC correctly simulated total rainfall runoff, while WEPP underestimated rainfall runoff.

Total sediment yields for rainfall runoff events in 1995 were overestimated by EPIC, but correctly simulated by WEPP. As the WEPP simulation of sediment yield was based on only one runoff event, better simulation of runoff would likely have resulted in overestimation of sediment yield. Both EPIC and WEPP overestimated sediment yield on an event basis for all of the rainfall events simulated in 1995. Total sediment yields were correctly simulated by EPIC in 1996, but overestimated by WEPP. On an event basis, EPIC overestimated sediment yield from one event with low soil loss in 1996, while underestimating sediment yield from two low runoff events with high sediment yield. WEPP overestimated sediment yield on an event basis in 1996.

EPIC simulations of snowmelt and rainfall runoff and sediment yield were more acceptable than those of WEPP (Figure 5.3). While the observed sediment yield to runoff ratios ranged from 15 to 223 kg ha^{-1} mm^{-1}, EPIC simulated sediment yield to runoff ratios ranged from 17 to 240 kg ha^{-1} mm^{-1}. With EPIC, the Green and Ampt method for estimation of infiltration, with peak rainfall input, resulted in satisfactory estimations of runoff for both snowmelt and rainfall. Improvements are needed for better simulation of daily snowmelt runoff.

WEPP was generally unable to simulate snowmelt or rainfall runoff in spite of using a similar method to estimate infiltration. WEPP-simulated sediment yield to runoff ratios ranged from 136 to 1125 kg ha^{-1} mm^{-1}. The inability to adequately simulate snowmelt runoff was likely due to inadequacies in the winter hydrology subroutines. WEPP appeared overly responsive for simulating snowmelt and infiltration on winter days when the maximum air temperature was above 0°C. Because rainfall runoff was not simulated by WEPP for most events for both years, this would suggest that WEPP parameters governing infiltration were not optimally determined for the Luvisolic soil at Breton, Alberta.

In related research, EPIC version 3090, WEPP version 94.3 and GLEAMS version 2.1 (Groundwater Loading Effects of Agricultural Management System) were used to simulate the effects of two tillage systems on runoff and losses of sediment, N and P from a field-sized watershed in Alabama (Yoon et al. 1997). Both EPIC and WEPP simulated runoff within an order of magnitude. WEPP, however, did not simulate the trend of increased runoff from a conservation tillage system versus a conventional tillage system. In contrast, WEPP closely simulated the observed trend of reduced sediment with the conservation tillage system. EPIC overestimated annual sediment losses by amounts four to sixteen times greater than observed losses using the MUSS equation for sediment estimation, and calculated runoff curve numbers. This overestimation was attributed to the inability to account for the non-uniform watershed slope profile, where considerable deposition was observed in a depressional area near the watershed outlet.

EPIC version 3090 and WEPP version 91.5 were tested using data from four previous erosion studies in Alberta (Izaurralde et al. 1994) with varied results. EPIC adequately simulated springmelt using the Modified USLE equation (MUSLE) for sediment estimation, and the runoff curve number method for runoff determination. In contrast, WEPP soil loss simulations were not satisfactory for spring erosion events. For the summer events studied, WEPP simulations of soil loss were closer to measured values and less variable than that simulated by EPIC. The accuracy of these simulations cannot be confirmed since the simulation study derived a considerable amount of input data from sources other than the original studies.

5.4. Discussion

This study demonstrated the ability of EPIC and WEPP to simulate runoff and sediment yield, based on measured runoff and erosion during a two-year period at Breton (Alberta) in combination with climate, landscape, soil and management data. The simulations were aimed at testing algorithms describing hydrology and associated soil movement processes under cryoboreal subhumid conditions. The runoff and erosion data collected during the field experiment will continue to be useful to test future versions of these and other models.

The use of either of these models is dependent on individual erosion prediction needs. Renard et al. (1994) suggested that USLE-based erosion prediction models such as EPIC were less data intensive, more simplistic and user-friendly, and adequately estimated interrill and rill erosion. WEPP, on the other hand, was suggested to be data intensive, less simplistic and user-friendly, more powerful by being process-based, and was evolving technology. This study demonstrated that EPIC was adequate in the prediction of interrill erosion under cryoboreal subhumid conditions from hillslopes. WEPP, on the other hand, may be better suited to answer similar research-related questions at a watershed level, or where deposition is a major erosion component.

5.5. Possibilities for Future Research

While a considerable amount of data was collected for use and comparison to current erosion simulation models, complete model evaluation was restricted by the lack of information on several key factors. Future research efforts in this field should include:

1). More intensive study of hydrologic factors such as infiltration, evapotranspiration, and subsurface flow. Runoff represents only one of the components in the water balance.

2). More intensive study of the dynamics of snowmelt with respect to meteorological conditions, soil moisture and soil temperature. Snowmelt was shown to contribute the majority of annual runoff.

3). More intensive study of the soil erodibility parameters in WEPP, specifically the baseline effective hydraulic conductivity (K_b) parameter. Model performance was dependent on estimation of the K_b parameter, whereas the remaining soil erodibility parameters were determined on Alberta soils.

5.6. References

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Table 5.1. Fundamental Differences between EPIC and WEPP.

EPIC[z]	WEPP[y]
Simulates interrill erosion.	Simulates interrill and rill erosion, in addition to deposition.
Uses the SCS Runoff Curve Number method, or a modified Green-Ampt equation, for infiltration/runoff estimation.	Computes infiltration using the Green-Ampt equation for unsteady rainfall; simulates runoff after accounting for depressional storage when infiltration is exceeded.
Sediment yield based on the USLE or one of five other equations which are modifications of the USLE.	Uses a steady-state continuity equation to describe the movement of sediment in a rill.
Potential ET based on one (user specified) of five equations including the Penman or Priestly-Taylor method.	Potential ET based on the Penman Method or Priestly-Taylor method, depending on meteorological data availability.
Can simulate an area up to 1 ha as it assumes soils and management are spatially homogeneous.	Can simulate several hillslopes with distinct characterizations, where individual hillslopes (> 260 ha) are assumed homogeneous.
Uses a snowmelt component similar to the CREAMS model.	Snowmelt based on a modification of the Hendrick equation, a generalized basin snowmelt equation

[z]Sharpley and Williams 1990.
[y]Flanagan and Livingston 1995.

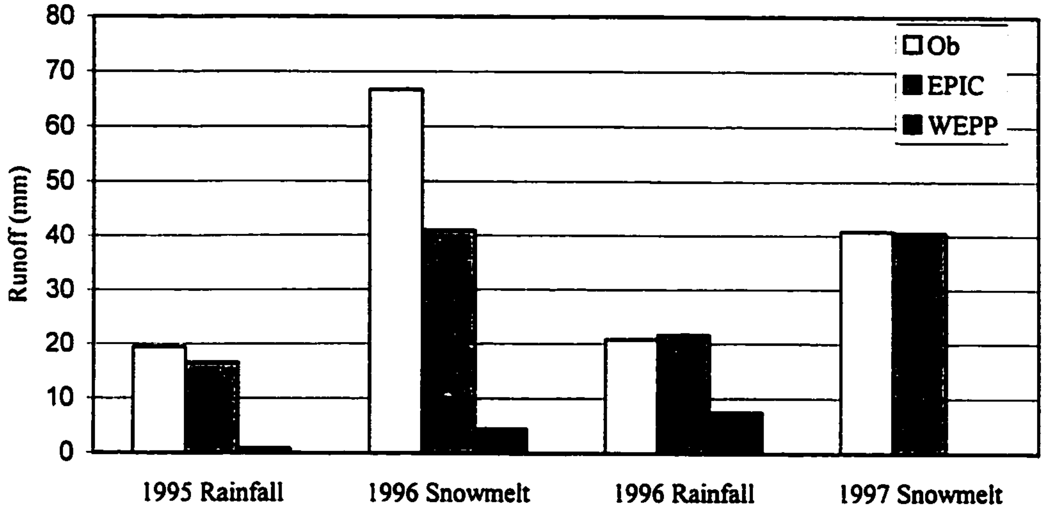

Figure 5.1. Seasonal runoff at Breton, Alberta during 1995 – 1997 as observed (Ob) on erosion plots and modeled with EPIC and WEPP. WEPP did not simulate snowmelt runoff in 1997.

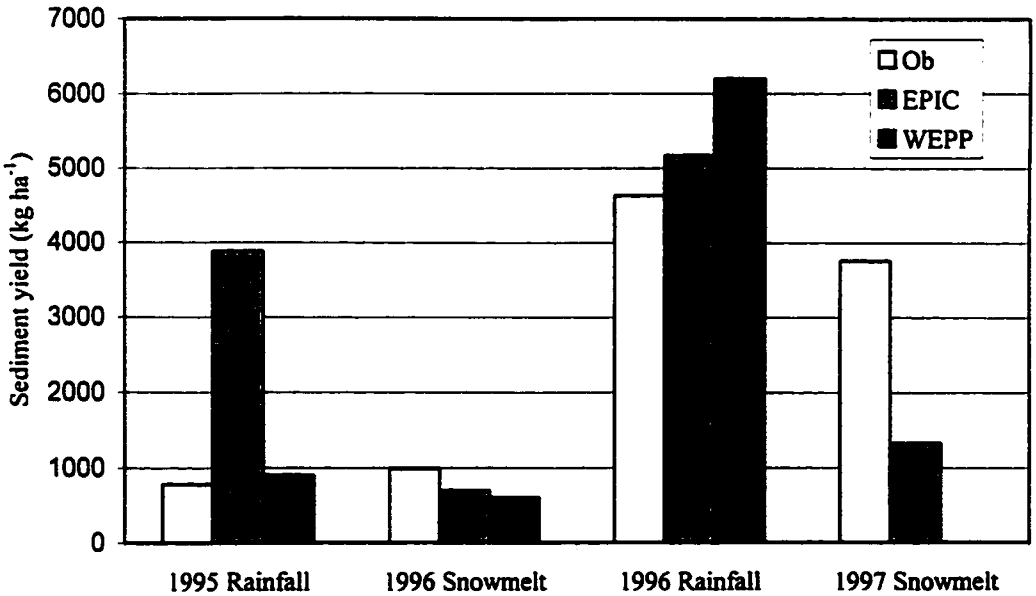

Figure 5.2. Seasonal sediment yield at Breton, Alberta during 1995 – 1997 as observed (Ob) on erosion plots and modeled with EPIC and WEPP. WEPP did not simulate snowmelt runoff in 1997.

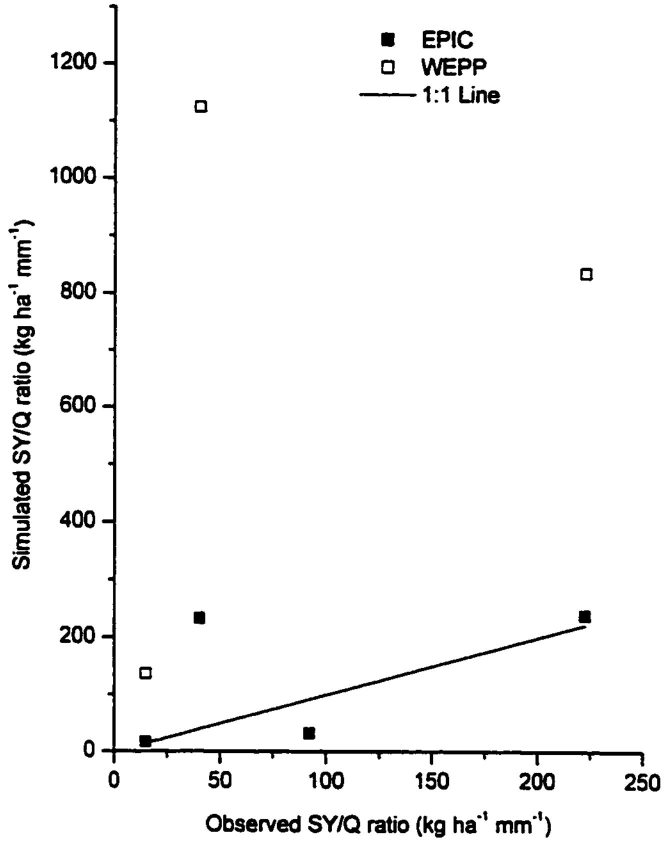

Figure 5.3. Comparison of Sediment Yield (SY) / Runoff (Q) ratios for observed and simulated data. The WEPP data point for the snowmelt period of 1997 is not plotted because it is undefined.

6. APPENDICES

Appendix 1.1. Rainfall Characteristics[z] at Breton for 1995

Date	Precipitation (mm)	Duration[y] (hr)	Time to peak[x] ratio	Peak Intensity[w] ratio
11-Apr	4.2	1.45	0.75	2.21
13 Apr	1.1	0.90	0.50	2.27
24 Apr	6.6	3.25	0.67	2.36
14 May	5.2	4.00	0.81	1.85
14 May	5.6	4.50	0.61	1.93
17 May	3.2	1.75	0.71	1.75
20 May	12.4	8.25	0.21	2.66
24 May	7.6	3.25	0.92	2.05
5 June	14.0	4.00	0.73	2.51
6 June	14.2	4.50	0.02	6.85
17 June	3.4	1.75	0.71	1.65
18 June	12.6	3.25	0.31	3.86
20 June	10.4	7.00	0.61	3.23
24 June	**8.8**	**1.00**	**0.17**	**3.18**
25 June	4.6	0.75	0.44	1.96
1 July	**14.6**	**1.75**	**0.19**	**3.74**
2 July	**13.2**	**7.00**	**0.39**	**4.67**
3 July	**6.0**	**2.75**	**0.09**	**2.57**
4 July	**19.6**	**4.75**	**0.74**	**4.00**
11 July	3.0	0.75	0.11	2.00
17 July	3.8	1.50	0.22	2.84
20 July	1.8	1.50	0.50	1.33
23 July	3.6	3.00	1.00	2.00
24 July	6.2	1.25	0.33	3.55
25 July	2.0	0.50	0.17	1.80
28 July	1.6	0.75	0.33	2.25
29 July	**30.2**	**11.00**	**0.16**	**4.37**
30 July	3.0	1.75	0.14	4.20
31 July	3.0	1.50	0.67	2.80
1 Aug	3.4	3.00	0.42	2.12
5 Aug	3.2	3.00	1.00	2.12
6 Aug	4.4	3.25	1.00	1.77
7 Aug	**16.4**	**8.75**	**0.97**	**4.70**
8 Aug	**17.8**	**16.75**	**0.07**	**5.06**
11 Aug	**10.6**	**9.75**	**0.26**	**2.21**
12 Aug	**1.8**	**1.50**	**0.50**	**2.67**

(Continued on page 107)

[z]Excludes storms less than 1 mm of precipitation. **Bolded** values are days with runoff.
[y]The summation of all 15-min time intervals with precipitation.
[x]The ratio of the time to rainfall peak divided by the rainfall duration.
[w]The ratio of the maximum 15-min rainfall intensity divided by the average rainfall intensity.

Appendix 1.1. (Continued from page 106).

Date	Precipitation (mm)	Duration[y] (hr)	Time to peak[x] ratio	Peak Intensity[w] ratio
13 Aug	**3.0**	**0.50**	**0.17**	**1.47**
15 Aug	**6.4**	**1.25**	**0.33**	**2.34**
19 Aug	**13.6**	**1.75**	**0.33**	**5.04**
21 Aug	**16.4**	**3.00**	**0.03**	**2.63**
29 Aug	4.8	3.00	0.88	2.00
6 Sept	4.6	3.25	0.10	3.96
15 Sept	3.4	2.50	0.70	2.94
17 Sept	4.2	4.00	1.00	1.52
30 Sept	3.2	1.50	0.26	1.88
1 Oct	2.0	1.50	1.00	1.20
14 Oct	1.6	1.75	1.00	0.88

[z]Excludes storms less than 1 mm of precipitation. **Bolded** values are days with runoff.

[y]The summation of all 15-min time intervals with precipitation.

[x]The ratio of the time to rainfall peak divided by the rainfall duration.

[w]The ratio of the maximum 15-min rainfall intensity divided by the average rainfall intensity.

Appendix 1.2. Rainfall Characteristics[z] at Breton for 1996

Date	Precipitation (mm)	Duration[y] (hr)	Time to peak[x] ratio	Peak Intensity[w] ratio
24 Apr	4.6	5.00	1.00	1.00
25 Apr	5.8	4.75	1.00	1.00
27 Apr	1.8	2.75	1.00	1.00
3 May	7.0	6.50	1.00	1.00
4 May	4.2	3.50	1.00	1.00
5 May	6.6	3.75	1.00	1.00
7 May	2.8	2.25	1.00	1.00
16 May	3.8	2.25	1.00	1.00
18 May	6.8	1.25	1.00	1.00
19 May	1.2	1.50	1.00	1.00
28 May	4.8	2.00	1.00	1.00
29 May	7.4	2.50	1.00	1.00
30 May	5.8	4.25	1.00	1.00
4 June	7.6	5.50	1.00	1.00
5 June	7.2	7.50	1.00	1.00
11 June	2.0	0.50	0.50	1.80
13 June	1.8	0.50	0.17	1.33
15 June	5.4	1.50	0.67	3.33
17 June	6.4	3.25	0.08	2.84
18 June	**62.2**	**18.75**	**0.32**	**3.14**
19 June	**21.6**	**16.25**	**0.66**	**3.01**
20 June	1.6	1.00	0.58	2.50
23 June	2.4	3.00	1.00	1.00
28 June	7.4	3.50	0.76	2.27
1 July	**10.2**	**1.25**	**0.13**	**2.94**
4 July	7.2	2.25	0.11	3.00
6 July	4.0	3.25	0.10	2.60
7 July	2.8	1.50	1.00	1.29
9 July	**12.0**	**6.25**	**0.04**	**2.08**
10 July	2.8	2.75	0.15	1.57
12 July	4.0	1.50	0.39	2.10
15 July	**9.6**	**2.00**	**0.33**	**4.33**
16 July	**4.2**	**4.00**	**0.81**	**2.29**
18 July	**6.0**	**1.25**	**0.47**	**2.83**
20 July	**4.8**	**4.50**	**1.00**	**2.25**
24 July	**6.2**	**0.50**	**0.17**	**1.55**

Continued on page 109.

[z]Excludes storms less than 1 mm of precipitation. **Bolded** values are days with runoff.
[y]The summation of all 15-minute time intervals with precipitation.
[x]The ratio of the time to rainfall peak divided by the rainfall duration.
[w]The ratio of the maximum 15-minute rainfall intensity divided by the average rainfall intensity.

Appendix 1.2. (Continued from page 108).

Date	Precipitation (mm)	Duration[y] (hr)	Time to peak[x] ratio	Peak Intensity[w] ratio
2 Aug	**17.2**	**1.75**	**0.09**	**2.28**
3 Aug	**58.4**	**16.00**	**0.49**	**3.07**
5 Aug	4.2	3.75	1.00	2.14
6 Aug	2.2	2.25	1.00	1.64
14 Aug	4.8	1.25	0.53	2.29
16 Aug	5.6	1.25	0.13	3.57
17 Aug	2.8	1.00	0.33	2.29
18 Aug	2.8	1.25	0.27	1.43
19 Aug	5.2	1.25	0.47	1.92
4 Sept	6.6	3.75	0.91	2.27
5 Sept	3.6	2.75	1.00	1.83
6 Sept	2.2	1.25	0.73	1.82
8 Sept	2.8	1.50	0.56	1.71
14 Sept	6.8	1.75	0.19	5.35
16 Sept	6.8	3.25	0.54	1.53
17 Sept	8.4	8.00	1.00	1.52
18 Sept	5.0	5.00	0.40	3.20
19 Sept	11.8	7.25	0.46	1.97

[z]Excludes storms less than 1 mm of precipitation. **Bolded** values are days with runoff.
[y]The summation of all 15-minute time intervals with precipitation.
[x]The ratio of the time to rainfall peak divided by the rainfall duration.
[w]The ratio of the maximum 15-minute rainfall intensity divided by the average rainfall intensity.