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Graham Alan WILKES

AUTEUR DE LA THÈSE - AUTHOR OF THESIS

M. Sc. (Geography)

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M. Sawada

DIRECTEUR DE LA THÈSE - THESIS SUPERVISOR

CO-DIRECTEUR DE LA THÈSE - THESIS CO-SUPERVISOR

EXAMINATEURS DE LA THÈSE - THESIS EXAMINERS

A. Bannari

K. Gajewski

J.-M. De Koninck, Ph.D.

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UTILIZING GEOGRAPHIC INFORMATION SYSTEMS (GIS)
FOR THE MODELING OF WARM SEASON SOIL LOSS IN EASTERN ONTARIO,
CANADA

By

Graham A. Wilkes

A thesis submitted to the Faculty of Graduate and
Postgraduate Studies in partial fulfillment of the requirements
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ABSTRACT

Soil loss in eastern Ontario is of great concern. The objective of this study is to map soil loss risk in Eastern Ontario for 2001. The universal soil loss equation (USLE), the universal soil loss equation 2 dimensions (USLE2D), and the unit stream power erosion deposition (USPED) models are applied within a Geographic Information System (GIS) to calculate soil loss within agricultural fields. Hourly precipitation, soil survey, digital elevation, field boundary, and satellite imagery data are main inputs used to generate model parameters at non-depositional areas. These datasets are integrated to compute mean annual and monthly soil loss at multiple scales. For precision agriculture purposes, results are given as a number of high precision, high accuracy soil loss grids and associated summary tables under a variety of farming practices and erosion processes. Results indicate that: 1) soil loss is occurring at intolerable levels ($> 6 \text{ t ha}^{-1} \text{ yr}^{-1}$) in the region, particularly in the southeastern study region, 2) slope steepness followed by the cropping and management factor affect soil loss to the greatest extent, and 3) under no tillage systems, a considerable amount of soil is lost at intolerable levels in high slope areas. Results indicate that conventional tillage farming modeled with high connectivity between field boundaries will provide mean soil loss rates for watersheds in the range 2.48 to $7.11 \text{ t ha}^{-1} \text{ yr}^{-1}$, with median values ranging between 0.66 to $3.53 \text{ t ha}^{-1} \text{ yr}^{-1}$. Under identical farming practices with minimal connectivity between fields, mean soil-loss rates for watersheds range between 2.23 to $5.68 \text{ t ha}^{-1} \text{ yr}^{-1}$, and median values range between 0.62 to $2.96 \text{ t ha}^{-1} \text{ yr}^{-1}$. While such numbers suggest that soil-loss rates are tolerable ($< 6 \text{ t ha}^{-1} \text{ yr}^{-1}$), these spatially derived means and medians are misleading as 7.8 to 11.5% of total field area in eastern Ontario is experiencing

intolerable levels of erosion under a variety of different farming scenarios. A major conclusion of this study is that potentially severe levels of soil loss cannot be identified without fine scale modeling. Those months modeled as experiencing high levels of erosion are August, September, and October, and so should be a focus of temporal soil loss mitigation strategies in the region. The novel method presented in this thesis can be applied in any agricultural region in Canada for assessment of soil loss for use in precision agriculture.

RÉSUMÉ

Les pertes des sols provoquent l'inquiétude dans l'est de l'Ontario. L'objectif de cette étude est l'illustration des problèmes des pertes des sols qui existent dans l'est de l'Ontario en 2001. Les modèles universal soil loss equation (USLE), universal soil loss equation 2 dimensions (USLE2D) et unit stream power erosion deposition (USPED) sont appliqués dans un système d'information géographique afin de calculer les pertes des sols parmi les champs agricoles. La quantité de pluie, l'analyse des sols, l'élévation numérique, la frontière des champs ainsi que l'imagerie satellite sont utilisés comme paramètres durant la modélisation des endroits enclins à l'érosion. Les données sont intégrées à plusieurs échelles afin de calculer les moyennes annuelles et mensuelles des pertes des sols. En ce qui concerne l'agriculture de précision, les résultats des pertes des sols sont présentés avec des grilles à haute précision et haute exactitude. De plus, les résultats sont accompagnés avec des tableaux décrivant les pratiques agricoles et les modes d'érosion. Les résultats indiquent: 1) les pertes des sols se produisent à des niveaux intolérables ($> 6 \text{ t ha}^{-1} \text{ yr}^{-1}$), particulièrement dans le sud-est de la région sujet à cette étude, 2) l'inclinaison des pentes ainsi que le facteur de culture/végétation et de gestion sont responsables pour les pertes majeures des sols, et 3) sans le travail du sol, un montant considérable de terre est perdu aux endroits où l'inclinaison est trop élevée. Les résultats indiquent que le travail du sol conventionnel entre les champs perméables produira des pertes moyennes des sols entre 2.48 à $7.11 \text{ t ha}^{-1} \text{ yr}^{-1}$ aux lignes de partage des eaux. Pour ces mêmes conditions, les valeurs médianes se retrouvent entre 0.66 et $3.53 \text{ t ha}^{-1} \text{ yr}^{-1}$. Sous les mêmes pratiques agricoles avec des champs imperméables, les taux moyens et médians des pertes des sols se situent respectivement entre 2.23 à $5.68 \text{ t ha}^{-1} \text{ yr}^{-1}$, et 0.62 à $2.96 \text{ t ha}^{-1} \text{ yr}^{-1}$. Quoique les valeurs suggèrent que les taux des pertes des sols sont tolérables ($< 6 \text{ t ha}^{-1} \text{ yr}^{-1}$), ces moyennes et médianes spatiales sont

trompeuses car 7.8 à 11.5% des champs dans l'est de l'Ontario éprouvent des niveaux intolérables d'érosion causés par plusieurs scénarios agricoles. Une conclusion majeure de cette étude révèle que l'identification des taux des pertes des sols requiert des modèles à échelle spatiale fine. Les mois exerçants des niveaux élevés d'érosion sont août, septembre et octobre et ils seront donc le point focal des pertes temporelles dans la région. La nouvelle méthode présentée dans cette thèse peut être appliquée, lors de l'agriculture à haute précision, dans toutes les régions agricoles au Canada afin d'évaluer les pertes des sols.

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PREFACE

The motivation for this research began during my time spent as a Research Technician at the Eastern Cereal and Oilseed Research Centre (ECORC) of Agriculture and Agri-Food Canada. During my summer employment as a GIS Research Technician, I began to realize an evident soil erosion problem in eastern Ontario during summer field work. The effects of soil loss were apparent on numerous agricultural fields and surrounding areas, from silted drainage ditches to sediment filled streams and rivers, to deposition occurring at the base of agricultural slopes and gullying occurring on farm land. These were the immediate visible effects which ultimately indicated a soil erosion problem in the region, not including the imperceptible erosion occurring on the landscape. Given the visible effects of soil loss, modeling the processes of erosion at finer scales for agricultural land use planning and soil loss mitigation in Ontario and greater Canada is a necessity for precise reduction of soil loss from agricultural plots. Little current information was available that identified the susceptibility of soil to water erosion at scales coincident with the farm management unit.

The field work experience was valuable in demonstrating the need for precision agriculture to reduce the potential for erosion in field areas experiencing net soil loss. Precision agriculture essentially improves farm management using technology and data which benefits the environment and the farmer. Precision agriculture, also known as site specific farming, is a system which helps farmers better administer cropping techniques, nutrient management, tillage practices, and land use for superior yields and reduced offsite impact of farming. Precision agriculture utilizes technologies that are emerging or newly developed. Such technologies include global positioning systems (GPS), GIS, remote sensing, yield monitoring devices, soil,

plant, and pest sensors amongst other technologies. All of these technologies are used to vary farming inputs for optimal crop output. Ultimately the goal is to improve profitability and sustainability by managing temporal and spatial variations in plant and soil characteristics or soil loss, thereby minimizing environmental degradation and unneeded applications of nutrients, pesticides, and herbicides.

There is a pressing need to apply precision agriculture to assess the susceptibility of soil to erosion in eastern Ontario. Precision agriculture is best exemplified in this thesis via the use of GPS, GIS, and remotes sensing outputs to assist in the determination of those agricultural fields at greater risk of eroding. Such precision will be applied at scales coincident with the farmer's field. This will improve the management and maintenance of soil productivity and fertility as well as environmental protection. As such, modeling erosion losses at the specific sites within fields will allow for the goals of precision agriculture and site specific farming.

A great deal of higher resolution elevation, and updated soil data was made available during my time at ECORC providing the perfect opportunity for a high resolution soil erosion analysis in the region. Previous attempts at soil erosion modeling in Canada utilized data that was national in scale and coarse in resolution with inappropriate models designed for application at the field scale. Doubts arose from the results of risks of water erosion analysis on crop land in publications like Environmental Sustainability of Canadian Agriculture – Report of the Agri-Environmental Indicator Project (McRae *et al.*, 2000), which show continuous tolerable risk of water erosion in eastern Ontario. The adjective tolerable in the report indicates that soil losses are within an acceptable range for maintaining soil quality and fertility. Such statements contrast the ad hoc observations made during field work. Instinct and common sense and discussion between Dr. Sawada and Ian Jarvis of Agriculture and Agri-Food Canada lead to the pursuit of the

investigation of these claims using USLE inputs at finer scales in GIS. What could be concluded from these discussions is that there are severe data limitations in national studies of soil erosion leading inevitably to coarse scale erosion estimates that are of little use in day-to-day management at the farm unit scale. This conclusion was seen as particularly problematic for a country as vast as Canada. There existed a critical need to visualize and analyze spatially the factors effecting erosion and finer spatial scales and investigate loss estimates with higher resolution data. It was expected that the end result from the soil loss modeling would provide us with more knowledge about the potential for unsustainable agriculture in the region.

This thesis is written to provide guidance and demonstrate the applicability of water erosion modeling for a variety of purposes. The same method(s) could be applied in eastern and western Canada for mitigation of water erosion. The results and resulting geographical datasets from this current work can be used as inputs into nutrient modeling and GIS analysis of water bodies at risk of sedimentation or contamination. Model factors should be used in engineering planning and design for ditches, earthen dams, water holding areas, and farm land use. Results will also be beneficial for county 'Official Plan' refinement in regards to agricultural practices limitations. Further, modeling the location of erosion susceptibility in GIS helps us, the conservationist and environmentalist, conceptualize the processes shaping the landscape spatially. Without the benefit of visualization via GIS, understanding and mitigating erosion would be extremely difficult. Utilizing the results of this work in combination with other visualization software will enable us to convey to farmers and other researchers the dominant factors causing or limiting detachment and transport of soil particles. The total extension of visualization related to the outputs of this body of work would likely encompass another undergraduate or graduate thesis. Additionally, outputs could be used to develop scenarios that

adjust potential losses for the control and collection of soil loss off the most critical fields. Minimally, the results could be summarized to notify agricultural land owners of the potential for soil loss on their property. The interface of GIS with the USLE modified provides the resource professional with an instrument to model large regions with a minimal amount of parameters that are very influential in demonstrating soil loss potential while providing the user with the opportunity to build a variety of scenarios to gauge loss through space and time.

The thesis produced the following results:

- a) Rainfall erosivity (R) maps through the various growing months (March, April, May, June, July, August, September, October) were produced for the lower Great Lakes region to provide input into erosion modeling analysis.
- b) A mean annual erosivity map for the lower Great Lakes region was generated to demonstrate the spatial distribution of rainfall erosivity over the landscape.
- c) A prediction standard error map for rainfall erosivity for the lower Great Lakes region was created.
- d) A soil erodibility map was produced for eastern Ontario generated from county soil survey data, and generated from this map was a standard error map of soil erodibility.
- e) Two slope length and steepness (LS) susceptibility maps were created for eastern Ontario with associated standard errors, one which calculates the LS factor by accounting for a 25% connectivity between field boundaries, while the second calculates the LS factor with exclusion of any field boundary limitation.
- f) Three crop management factor (C) maps with associated errors were produced to exhibit how crop cover affects soil loss under conventional tillage, conservation tillage, and no tillage farming systems.
- g) Six annual soil loss estimate scenarios with associated error were generated for the various LS and C factor scenarios with results summarized in tabular format.
- h) Eight monthly estimates of soil loss were developed for 25% parcel connectivity between fields under conventional tillage to display the susceptibility of soil to erosion over the growing season.

i) Two maps were generated that depict the most dominant factor effecting erosion, one examines all USLE factors while the second only compares the slope length and steepness and crop management factor.

j) Finally, output grids depicting net deposition or erosion were developed using the unit stream power erosion deposition model (USPED) so that the estimates of soil loss could be limited to areas experiencing overall soil loss.

The results improve the decision-making process in eastern Ontario for the allocation of funding to those areas that are most susceptible to erosion for encouragement of agricultural best management practices, including the adoption of conservation tillage, cross slope cultivation, and stripcropping. The method demonstrated and applied in this analysis at the national scale would vastly improve our knowledge of water soil erosion susceptibility in Canada. Finally, strategies for improving surface water clarity and quality could also be enhanced with information provided by model outputs with the use of sediment routing models that consider deposition, see Singh (1992; page 720) for a demonstration of methods provided to compute sediment delivery ratios to water bodies.

The general audience for this thesis is researchers (GIS, Geography, Agriculture, and Earth Science), rural planners, farmers, environmentalists, biologists, and agricultural and civil engineers. Individuals that will benefit from reading this thesis are likely the aforementioned.

Thesis Scope

This thesis covers the method(s) undertaken to calculate water induced soil erosion estimates at scales more coincident with the farm management unit at a higher degree of precision on a cell by cell raster tessellation using the USLE and USLE2D in conjunction with GIS. Precision agriculture or the philosophical shift in the management of variability within agricultural industries (Whelan and McBratney, 2000) will be adopted and applied to demonstrate the

variability of soil loss within a farmer's field. Essentially the following steps in precision agricultural will be applied. The spatial variability of soil loss within a farmer's field will be mapped, and the reasoning for the largest variation will be provided via the determination of the most dominant factor effecting erosion on a cell by cell basis. Prescriptions for soil loss reduction will also be provided indirectly from the determination of the most dominant factor effecting erosion. Beyond the scope of this analysis is the implementation of site specific field management practices, evaluating the effect of the treatment, and summarizing to the results for improving future agricultural management decision making.

To our knowledge no one has attempted an analysis at such a scale and over such a large area in Ontario or Canada. The thesis will also familiarize the reader with the current state of erosion modeling in Canada. Additionally, the thesis will summarize the difficulties and basic assumptions made when modeling water induced soil erosion in eastern Ontario.

Thesis Organization

The thesis is organized into four main components. Chapter one provides the purpose of the thesis, a general introduction to the topic, and a description of the USLE, USLE2D, and the USPED models. Chapter two presents updated rainfall erosivity maps for the Great Lakes region and presents a novel approach of mapping the rainfall erosivity factor through pluvial months for the region. Chapter 2 examines and maps the variation in the rainfall erosivity at macroscales for precision agriculture. Variation in the rainfall erosivity factor is minimal over short distances in comparison to other USLE factors, and thus, can be mapped over large regions for precision agriculture. Chapter three describes the calculation and analysis of all other factors of the USLE, USLE2D, and USPED in eastern Ontario. Conclusions and future directions are provided in the fourth and final chapter. The final section(s) of the thesis (Appendices) provide more detailed

information related to the methods applied in chapters two and three. The development of computer programs was necessary in this work due to the vast quantity of precipitation data analyzed for the rainfall erosivity factor as well as the analysis performed on the soil survey data. This code is provided in Appendices. Some aspects of the first chapter are repeated in brief within the body of the second and third chapter of the thesis. The second and third (albeit quite large) chapters are in the form of self-contained scientific papers that are to be submitted to refereed journals.

CHAPTER 1

THESIS PURPOSE, BACKGROUND, AND STUDY AREA

1.1 Introduction

It is difficult to quantify the cost of soil erosion on agricultural production but estimates suggest the value ranges between U.S. \$300 million and U.S. \$27 billion in North America (Wiebe, 2000). Dumanski *et al.* (1986) indicate the annual on-farm cost of water erosion in Canada is between \$266 and \$424 million per year, where the Prairie Provinces have the highest monetary loss (\$155-197 million per year – water erosion), followed closely by Ontario (\$68-157 million per year – water erosion). In southwestern Ontario farm yields may be decreased by as much as 40% because of water related erosion (Environment Canada, 1991). In Ontario, the majority of monetary loss from erosion is a result of rainfall and runoff, while in the Prairie Provinces a greater proportion of monetary loss is associated with wind erosion (Dumanski *et al.*, 1986). The dollar costs are staggering and should serve as an indication of the severity and economic cost to agriculture of water erosion.

The monetary costs of soil erosion and sedimentation are significant but so too are the offsite environmental costs. The offsite problems of soil loss and sedimentation include roadway, sewer and basement siltation, drainage disruption, gullyng of roads, earth dam failures, eutrophication of waterways, harbor and channel siltation, destruction of wildlife habitat and riparian ecology, flooding, and damage to human health (Pimental *et al.*, 1995). Fractions of soil entrained in water remain on the field itself, but a portion of soil particles and adsorbed chemical compounds and elements end up in watercourses. Saginaw Bay and the associated

watershed of Saginaw River in Michigan serve as a prime example of the results of agricultural land use and their effect on surface water in the Bay. Over half the land use in the region is agricultural and the Saginaw Bay contains contaminated sediments, suffers from degraded fisheries and fish consumption and recreational advisories which are mostly attributed to high amounts of soil erosion, with excessive nutrients such as phosphorous and nitrogen entering the water (Hummer, 2001; Mitsch and Wang, 2000).

There are many examples in Ontario of sites that suffer from agricultural contamination. The Bay of Quinte, an inlet on the south shore of Lake Ontario suffers from high agricultural runoff loaded with sediment (Environment Canada, 2004). Remedial actions are being taken to improve water quality conditions. In an effort to reduce phosphorous inputs, 27 000 hectares of farmland have undertaken conservation tillage to reduce phosphorous loadings (Environment Canada, 2004).

Significant problems associated with agricultural runoff also exist in Eastern Ontario. One study is being performed in a small portion of the Raisin River watershed (see Fig. 1), specifically the Sutherland Creek Watershed, by the Raisin River Conservation Authority to investigate the source of declining water and fish quality in Bainsville Bay. Agricultural pollution is understood to be the cause of the problem, with phosphorous inputs beyond provincial guidelines entering the watercourse (RRCA, 2004). There is a need to understand what specific spatial locations are contributing higher levels of contaminants to the creek at the watershed scale. A similar study is underway in the North Castor watershed via the North Castor Watershed Water Quality Study of the South Nation Conservation Authority (SNCA, 2004). These studies would benefit from within field and basin estimates of soil erosion from the agricultural lands within the drainage basins encompassing the counties depicted in Fig. 2.

Further, these studies would benefit from soil loss estimates that are specific to field regions only (Fig. 3).

Eastern Ontario is an important area of agricultural production in the St. Lawrence region. The soils are generally rich and neutral to alkaline and produce high yields of corn, soybean, and grains. To the west of these fertile soils are acidic soils which overlay the Precambrian Shield limiting agricultural production. Many livelihoods are supported in the region by agriculture and agriculture is an important economic driver. Loss of these soils to erosion and sedimentation would have detrimental effects in the region economically, socially, and environmentally.

There are high costs to agricultural productivity and water quality associated with soil erosion from agricultural fields in Eastern Ontario. Mitigation scale soil erosion modeling, or modeling at scales that allows for functional implementation of soil loss reduction technology, is required to protect the environment and to sustain agricultural production. Existing soil erosion modeling falls short of this need at the national and provincial scales because existing models are built on coarse spatial datasets that provide results at the policy making scale, and not the mitigation scale. One example is The Federal Provincial Crop Insurance Program which utilizes macro scale data (1:1 million) for modeling erosion. The results of the exercise should satisfy both soil policy and management objectives related to precision agriculture.

Chapter 1 is organized into twelve sections. Provided first is a brief introduction to the chapter, followed by the purpose statement and listed thesis goals. A background discussion of erosion modeling is examined next, leading to an explanation and examination of erosion and types of soil loss models. The chapter ends with a summary of the methods of analysis proposed in the thesis and description of the study region and soils contained within the study region.

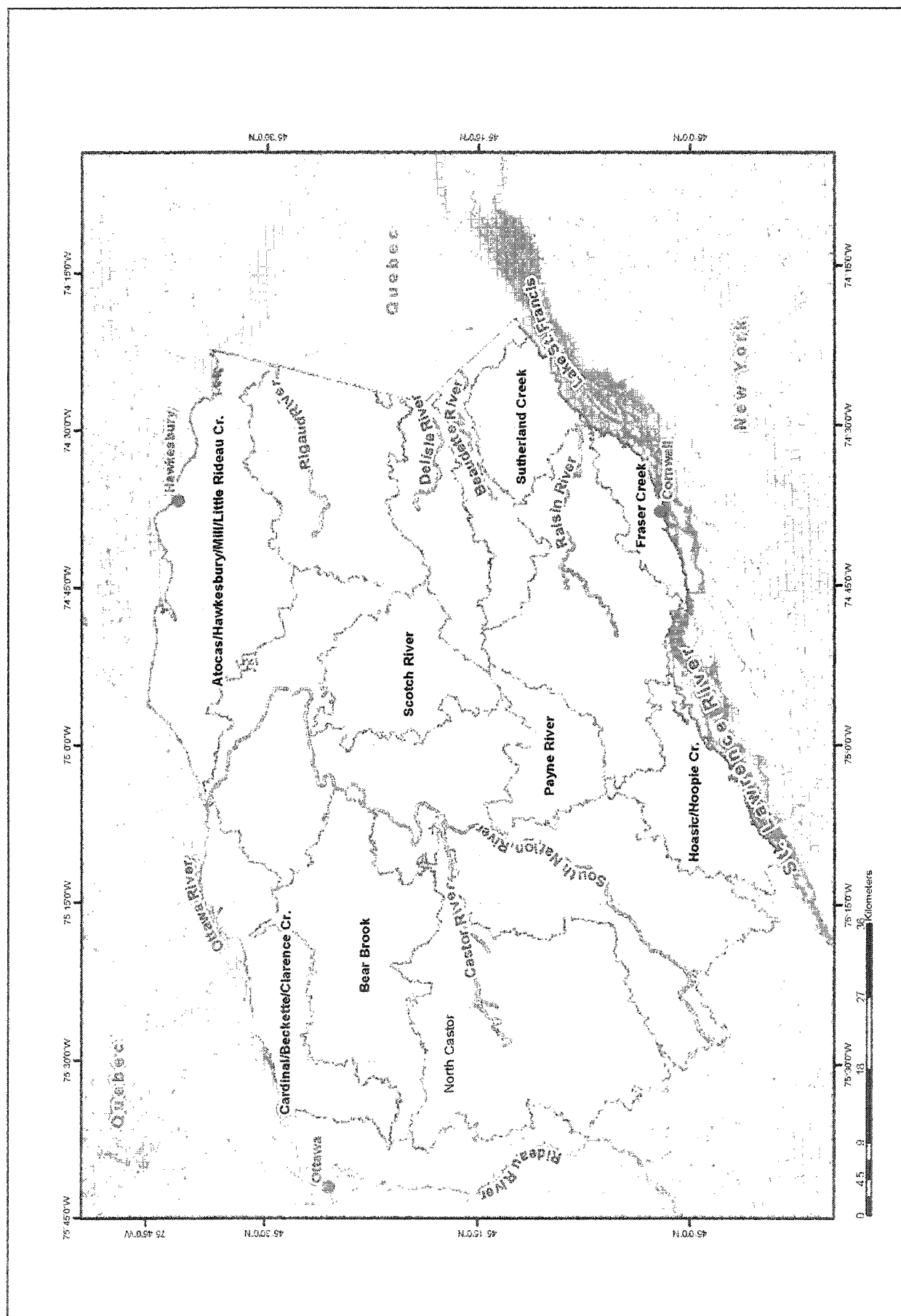


Fig. 1. Extent of thesis study region encompassing all delimited watersheds.

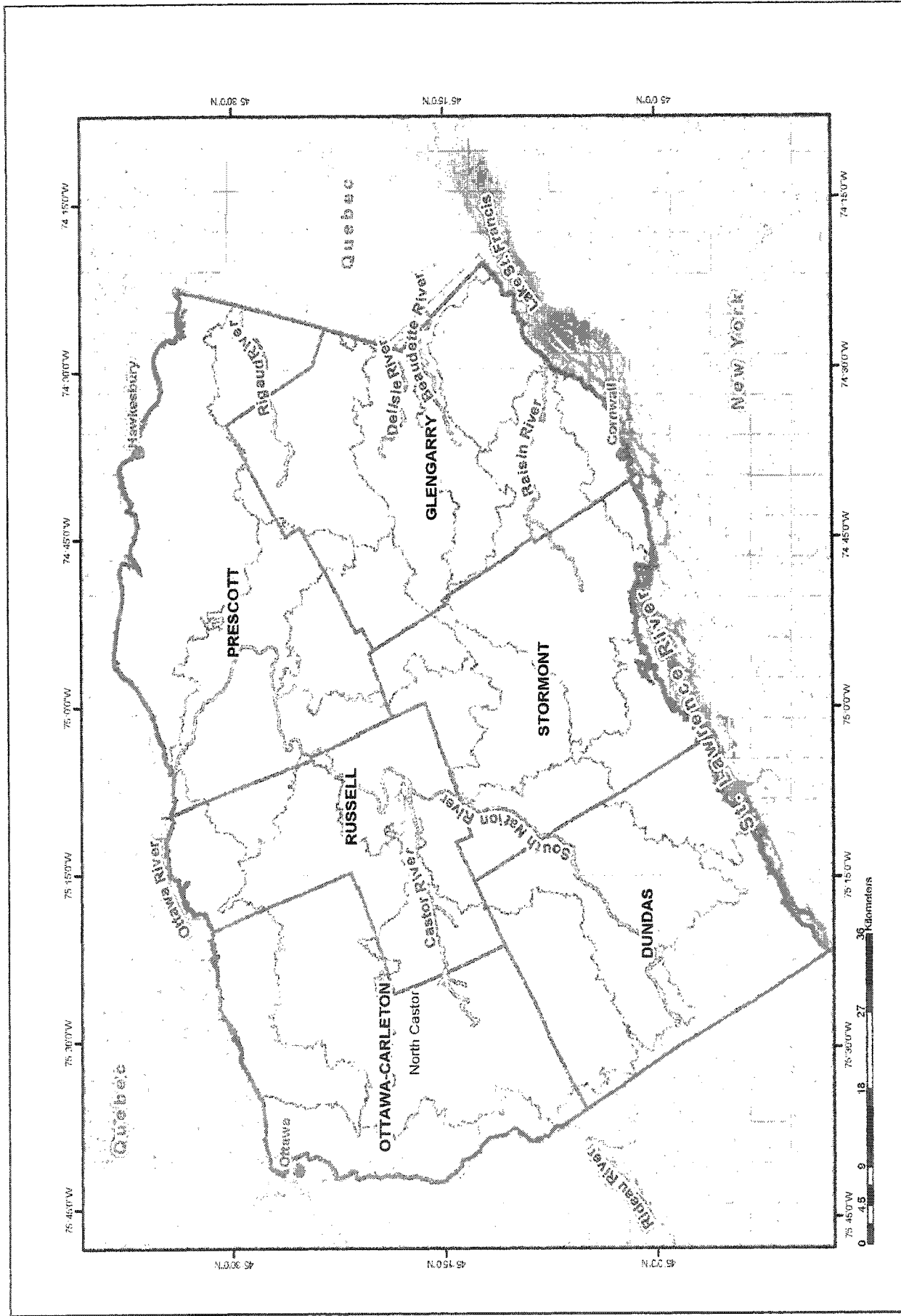


Fig. 2. Extent of the thesis study region encompassing all delimited watersheds and all counties depicted in red with the exception of Dundas and Ottawa-Carleton which are partially included in the thesis analysis.

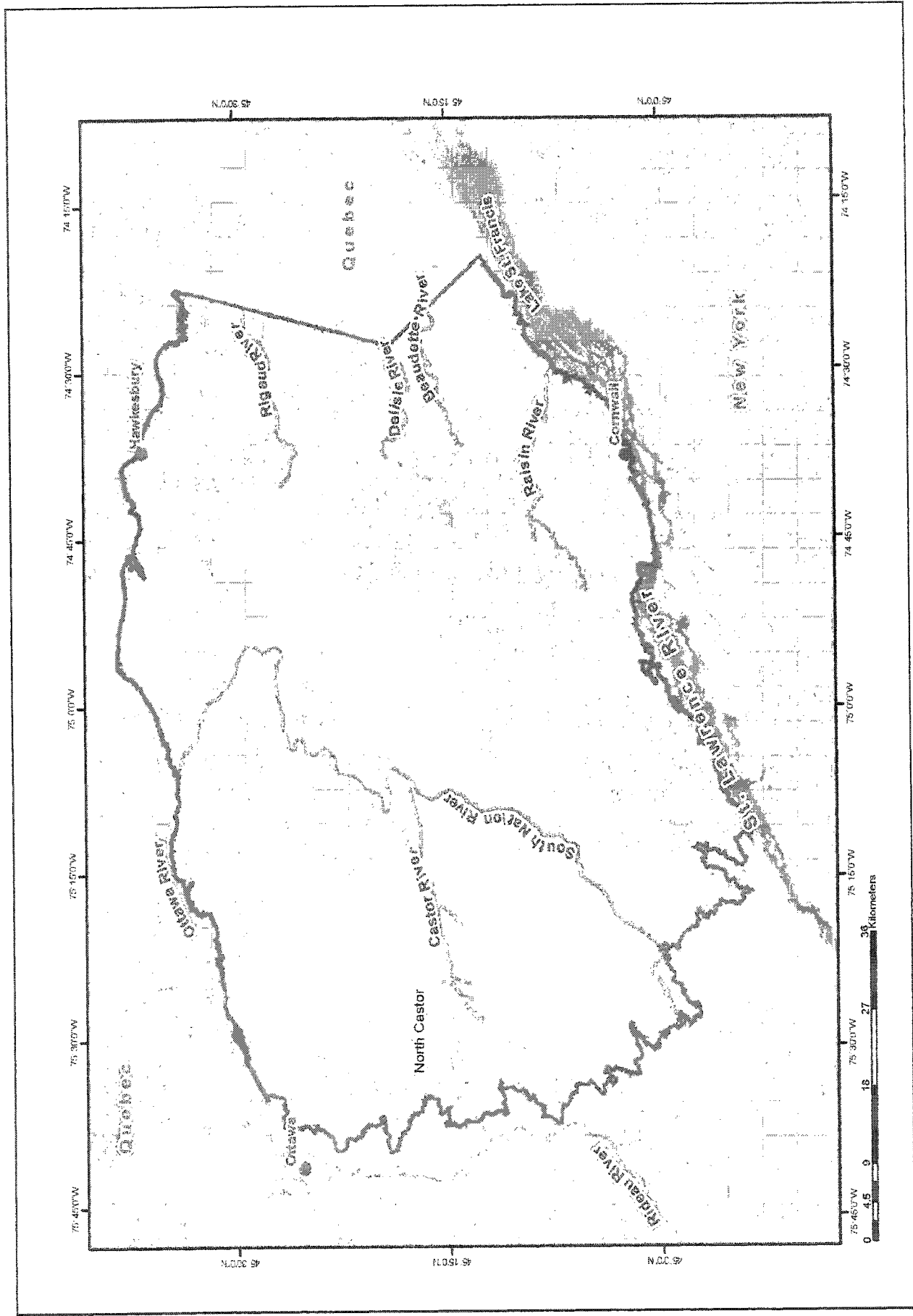


Fig. 3. Extent of thesis study region encompassing all the agricultural land highlighted in green.

1.2 Thesis Purpose

Water erosion potential in Eastern Ontario in various locations surpasses tolerable levels, which are values that range beyond 6 tonnes of soil per hectare, per year. The objective of this thesis is to map these higher risk areas at fine spatial scales (or scales finer than current status quo of environmental modeling at resolutions of 25 meters to 1 km) for soil loss mitigation.

1.3 Thesis Goals

Specific goals of this thesis are listed below. These goals are addressed in Chapters 2 and

3. The goals of this thesis are to:

1. Use a field scale model, the USLE, in conjunction with a GIS to create spatially detailed soil erosion estimates for eastern Ontario in agricultural fields at resolutions coincident with the farm management unit.
2. Produce erosion maps.
3. Produce updated isoerodent maps (rainfall erosivity maps) for the Ontario region and northeastern U.S., at annual and monthly temporal resolutions. Current isoerodent maps are needed for an adequate assessment and prediction of soil loss throughout the growing season. This has not been done to our knowledge.
4. Produce prediction standard error estimates for the lower Great Lakes region for mean annual rainfall erosivity.
5. Generate mean annual soil loss estimates under three tillage scenarios: conventional tillage; conservation tillage; and no tillage farming systems.
6. Determined the impact of slope length and steepness on effecting soil loss in eastern Ontario for two scenarios, one which accounts for field boundaries when calculating slope length, a second scenario which does not include any field boundary influence for the determination of slope length.
7. Generate annual estimates of soil loss using inputs from 3, 4, 5, and 6.
8. Produce standard error estimates for outputs in step 7 to gain a better understanding of the uncertainty related to USLE outputs in GIS.

9. Mask out estimates generated in step seven with areas expected to only provide net loss using the unit stream power erosion deposition model (USPED) of Mitas and Mitasova (1998). This will provide better estimates of the spatial susceptibility of erosion as the USPED accounts for the transport limited case of an erosion process while the USLE does not account for transport but only detachment limited erosion.
10. Rank the primary variables in the study region according to their influence on soil erosion.

1.4 The History of Soil Erosion Modeling in Brief

The science of soil erosion modeling is more than sixty years old and initially stems from the work of M.F. Miller in 1914 at the University of Missouri with his establishment of erosion plots. The investigation of slope length and steepness and their combined effect on erosion began with the work of Zingg (1940). Through time, more factors were linked to soil loss, including rainfall (Musgrave, 1947), soil type, crop type, and conservation practices (Browning *et al.*, 1947; Smith 1958). The previous factors were combined, refined, and popularized to form the USLE (Wischmeier and Smith, 1965). The USLE is a hybrid of the Musgrave Equation which modeled soil loss as a five factor relationship of soil, degree of slope, slope length, crop cover and rainfall.

Erosion defined as the wearing away of the land surface by natural agents of running water, ice, wave action, and wind and the transport of the resulting debris (Clarke, 1998a). There are four identifiable steps involved in water erosion (Ellison, 1947; Singh, 1992, page 703):

- 1) detachment by raindrop impact,
- 2) detachment by splash,
- 3) detachment by runoff, and
- 4) transport by runoff.

Accelerated erosion is soil erosion occurring at rates that exceed a soil's genesis or replenishment rate.

Energy plays a fundamental role in all erosion processes. Raindrops by definition possess kinetic energy as a result of their mass and velocity (Summerfield, 1991). The kinetic energy of the raindrop impact is capable of breaking bonds between soil particles and launching particles at distance which can further impact or loosen the bonds between adjacent particles. The relationship between kinetic energy, mass, and terminal velocity of the raindrop is given by (Briggs *et al.*, 1993):

$$E = 0.5M(V)^2 \quad (1.1)$$

where,

E is the kinetic energy of the raindrop,

V is the terminal velocity of the raindrop,

M is the mass of the raindrop.

Examination of equation (1.1) indicates that for a given mass, as the terminal velocity increases the kinetic energy of the raindrop increases. Terminal velocity is the maximum velocity the raindrop can reach while falling through the atmosphere. Raindrops with high mass and higher velocities possess higher kinetic energies, and one would expect that these raindrops would dislodge more particles for entrainment and transport due to these heightened energies. Other forms of detachment are plucking and cavitation, but these forms are understood to have little influence on agricultural soil erosion.

1.5 Types and Varieties of Erosion Models

A description of common abbreviations is provided in Appendix A, describing some common models referenced herein. Many types of erosion models have been developed since the inception of Miller's work in 1914. They are commonly grouped into two forms, those that are stochastic and those that are based on physical process, which are deemed deterministic models. Ideally, erosion is based on the physical laws and the landscape processes that occur in the natural world (Doe and Harmon, 2001). If soil loss is to be modeled accurately, both groups of models should describe detachment, transportation, and deposition of soil particles empirically or physically (Doe and Harmon, 2001). One of the main differences between stochastic and physical models is that physical models can be applied across a wide range of landscapes due to modeled mathematical relationships that are based on physical laws which must apply in all cases. Stochastic models are limited to the regions in which their stochastic relationships to soil loss were developed or to regions for which model parameter conditions are similar. In Table 1 below, strengths and weaknesses are compared between stochastic and physical soil loss models.

<i>Description</i>	<i>Deterministic Models</i>	<i>Stochastic Models</i>
Applicability	Over all landscapes	Limited to source region
Complexity	Highly complex	Simple
Continuity	Simulations can be continuous in space and time	Normally averages loss over two time intervals
Data input	Extensive	Limited
Accuracy	Conflicting views	Conflicting views
Processing restraints (Algorithms)	High	Low
Models events	Yes	No
Sensitivity	High	Moderate
Prevalence of use for erosion prediction	Low	High
Processing constraints (spatial)	High	Low

Table 1. A general comparison of deterministic and stochastic erosion models.

Physical models can come in two forms, those that are continuous and those that are event based (Morgan and Quinton, 2001). Continuous models (CREAMS and EPIC) represent changes in environmental conditions over successive time intervals, recomputing sediment and water balances during iterations. With continuous models you can observe the progressive movement of sediment over space and time. Drawbacks to continuous models are the requirement of large amounts of input data on meteorological conditions, antecedent soil, vegetation, and topographical conditions as they attempt to determine the conditions prior to rainfall events. They also model small events that may not contribute any significant annual soil loss, reducing model efficiency.

Event models (ANSWERS and WEPP) try to replicate whole-catchment response to individual storms. One can generalize continuous models as a combination of interval events models that are so fine in temporal resolution that they model conditions within the event. In single event models, the user establishes the initial conditions of soil moisture, surface moisture, et cetera, requiring the user to have greater prior knowledge about expected starting conditions (Doe and Harmon, 2001). Beyond the limitations mentioned in Table 1, there have been a number of problems identified with physical models:

1. They are limited by the complexity of making precise in situ measurements of water flow (Renard, 1997). Essentially, there are data instrumentation limitations which confound identified relationships in soil loss mechanics.
2. Interflow, perched groundwater contributions to runoff, and complex runoff run-on interactions are difficult to model physically (Woolhiser, 1996).
3. Most momentum equations of physically based models are one dimensional (Lane *et al.*, 1988) making significant abstractions of sheet and rill flow.
4. Few physically based models account for the seasonally and spatially changing infiltration characteristics of soil (Renard, 1997).

In contrast, empirical models (USLE and RUSLE) are based on statistical relationships between variables affecting soil loss and are applicable only when a reasonable input database exists for their application (Gregory and Walling, 1973; Morgan, 1995). There is a lack of appropriately scaled data for the physical modeling of soil loss in eastern Ontario. Further, the USLE is simple and is perceived by many researchers to be less susceptible to user error. As well, there is a larger amount of acceptable data for input into the USLE for the region, and USLE computational processing restraints are limited. Additionally, USLE model sensitivity is less than that of other physically based models. For these reasons the USLE modified in combination with the USLE2D and USPED model for use in GIS were chosen for application in this study.

1.6 The Universal Soil Loss Equation (USLE)

The USLE is a six parameter multiplicative model that estimates potential long term annual soil loss. It consists of a rainfall runoff factor (R), a soil erodibility factor (K), a slope length factor (L) and steepness factor (S), a cropping factor (C), and a support management factor (P) (Fig. 4).

The R factor is a function of energy and intensity of rainfall, parameterizing the force of raindrop impact on detachment of soil, soil saturation and runoff. The K factor parameterizes how the soil will react to the impact of rainfall energy and runoff, indicating the susceptibility of the soil to dislodgement, detachment and transport. Slope length (L) and steepness (S) factors interact with R and K, determining how slope angle and length contribute to soil loss. Crop canopy and associated cover intercepts falling raindrops and reduces the erosive potential of rainfall,

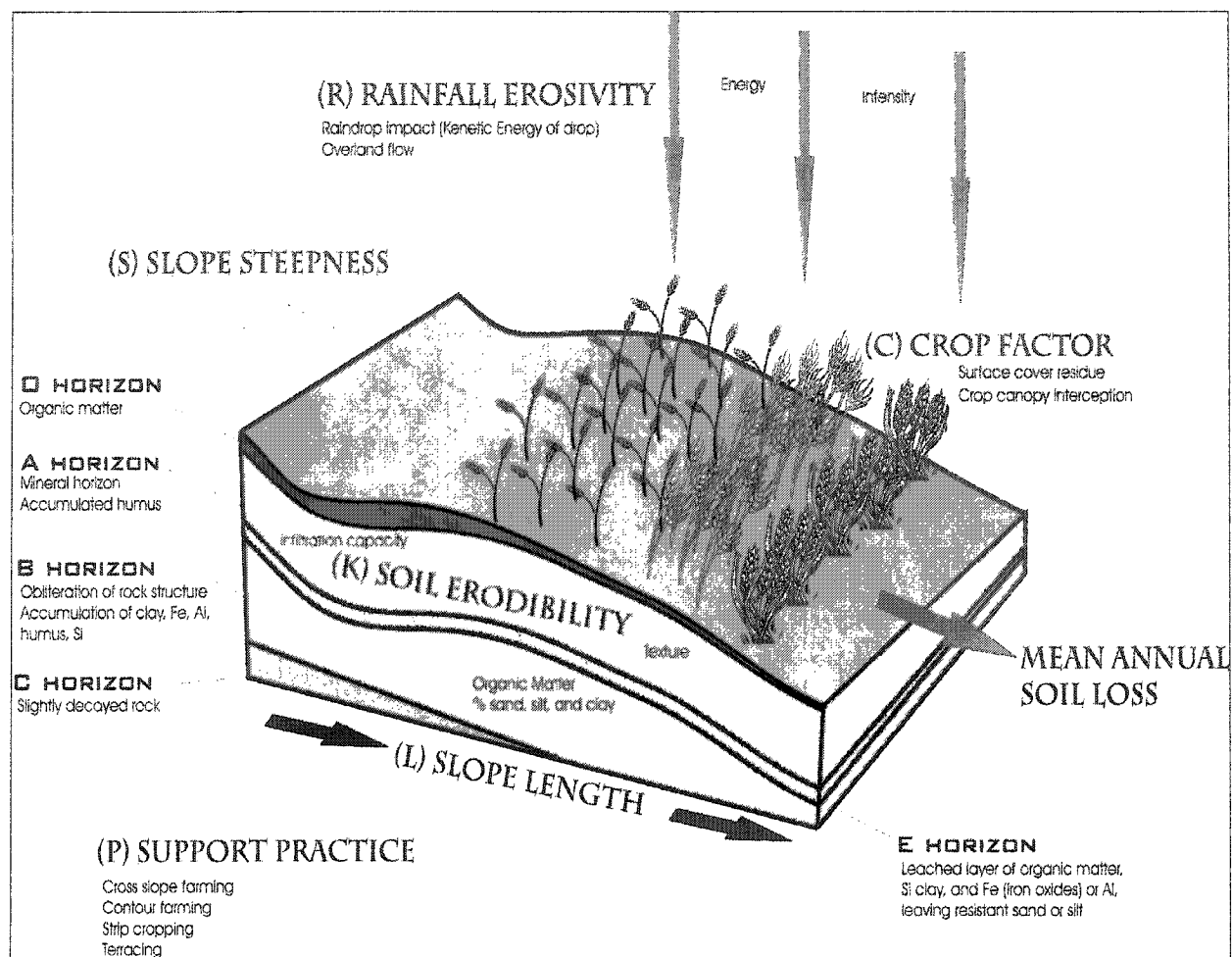


Fig. 4. Graphical representation of the factors utilized in the universal soil loss equation to compute detachment limited mean annual soil loss off of an agricultural field slope.

And therefore, C and R are related. Finally, anthropogenic change of slope and surface roughness, residue, and tillage practices alter the characteristics of soil and other factors which are adjusted in the support management (P) factor to calculate mean annual soil loss.

1.7 Applications of the USLE in Canada

First applications of the USLE in Canada occurred in the 1970s when Stewart and Himelson (1975) began erosion plots in Prince Edward Island (Wall *et al.*, 2002). In 1976 Van Vliet *et al.* published the first Canadian refereed scientific article using the USLE in studying land use effects on erosion in southern Ontario. The USLE was also applied in the PLUARG

(Pollution from Land Use Activities Reference Group) studies of the International Joint Commission for the Canadian Great Lakes Basin (van Vliet *et al.*, 1978; Wall *et al.*, 2002).

The revised universal soil loss equation for application in Canada (RUSLEFAC) was developed by the Research Branch of Agriculture and Agri-Food Canada for estimating soil loss from water erosion in Canada. Many organizations also provided input into the document, including, a) British Columbia Ministry of Agriculture, b) Newfoundland Department of Forestry & Agriculture, c) New Brunswick Department of Agriculture, d) Ontario Ministry of Agriculture, Food & Rural Affairs, e) Alberta Agriculture, Food and Rural Development, f) Manitoba Agriculture, g) Saskatchewan Agriculture & Food, and h) Nova Scotia Department of Agriculture & Marketing, Plant Industry Branch. Within the handbook, there is a compilation of data that is necessary to make soil loss predictions for Canadian conditions (Wall *et al.*, 2002). The revised universal soil loss equation for application in Canada provides a significant source of data for soil loss modeling in many parts of Canada where water related soil loss is the dominant method of soil movement off of agricultural lands.

Many of the methods of the handbook are those presented by Wischmeier and Smith (1965, 1978), revisions of these (McCool *et al.*, 1991), and Canadian implementations (Cooke, 1985; Hayhoe *et al.*, 1992; Hayhoe *et al.*, 1993) of these revisions (Wall *et al.*, 2002). The difference between the USLE and RUSLE lies in how various soil erosion factors are derived. In Chapter 3, the generalized C values for Ontario from this handbook will be used in the analysis as well as K estimates for Ontario soils with varying textures for a limited number of soils which are missing sufficient attribute information to calculate soil erodibility using Wischmeier and Smith's (1978) numerical approximation of soil erodibility based on soil properties.

1.8 The USLE2D Model

Desmet and Govers (1996a) published a GIS procedure for routinely calculating the USLE LS factor on topographically complex landscape units. In their article, an algorithm is presented for calculating the USLE and RUSLE LS factors. They proposed that the manual method undertaken via field survey and measurement for computing the slope length and steepness factor is replaceable with the GIS method of calculating the LS factor using an input digital elevation model (DEM). They further suggest that the manual method underestimates erosion risk because flow convergence is not accounted for in the traditional USLE and RUSLE. In their model, land units, or in their terms – ‘parcels’ can be considered hydrologically isolated or continuous. Separation between land units can be made to mimic the natural inhibition of flow that occurs due to fences and ditches along field boundaries. An example of a land unit could be a farmer’s field or pasture land. A comparison by Desmet and Govers (1996a) of model results with soil data show a reasonably good agreement between predicted erosion risk and the intensity of soil truncation or the decrease in depth of productive soil in a test site in Belgium. In their article, the USLE2D method is presented at a very small watershed scale. Desmet and Govers (1996a) indicate that this method of calculating LS generally benefits from higher resolution input elevation data. They further suggest that the uniform slope method (Fig. 5a) normally applied in USLE modeling consistently underestimates LS values compared to the point method applied on irregular slopes. In the manual method the measure of slope length is that from the point in question to an identifiable divide. However, real two dimensional water flow which causes erosion is not really dependent on the distance to divide, but on the area per unit contour length contributing to that point (Fig. 5b). Described another way, the method that better approximates the slope length and steepness factor goes beyond accounting for the length

of the field at one particular point, but adjusts the susceptibility of erosion based on the amount of contributing area to that particular point from multiple directions within the field, not just the steepest slope within the field. Desmet and Govers' (1996a) views that the slope length and steepness factor calculated using the traditional USLE or RUSLE method on a uniform slope are unrepresentative are accepted in this work. USLE2D will be utilized to calculate the USLE LS factor.

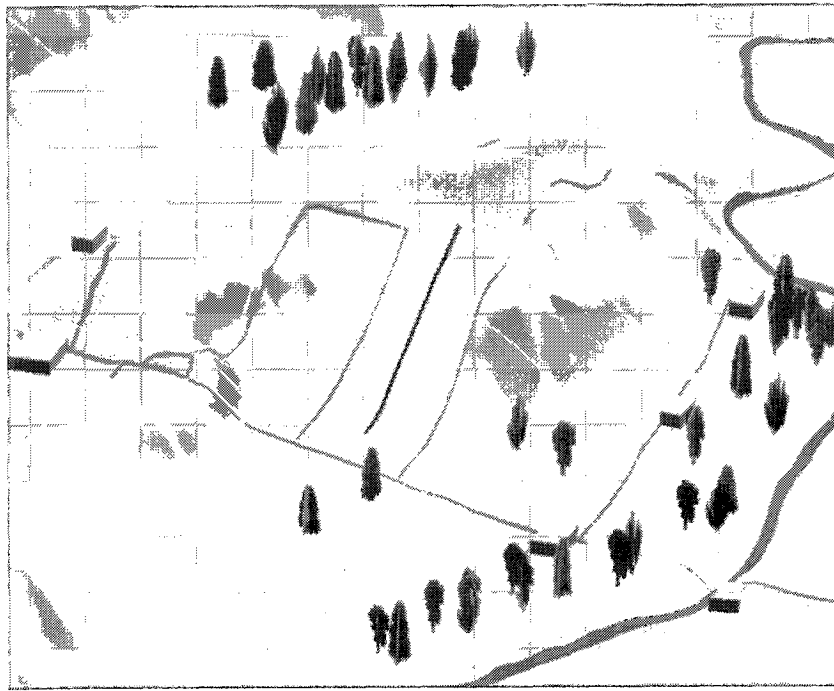


Fig. 5a. The simple slope method computed for use in the universal soil loss equation. Slope length is that of the black line centre measured adjacent to the hypotenuse following the length of the slope.

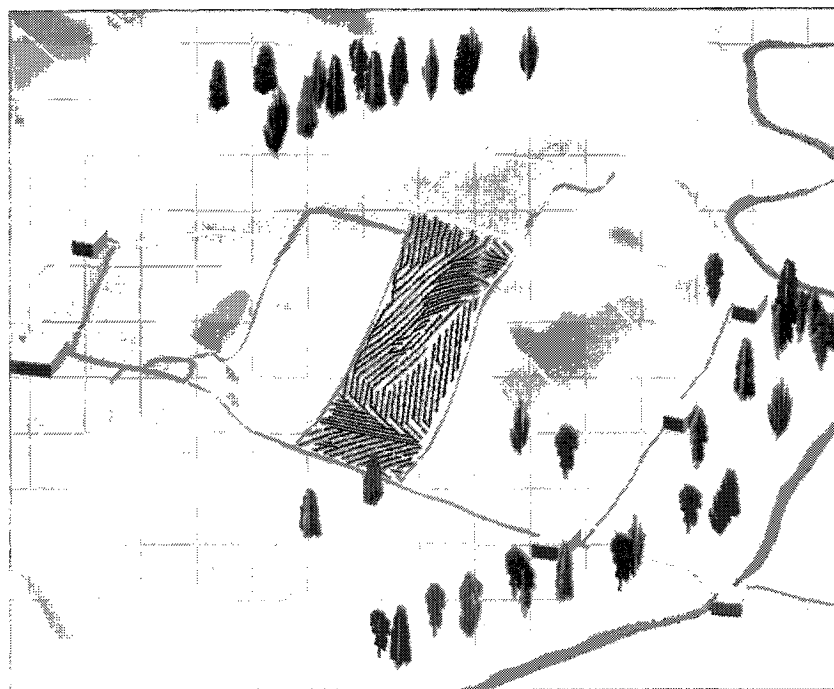


Fig. 5b. The multi-linear convergence of flow paths that are used to compute the slope length factor via the USLE2D model for use in the universal soil loss equation. Convergent paths are shown using black lineage on one specific field (centre). Scene generate in ESRI's © ArcScene 8.3 (Build 800) with use of developer sample extensions fog and haze, plant trees, and textured façade. Field boundaries are symbolized grey, roads are symbolized red.

1.9 Erosion Modeling within a Geographic Information System (GIS)

Three types of couplings between erosion models and GIS that are available are linking, combining, and integrating. Linking is the passing of input and output between GIS and model, combining is the automatic exchange, and integrating is the full embedding of a model within a GIS (Hartkamp, 1999). In this analysis the model will be linked to a GIS. Model inputs will be derived via a GIS, imported into a GIS, and analyzed within GIS.

Fistikoglu and Harmancioglu (2002) integrated the USLE with GIS to assess erosion risk in the Gediz River, Turkey, which empties into the Aegean Sea. The purpose of their work was to identify gross erosion using the USLE and a sediment delivery ratio for a small watershed in the region. They followed a multimedia approach to assess those areas at risk to improve land use decision making. They indicate that the movement towards the use of more complex models on small watersheds needs caution and improvement due to data constraints as model complexity increases. If adequate data is not available, model complexity becomes a serious disadvantage. Results indicate that GIS can be used in combination with a simple soil loss model to locate areas at risk of erosion.

There are many more recent examples which demonstrate the continued linking of the USLE and GIS to assess erosion risk. Lee (2004) applied the USLE in GIS for the Boun region of Korea to evaluate the hazard of soil erosion in relation to landslides. Chang *et al.* (2003) applied the USLE within a GIS for estimation of soil erosion related to reservoir sedimentation for the Charles Mill Lake reservoir in Ohio. Estimates of the amount of erosion sediment deposited in the reservoir each year were made. Jain and *et al.* (2001) applied the USLE in the Himalayas for soil loss assessment. Millward and Mersey (1999) integrated the RUSLE with a GIS to model erosion potential for the Sierra de Manantlán Biosphere Reserve in Mexico. They

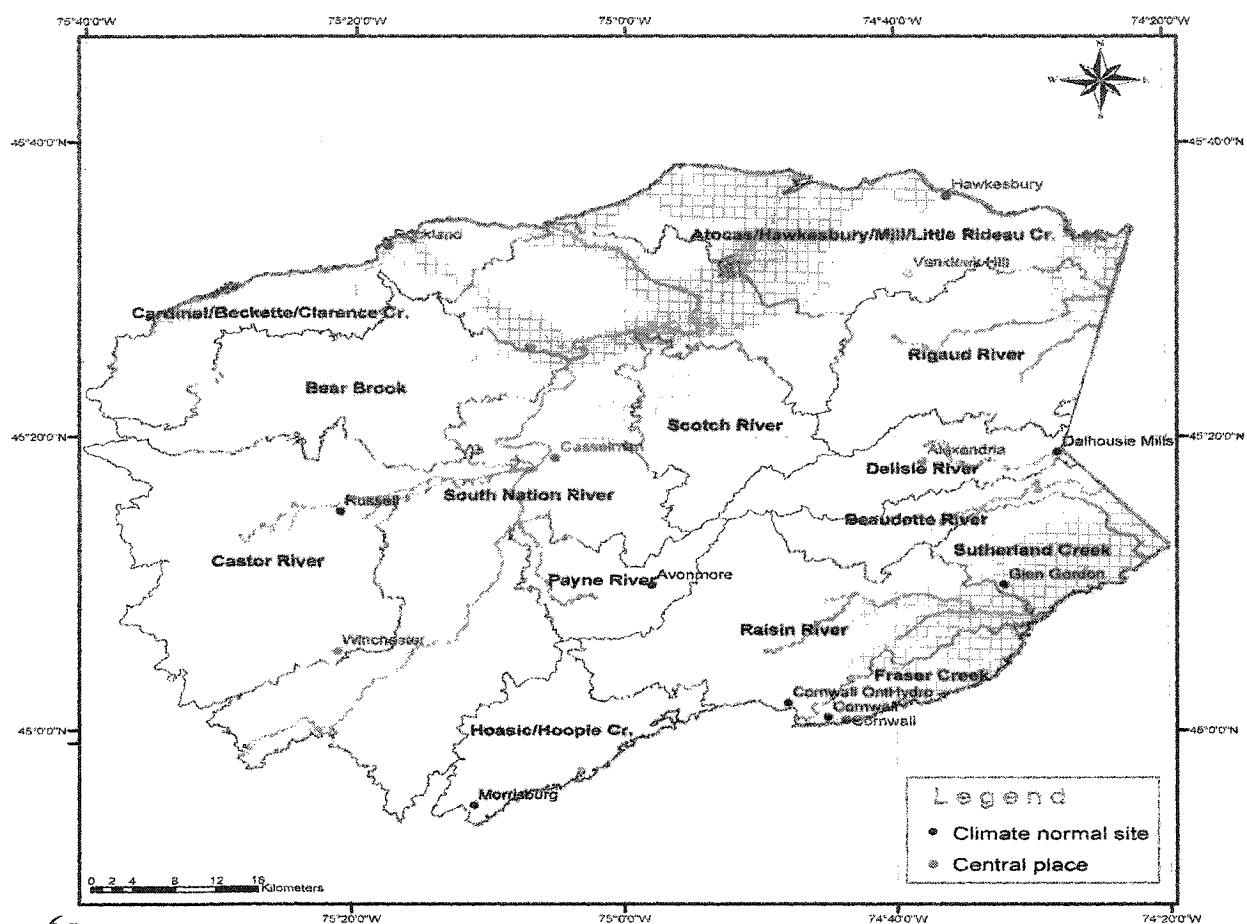
employed the upslope drainage substitution method to generate LS values, which more comprehensively considers the cumulative effects of overland flow on erosivity. Mati *et al.* (2000) utilized the USLE and GIS to assess erosion hazard in the Upper Ewaso Ng'iro North basin of Kenya. Cox and Madramootoo (1998) utilized the RUSLE equation for watershed management of soil loss in St. Lucia. Prato *et al.* (1989) used a GIS to assemble and retrieve the parameters required to estimate sheet and rill erosion and water quality effects for a number of land use scenarios with success for 16 farms in Idaho's Tom Beall watershed. Within the 45.6 km² watershed, soil type, topography, watercourse layers, cropping pattern, and watershed and field boundaries were used as input into their model.

A review of the previous literature indicates most if not all applications of soil loss modeling have been made on small watersheds at very coarse resolutions (50 to 100 meter) due to computational restraints and data limitations. A logical next step is to model erosion at finer resolutions over larger regions, spanning multiple watersheds, for more precise soil loss identification.

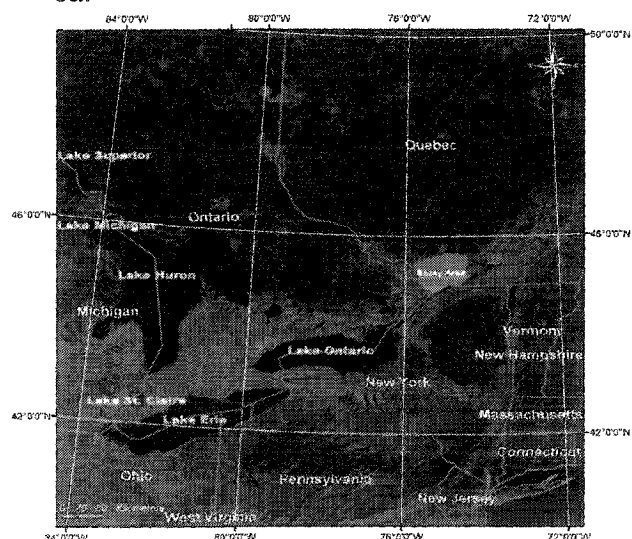
1.10 Study Area

The study area (74.33° - 75.67°W, 44.90° - 45.64°N) is located in eastern Ontario (Fig. 6b). The study area comprises all fields within fourteen watersheds (see Preface Fig. 3) (OMNR, 2002). The two major rivers of the region are the South Nation and Raisin River, and minor rivers include the Castor, Rigaud, Delisle, Beaudette, and Payne. The study region extends west to the Rideau River, north to the Ottawa River, south to the St. Lawrence, and east to the Quebec border. Areas of higher elevation extend over the south central region of eastern Ontario (Fig. 5c).

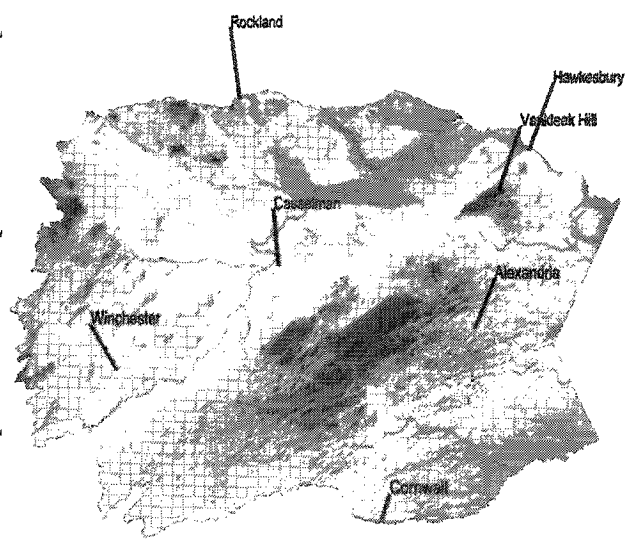
Some of the towns intersecting the region include Winchester, Crysler, Lancaster, Alexandria, Hawkesbury, Rockland, Navan, and St. Isidore. The County of Prescott and Russell covers a large portion of the northern extent of the study region and Stormont, Dundas and Glengarry covers the majority of the southern extent of the region (Fig. 2). The area has a rich agricultural heritage and much of the economy is dependent on agriculture. Table 2 is given to list the major crops grown in the region during the year 2003.



6a.



6b.



6c.

Fig. 6. Watersheds under study in eastern Ontario for potential soil loss estimate and analysis. Climate normals provided in Table 3 are for locations symbolized by a black dot. (a) Spatial extent of each watershed under analysis. (b) Watersheds in Great Lakes region. (c) Elevation model of the region.

	<i>Fodder Corn</i>	<i>Grain Corn</i>	<i>Hay</i>	<i>Barley</i>	<i>Mixed Grain</i>	<i>Oats</i>	<i>Soybean</i>	<i>Spring Wheat</i>	<i>Winter Wheat</i>
	<i>Area Seeded (acres)</i>	<i>Area Seeded (acres)</i>	<i>Area Seeded (acres)</i>	<i>Area Seeded (acres)</i>	<i>Area Seeded (acres)</i>	<i>Area Seeded (acres)</i>	<i>Area Seeded (acres)</i>	<i>Area Seeded (acres)</i>	<i>Area Seeded (acres)</i>
Prescott and Russell	7,100	53,800	113,700	10,800	2,800	3,200	37,700	9,400	1,200
Stormont, Dundas and Glengarry	19,100	107,600	100,500	11,100	1,400	2,800	72,300	14,000	1,900
Leeds and Grenville	7,700	28,000	83,300	4,700	1,800	1,400	11,400	1,300	700
Ottawa	7,200	43,700	65,800	4,100	1,800	1,800	26,400	11,100	600
	<i>Production</i>	<i>Production</i>	<i>Production</i>	<i>Production</i>	<i>Production</i>	<i>Production</i>	<i>Production</i>	<i>Production</i>	<i>Production</i>
Prescott and Russell	100.6	169.4	259.4	14	3.7	3.3	43.9	13.2	1.7
Stormont, Dundas and Glengarry	254.9	356.9	207.2	12.9	1.1	3.1	85	19.6	2.8
Leeds and Grenville	76.9	82.2	188.7	5.1	1.9	1.1	11.6	1.8	1.1
Ottawa	83.7	142.4	138	6	2.1	1.4	31.1	16.2	0.8

Table 2. Breakdown of field crop production (in thousands) and area seeded (acres) for the summer of 2003 for study region counties. Data from the Ontario Ministry of Agriculture and Food (OMAFRA, 2004).

Within Table 2, statistics are provided for the area seeded and the production of the various classes of field crops grown in the region. Of the four counties that intersect or are adjacent to the study region, hay, grain corn, and fodder corn (livestock feed) are the most produced crops. Hay is seeded over all regions followed by grain corn and soybeans. Spring wheat is sown in larger volumes than winter wheat in eastern Ontario.

Elevation in the region is generally flat, with some slightly rolling topography in the southern and eastern portions of the study region. Before land clearing by European settlers the region was mainly deciduous forest (LRC 1997). Most if not all of these forests were cleared and the remaining stands that are left are those situated on soil that is too rocky or too poor to farm.

Soils of the region are underlain by sedimentary rock. Most of the Raisin, Beaudette, Delisle River, and Fraser Creek watersheds are overlain with strongly calcareous soils. These are soils that were formed by the weathering of calcareous rock and can be very fertile if adequate

moisture sources exists. The Atocas/Hawkesbury/Mill/Little Rideau and Castor River watersheds are covered in 20 to 50% calcareous soils as well, with the rest of the watersheds in the region classified as containing non-calcareous soils.

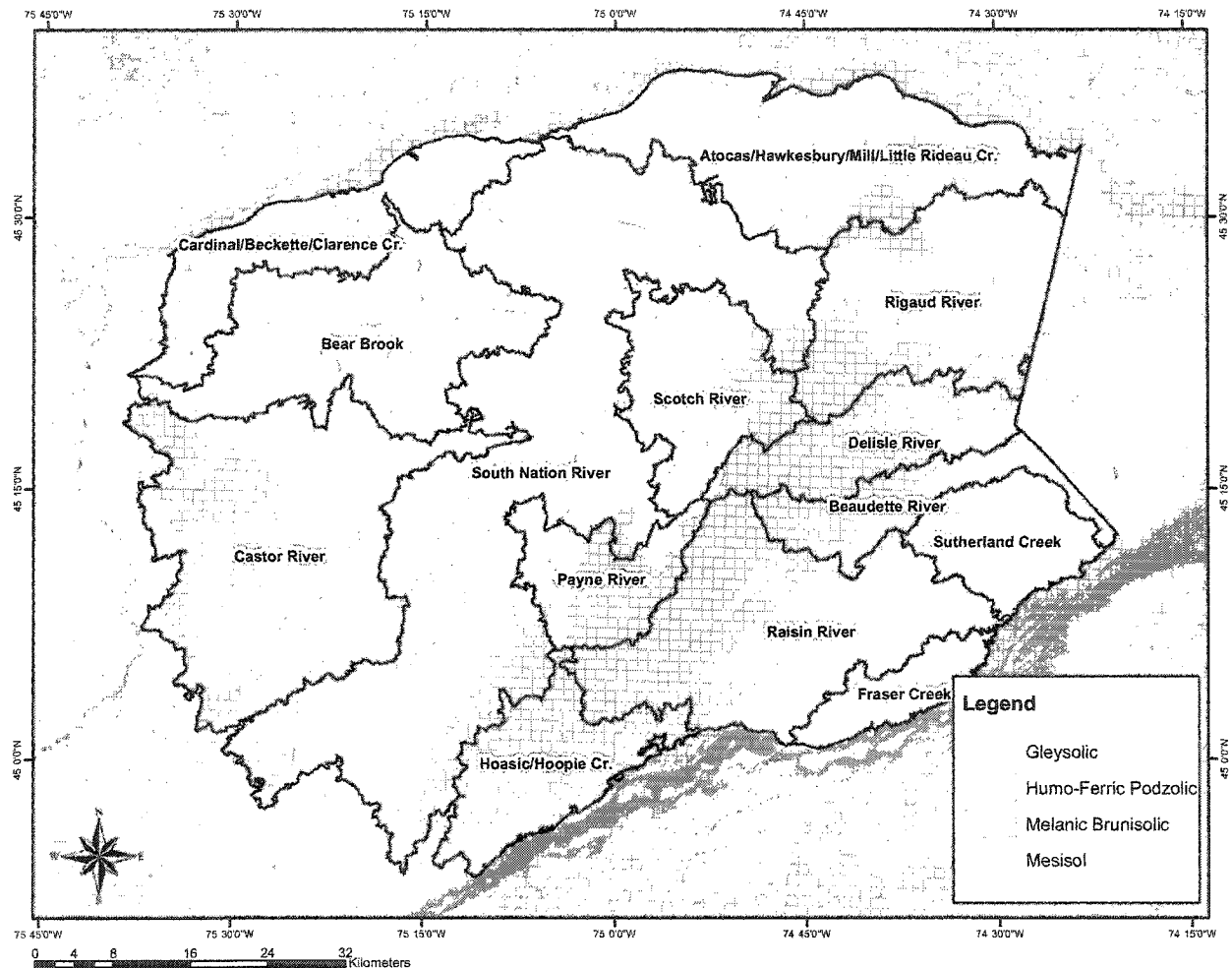


Fig. 7. Soil order map for the study region superimposed with watershed boundaries and Landsat 7 image, eastern Ontario (soil data source - Centre for Land and Biological Resources Research, 1996).

The study region has a high prevalence of mineral soils. The majority of the southern watersheds are covered in Melanic Brunisols, with the exception of Sutherland Creek which is overlain with Gleysolic soils (Fig. 7). Soils of the Brunisolic order have moderate development, excluding them from other classifications of highly developed and very young soils (Haynes, 1998).

Melanic Brunisols of the St. Lawrence lowlands have a high moisture regime. Melanic Brunisols have a dark colored Ah horizon and a relatively high degree of base saturation (Haynes, 1998). Gleysolic soils are poorly drained or permanently waterlogged and are classified in Canada on the basis of color and mottling, which are characteristic of periodic or sustained reducing conditions (Haynes, 1998). The Gleysols of Sutherland Creek and the northern portion of the study area lack a well developed mineral-organic surface layer and occur at poorly drained positions. The next major soil type in the region are Humo-Ferric Podzols which are in general strongly acidic, with an organic surface horizon and a brown to black B horizon normally rich in iron oxide. The majority of these soils occur in the lower portion of the South Nation and surrounding watersheds. Mesisols are composed of a great deal of organic material with a surface tier of organic material less than 20 cm in depth, followed by mineral material. This soil dominates in the Alfred Bog.

Many of the soils described above correspond to large physiographic regions. Most of the Melanic Brunisols occur on the Glengarry Till Plain, extending across the Hoasie/Hoppie Creek and Raisin River watershed. This region has a rolling landform and is noted for its stoniness (LRC, 1997). A second major physiographic region, the Winchester Clay Plain, extends in a northeast direction from Winchester. A majority of Gleysols occur here. This plain is known for its poor drainage and low topography which extends around the Prescott and Russell Sand Plain region in a U shape adjacent to the Ottawa River. Humo-Ferric Podzols exist in the Prescott and Russell Sand Plain which is known for its good drainage and progressively finer deposits as one moves south (LRC, 1997). The final and notably the smallest major physiographic area is the Lancaster flats which are till plains buried beneath deposits of clay and sand (LRC, 1997). This

area of lower topography, due to its proximity to the St. Lawrence, is commonly known to have poorly drained soils.

The temperature regime of the region is continental, peaking in July with low January temperatures. Total snowfall tends to be greater on average in the southeast, although there are few stations with supporting climate normal data in the northern extent of the study region. Mean daily temperature (yearly, January, and July) does not show great variation over the region. Mean annual rainfall ranges between 729.5 and 820.6 mm, with a range of 91.1 mm. Climate monitoring stations providing climate normals for the northern extent of the study region are non-existent.

Site	Lat.	Long.	Elevation (m)	Mean daily Temp. (°C)	Mean daily Temp. January (°C)	Mean daily Temp. July (°C)	Total Rainfall (mm)	Total Snowfall (cm)
Avonmore	45°10'N	74°58'W	91	5.8	-10.7	20.1	775.8	207.5
Cornwall	45°01'N	74°45'W	64	7.2	-8.8	18.7	794.8	207.1
Cornwall (Ont. Hydro)	45°02'N	74°48'W	76	6.8	-9.4	21.4	778.7	207.5
Dalhousie mills	45°19'N	74°28'W	69	5.4	-11.3	19.9	819.4	245.6
Glen Gordon	45°10'N	74°32'W	53	5.7	-10.5	20.3	729.5	230.3
Morrisburg	44°55'N	75°11'W	82	6.2	-10	20.4	820.6	208
Russell	45°15'N	75°21'W	76	6.2	-10.3	20.7	771.3	191.2

Table 3. Canadian climate normals for years 1971 to 2000 for sites listed in Fig.1. Data made available from Environment Canada (2000).

Of the climate data provided by Environment Canada, the data that is the most helpful in describing those months that are likely to experience larger losses of soil from rainfall are climate rainfall extremes. Below (Table 4) are rainfall extremes for climate normal sites in the region given by month. The months of July and August show the largest extreme rainfalls for most stations. Morrisburg, the station the furthest southwest tends to have higher extreme rainfalls than all other stations. Some deviations to this trend include the 11 cm of rainfall that

occurred at the Cornwall meteorological station in the month of September, and the 38.1 cm of rainfall that fell in Russell in March.

Site	Jan. (mm)	Feb. (mm)	Mar. (mm)	Apr. (mm)	May. (mm)	Jun. (mm)	Jul. (mm)	Aug. (mm)	Sep. (mm)	Oct. (mm)	Nov. (mm)	Dec. (mm)
Avonmore	47.8	30.2	28.8	36.6	51.2	53.4	45.6	75.2	97.6	47.2	56.8	35.2
Cornwall	37.5	37.6	39.1	33.8	46.8	58.9	73.0	70.9	110.4	60.0	46.4	35.0
Cornwall (Ont. Hydro)	38.1	50.0	37.3	38.1	33.0	62.0	55.1	70.6	90.2	48.3	49.8	56.7
Dalhousie mills	41.2	39.4	34.5	35.2	42.2	41.6	53.8	78.9	86.0	56.2	54.6	34.0
Glen Gordon	36.2	29.0	28.2	41.0	48.3	60.6	49.0	96.4	71.6	71.0	50.8	35.6
Morrisburg	62.2	37.4	31.8	41.9	89.9	90.2	61.2	114.3	107.2	75.0	59.4	51.6
Russell	53.2	33.0	38.1	36.8	35.6	60.0	69.2	68.0	90.6	62.8	43.6	31.4

Table 4. Canadian climate normals for extreme rainfall for years 1971 to 2000 for sites shown in Fig.5a. Data made available from Environment Canada (2000).

CHAPTER 2

INTEGRATION AND CALCULATION OF US AND CANADIAN METEOROLOGICAL DATA FOR GENERATING THE RAINFALL EROSION FACTOR OF THE USLE OVER LARGE REGIONS

2.1 Abstract

The R factor, an index of rainfall erosivity of the universal soil loss equation (USLE), fundamentally governs water related soil loss from agricultural plots and is based on well-studied and widely-known empirical relations. Soil particles and absorbed contaminants inevitably end up in watercourses and ultimately the Great Lakes system, disturbing natural habitat, reducing water clarity and quality. We here use over twenty-two years of records containing hourly precipitation recordings for 453 sites in Ontario, southeastern Quebec, Michigan, Ohio, Pennsylvania, and New York to estimate the R factor surrounding the lower Laurentian Great Lakes. R-factor maps were generated for major growing season months to aid in agricultural land use planning. After building the hourly precipitation database, cleaning, querying and processing, a total of 453 locations were available for generation of multiple R factor surface maps. Results suggest a strong northeast to southwest trend in decreasing erosivity of rainfall in the study area west of Lake Erie and Lake Ontario. The mean R value for 453 sites was $1599 \text{ MJ mm}^{-1} \text{ ha}^{-1} \text{ yr}^{-1}$, with a standard deviation of $591 \text{ MJ mm}^{-1} \text{ ha}^{-1} \text{ yr}^{-1}$. Results are in general agreement with other published work but show some spatial differences.

2.2 Introduction

Drainage basins surrounding the lower Great Lakes are heavily developed for agriculture, particularly on the Canadian side. Densification is expected to increase due to the expansion of factory farming and the adoption of high-intensity agriculture. Agriculture with associated soil loss is a major non-point source of water pollution (Meyers *et al.*, 1985; Bhuyen *et al.*, 2002). For example, excessive phosphorous in surface waters can cause eutrophication (Mallarino *et al.*, 2002) (with higher prevalence in near shore areas) as evident within the Great Lakes (Fuller *et al.*, 1995; Neilson *et al.*, 1995; Hummerman, 2001). While some studies suggest that total phosphorous loads into Lake Ontario have declined (Hartig *et al.*, 1991; Makarewicz *et al.*, 1995), others indicate increasing concentrations of other pollutants from agricultural lands. It has been estimated that nitrogen content of water has increased by more than 1 mg/L on 68% of the farmland in Ontario and 77% of the farmland in Quebec between 1981 and 1996 (MacDonald, 2000). In Canada, the highest nitrogen deposition and NO_3^- concentrations in surface waters occur in south-central Ontario and southwestern Quebec (Fenn *et al.*, 1998). These results indicate that there is a pressing need to monitor soil loss factors, particularly those involving rainfall-induced erosion and use these data for mitigation purposes and agricultural land use planning within the prioritization of basin conservation strategies.

To our knowledge, no attempt has been made to map rainfall erosivity continuously over U.S./Canada boundaries for recent time periods. Previous work has been restricted to the comparison of a limited number of station values in the U.S. and Canada to generate contour values for only one country (Van Vliet *et al.*, 1976; Wall *et al.*, 1983). Madramootoo and (1988) and Gordon and Madramootoo (1989) published rainfall erosivity maps for Ontario and eastern Canada by estimating the erosivity of rainfall from a once-in-two-year, 6-h extreme rainfall from

the Rainfall Frequency Atlas of Canada (Hogg and Carr, 1985). However, these scientists generated mean annual extreme rainfalls from tipping bucket and long duration rainfall data prior to 1984, with most collection beginning in the early 1960's. Concerns exist over the current validity of the estimates due to changing climatic regimes. Two decades have passed since these publications and their data collection period. These studies are restricted to either the Canadian or US political boundaries and there have been no published attempts or methodologies presented to unify the calculation of R factors across borders.

There is a clear need to update erosivity values in the Canadian Great Lakes for planning strategies. Here we utilize 453 meteorological stations with over 22 years of precipitation and generate new once-in-two-year, 6-h extreme rainfall erosivity maps (Ateshian, 1974) for the lower Great Lakes and surrounding region. We present the methods and considerations required to combine data from weather stations in Ontario, southwestern Quebec, Michigan, Ohio, Pennsylvania, and New York. Secondly, we provide rainfall erosivity maps for growing season months. Thirdly, we present cross border estimates of rainfall erosivity. We make these maps available as standard gridded datasets for use in erosion and pollution studies in the Lower Great Lakes region.

2.3 Background of the USLE

The R or rainfall erosivity factor is a crucial element of the universal soil loss equation (USLE) which derives from the early work of M.F. Miller in (1914), Zingg (1940), Musgrave (1947), and Browning *et al.* (1947). This method of erosion estimates was popularized by Wischmeier and Smith (1965) who generalized the relationships between climate, topographic, vegetative, soil, and anthropogenic factors in effecting soil loss on agricultural slopes. The equation is multiplicative in nature, and is as follows:

$$A = RKLSCP \quad (2.1)$$

where:

- A = potential long term annual soil loss ($\text{t ha}^{-1} \text{ yr}^{-1}$),
- R = rainfall and runoff erosivity factor ($\text{MJ mm ha}^{-1} \text{ h}^{-1} \text{ yr}^{-1}$),
- K = soil erodibility factor ($\text{t h MJ}^{-1} \text{ mm}^{-1}$),
- L = slope length coefficient,
- S = slope gradient coefficient,
- C = cropping management coefficient,
- P = support practice coefficient.

The rainfall and runoff erosivity parameter is the primary factor for computing soil loss. The USLE estimates average annual rill and interrill erosion for an entire agricultural field, and was not designed to model erosion from individual storm events, gully erosion, or deposition. Through refinement and revision of factor value determination, Wischmeier's empirically-based detachment-limited model has been updated to form the revised universal soil loss equation (RUSLE) (Renard *et al.*, 1991) and more recent versions of the unpublished RUSLE2 model (Yoder *et al.*, 2003). USLE based models are essentially empirical but easily applied over large regions whereas process-based models (Knisel, 1980; Leonard and Still, 1987; Smith *et al.*, 1995; Bouraoui and Dillaha, 1996; De Roo *et al.*, 1996a; De Roo *et al.*, 1996b; Laflen *et al.*, 1997; Morgan *et al.*, 1998; Bouraoui and Dillaha, 2000) are difficult to apply beyond the small catchment scale. Models such as the USLE will continue to provide the basis for modeling rainfall erosion and in that the R factor is paramount.

2.4 Method of Isoerodent Map Generation

Rainfall and associated runoff are the dominant factors of the USLE and is computed as the mean annual sum of storms erosivity. The rainfall erosivity factor is derived using the following equation (Renard *et al.*, 1996):

$$R = \frac{\left[\sum_{m=1}^N \sum_{i=1}^j (EI_{30})_i \right]}{N} \quad (2.2)$$

where:

R = rainfall and runoff factor (MJ mm ha⁻¹ h⁻¹),

i = storm number in year period,

j = number of storms in mth year,

N = the number of years of recording,

E = rainstorm kinetic energy (MJ ha⁻¹),

I₃₀ = maximum storm intensity occurring in 30 minutes (mm h⁻¹),

m = index for the year.

The index EI₃₀ has been shown to most closely correlate to soil loss when all other factors of the USLE are held constant. The factor R has been proven difficult to calculate given the fact that a minimum of 22 years of consistent data are needed to smooth out short term variations in R. Rainstorm kinetic energy can be calculated using a variety of formulas which derive kinetic energy as a function of rainfall intensity (Marshall and Palmer, 1948; Wischmeier and Smith, 1958; Hudson, 1965; Brown and Foster, 1987).

The unit energy equation (Brown and Foster, 1987) is recommended (Renard *et al.*, 1996) for computation of R and is given as (Yu, 1999):

$$e(i) = e_o \left(1 - \alpha e^{-\frac{i}{i_o}} \right) \quad (2.3)$$

where:

- $e(i)$ = unit energy (MJ ha⁻¹ mm⁻¹),
- e_o = maximum unit energy as intensity approaches infinity [0.29 (MJ ha⁻¹ mm⁻¹)],
- α = empirical coefficient [0.72],
- e = base of natural log; [≈ 2.71828],
- i = intensity (mm h⁻¹),
- i_o = coefficient [20 mm h⁻¹].

This formula (2.3) is suggested for calculating unit energy due to its finite positive value at zero and its asymptotical behavior at high intensities (Brown and Foster, 1987; Renard *et al.*, 1996). For each storm, unit energy is summed using the following formula to derive E or rainstorm kinetic energy:

$$E = \sum_{i=1}^j (eV)_i \quad (2.4)$$

where:

- E = rainstorm kinetic energy (MJ ha⁻¹),
- i = time interval of storm,
- e = unit energy of the time interval (MJ ha⁻¹ mm⁻¹),
- V = volume of rainfall in time interval (mm).

Data limitations in the lower Great Lakes region, and processing restraints dictate that the R factor be approximated using Ateshian's (1974) method. Variable width recordings of rainfall with a time resolution fine enough for calculation of R using equation (2.2) and equation (2.3) are

not distributed by Environment Canada Climate Data Centre in digital form. If available, the processing of variable width data is time consuming and has a higher potential for error due to the increased dataset size. Approximations of R using once-in-two-year, 6-h duration extreme rainfall has been proven acceptable and less cumbersome (Ateshian, 1974). This leads us to the use of Ateshian's (1974) approximation, which is less error prone and tedious.

$$R \approx 0.417(P^{2.17}) \quad (2.5)$$

where:

R = rainfall erosivity factor approximated ($\text{MJ mm ha}^{-1} \text{ h}^{-1}$),

P = once-in-two-year, 6-h duration extreme rainfall (mm).

The once-in-two-year, 6-h duration extreme rainfall can be calculated using a lengthy complete set of hourly precipitation observations at meteorological recording sites. It is general practice to use at least a duration of data that exceeds a given return period and more robustly one that greatly exceeds the required return period. The Gumbel (1941) double exponential distribution for annual extremes and fitting by the method of moments (Hogg and Carr, 1985) was used to compute the once-in-two-year, 6-hr duration extreme rainfall for sites with greater than 22 years of data:

$$X = \mu + K(T)\sigma \quad (2.6)$$

where:

X = is the exceedence value,

μ = population mean,

σ = is the population standard deviation,

$K(T)$ = return period frequency factor (-0.164 for a 2-yr return period).

To calculate the exceedence value, the sample mean and standard deviation evaluated at each site for the yearly maximum six hour duration storm (annual series) were substituted in place of the population mean and standard deviation. Benefits of using the method of moments is its nearly unbiased nature (Hogg and Carr, 1985), its simplicity, and the fact that a three parameter or higher distributions will fit the sample better but does not ensure a better probability estimate when larger samples are obtained (Hogg, 2004; personal communication).

2.5 Meteorological Data Processing

National Climatic Data Center (NCDC) hourly precipitation data (Data set 3240) for Michigan (Code 20), Ohio (33), Pennsylvania (36), and New York (30) were obtained from the NOAA Hydrological Systems Group as a variable width text file for each individual state (NOAA, 2003). A variable width format of data storage does not store zero values explicitly. The temporal range of the dataset was year 1900 to roughly year 1993, with a majority of stations beginning observations in year 1948.

Each state file was parsed to fixed-width format using a program written in Microsoft Visual Basic 6 (Microsoft, 2000a) (see Appendix A for code). The data (ASCII text files) were imported into a Microsoft Access database with hourly columns set to text to accept flagged values and station identifications set to text to accept all stations including some with character attributes (Microsoft, 2000b). Separate year, month and day columns for each station file were aggregated into one common date/time attribute (See Appendix B for SQL statement). All missing hourly precipitation values were set to -99999M (See Appendix C). Null records, as a result of the variable width to fixed width conversion, were reset to zero (See Appendix D). Lastly, precipitation values were converted from hundredths of an inch to tenths of a millimeter to adhere to the Canadian hourly data format (See Appendix E).

Precipitation data were obtained in fixed-width format for Ontario and Quebec from the Ontario Climate Centre of Environment Canada. Data were received for climatological districts 601 to 616 (spanning all of Ontario) and districts 701-703, 707 and 708 of Quebec (southwestern Quebec) (OCC, 2003). These data mostly range in collection from year 1960 to 1998.

All stations with greater than 22 years of records or more were selected for additional study (See Appendix F). The station data (individual text files for each station) for these sites were exported from the database (Appendix G) and read into a program designed by the author(s) to calculate the R factor. The program cycles a 6 hour moving window through the hourly observations and stores the maximum value calculated for each year, and subsequently prints each or the maxima for each year to a file (Appendix H). A correction factor of 1.02 was applied to the yearly maxima to account for the fixed window effect of a six hour interval (Weiss, 1964). The program then loops through the maxima files and calculates the R factor for each station by means of equation (2.5) and equation (2.6). A smaller routine was built to generate a count of the Julian occurrence of each of the yearly maximums (Appendix I).

Monthly erosivity values were calculated by determining the percentage of precipitation that occurs in each of the growing season months and multiplying this value by the total R factor for each station, to estimate the R factor occurring in that particular month at that station over the recording period (Appendix J). Total precipitation for each month was computed using a separate program to sum precipitation amounts by month via a looping routine that reads and calculates the station files. Next these monthly values were averaged over the recording period. Arbitrary limitations were imposed on the Canadian data. Months with less than 20 days of record were not included in the monthly averaging as totals for such months would skew the monthly averages. For the U.S. data, those months with missing recordings were also dropped in the

analysis of monthly precipitation. Within the yearly window of collection for each station the percentage of precipitation per month was multiplied against the gross rainfall erosivity to provide an estimate of monthly erosivity.

Maps were produced by interpolating the results using ordinary kriging (Burrough and McDonnell, 1998; page 139) due to its ability to capture global trends and relaxed assumption of normality. Ordinary kriging is a geostatistical approach to surface modeling which weights estimates based on the spatial correlation structure of data in a region where the variogram is known in combination with an estimated constant mean and estimated component of variation.

2.6 Results

Annual six hour maximum precipitation in the lower Great Lakes most often occurs between Julian days 140 and 275, from the end of May to early October (Fig. 8). A general peak occurs at Julian day 201 corresponding to mid to late July.

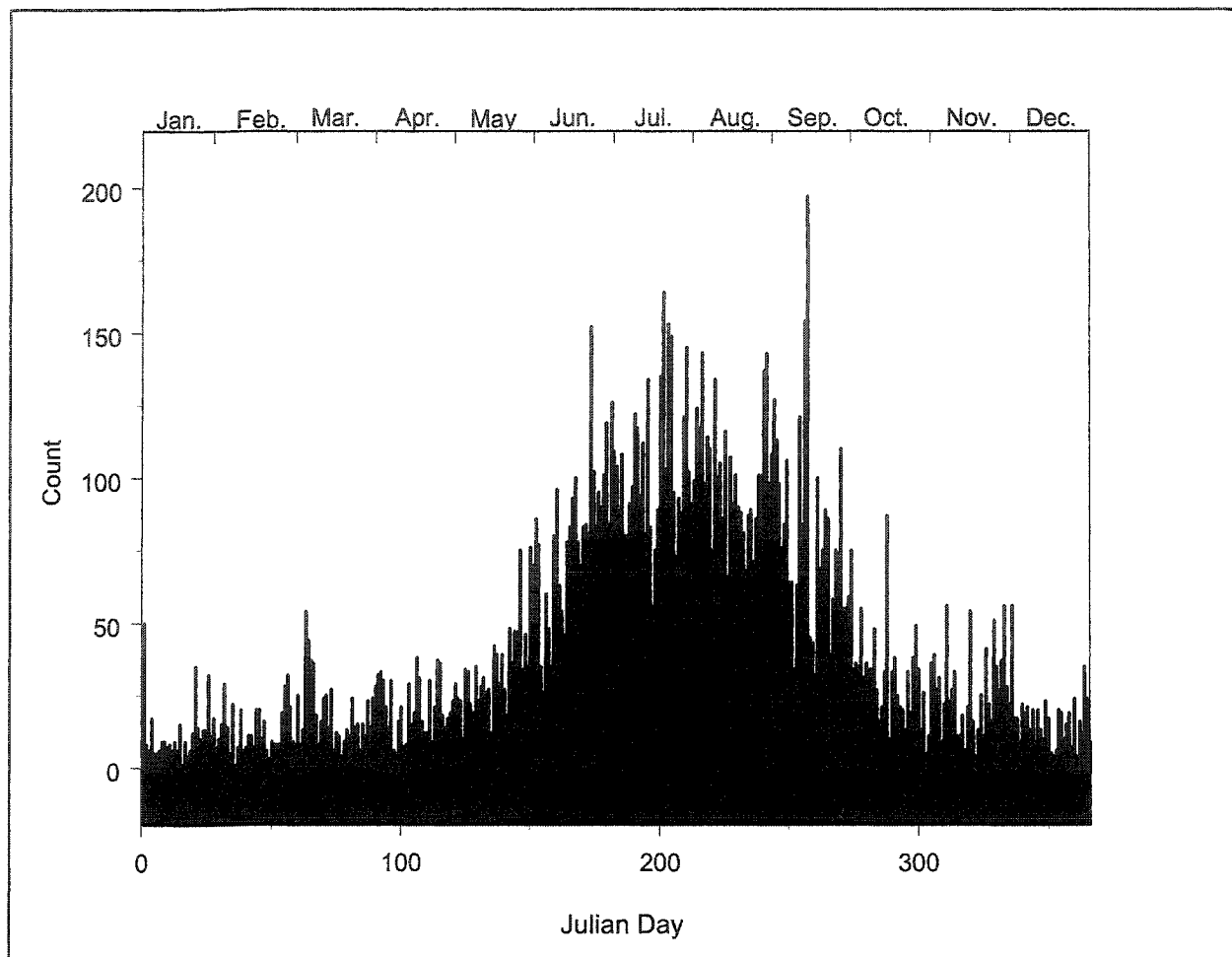


Fig. 8. Distribution of yearly maximum 6 hour precipitation events throughout the Julian year for the lower Great Lakes across all 453 meteorological stations (see text).

The total average erosivity value for months March to October is $1472.81 \text{ MJ mm ha}^{-1} \text{ h}^{-1}$, of which 13.6 % of estimated rainfall erosivity occurs in the month of March on average for the period. This value is high in comparison to the 15.4 % of rainfall erosivity that occurs in July for the same period.

Approximate mean monthly values for rainfall erosivity differ only by $26.98 \text{ MJ mm ha}^{-1} \text{ h}^{-1}$ between the months of March and July (Table 5), indicating that the early Spring period contains a significant quantity of potential erosivity in the study region. This high erosivity potential is during a major period of concern for soil sediment loading in surface water bodies as

a result of spring snow pack melt and surface water shock. The greatest variation in rainfall erosivity occurs in March and July, with standard deviations of 84.84 MJ mm ha⁻¹ h⁻¹ and 83.08 MJ mm ha⁻¹ h⁻¹ respectively. October shows the lowest variation in rainfall erosivity as well as the overall lowest density of erosivity. September is a month of concern with 14.0 % of the March to October average rainfall erosivity falling in this month (Table 5). However, the potential of rainfall falling on frozen bare soil is far less than that seen in March when frost is more extensive.

Temporal Period	Minimum value	1 st Quartile	Mean value	Median value	3 rd Quartile	Maximum value	Number of Observations	Standard deviation
All months	550.34	1172.00	1599.13	1521.20	1927.63	3616.00	453	591.74
March	27.55	145.82	199.64	185.50	250.21	544.11	372	84.84
April	7.15	136.99	196.91	190.82	243.68	486.00	435	82.31
May	39.67	149.57	209.73	192.12	260.03	546.33	451	80.38
June	80.13	162.24	218.53	209.95	262.62	494.44	451	71.45
July	53.59	164.31	226.62	214.18	275.00	641.84	451	83.08
August	69.36	165.13	215.60	201.83	244.26	536.13	451	73.71
September	92.56	160.91	205.78	191.62	235.43	495.81	451	67.74
October	39.33	130.32	170.64	156.93	190.55	434.40	451	60.68

Table 5. Summary statistics for calculated rainfall erosivity values based on point sample results by temporal period for the lower Great Lakes based on a minimum of twenty-two years of hourly precipitation observations (units - MJ mm ha⁻¹ h⁻¹).

Annual rainfall erosivity and runoff values are presented from north of Lake Superior to the mouth of the St. Lawrence to eastern Pennsylvania and southern Ohio (Fig. 9). Prediction errors for the same region are presented in Fig. 10. Figures 11 through 18 display isoerodent densities for the months March to October.

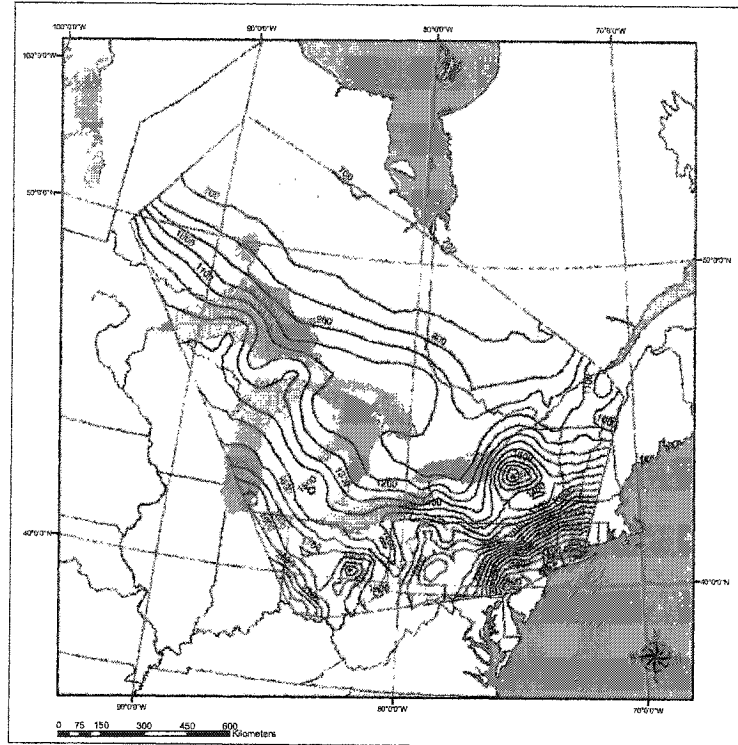


Fig. 9. Distribution of mean annual rainfall erosivity values (R) for the lower Great Lakes calculated for 453 meteorological sites, interpolated using ordinary kriging (contours units - $\text{MJ mm ha}^{-1} \text{h}^{-1}$).

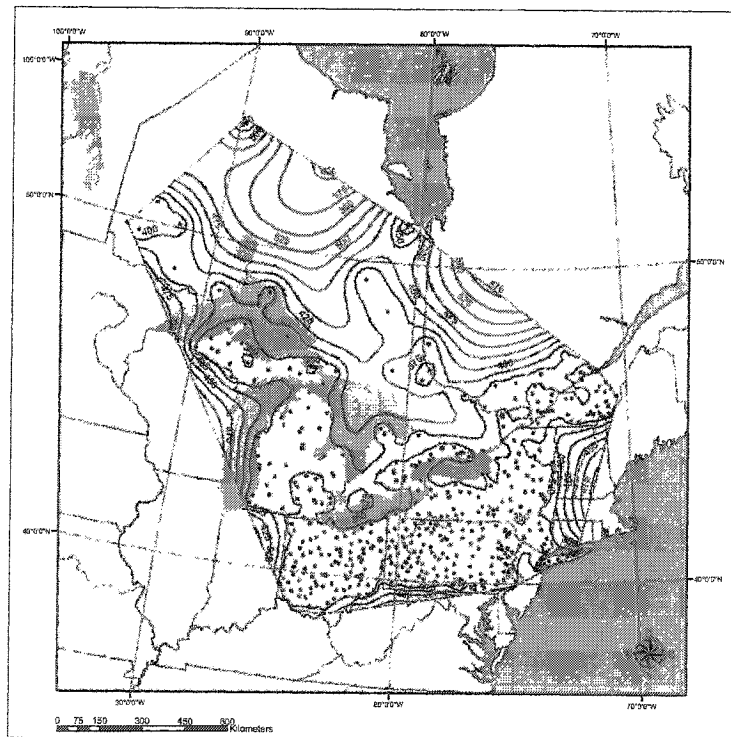


Fig. 10. Prediction standard error values (square root of variance of a prediction) of mean annual rainfall erosivity values (R) for the lower Great Lakes region computed from 451 meteorological sites based on results of Fig. 2 (contours units - $\text{MJ mm ha}^{-1} \text{h}^{-1}$).

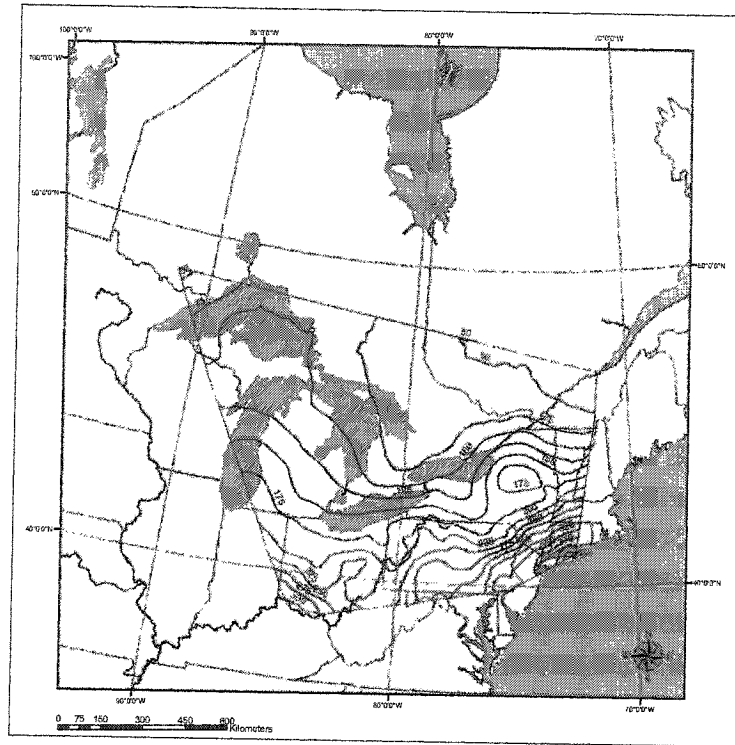


Fig. 11. Distribution of rainfall erosivity values (R) for the Great Lakes for the month of March calculated for 372 meteorological sites, interpolated using ordinary kriging (contours units - $\text{MJ mm ha}^{-1} \text{h}^{-1}$).

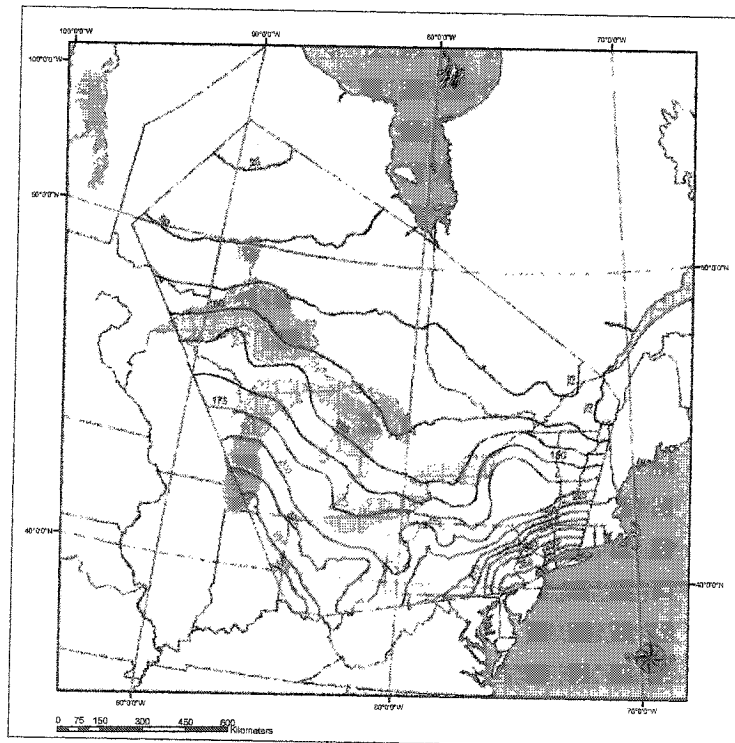


Fig. 12. Rainfall erosivity values (R) for the lower Great Lakes region for the month of April calculated for 435 meteorological sites, interpolated using ordinary kriging (contours units - $\text{MJ mm ha}^{-1} \text{h}^{-1}$).

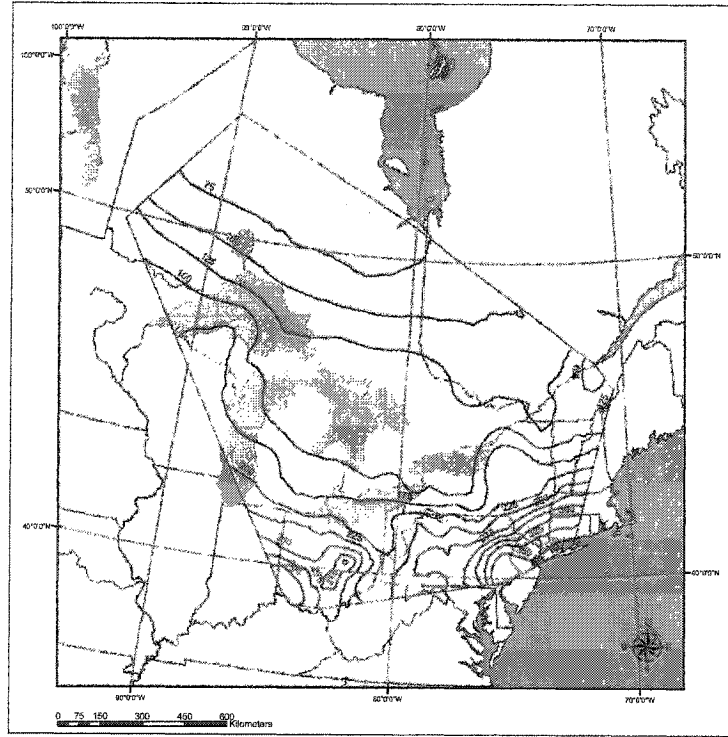


Fig. 13. Distribution of rainfall erosivity values (R) for the Great Lakes for the month of May calculated for 451 meteorological sites, interpolated using ordinary kriging (contours units - $\text{MJ mm ha}^{-1} \text{h}^{-1}$).

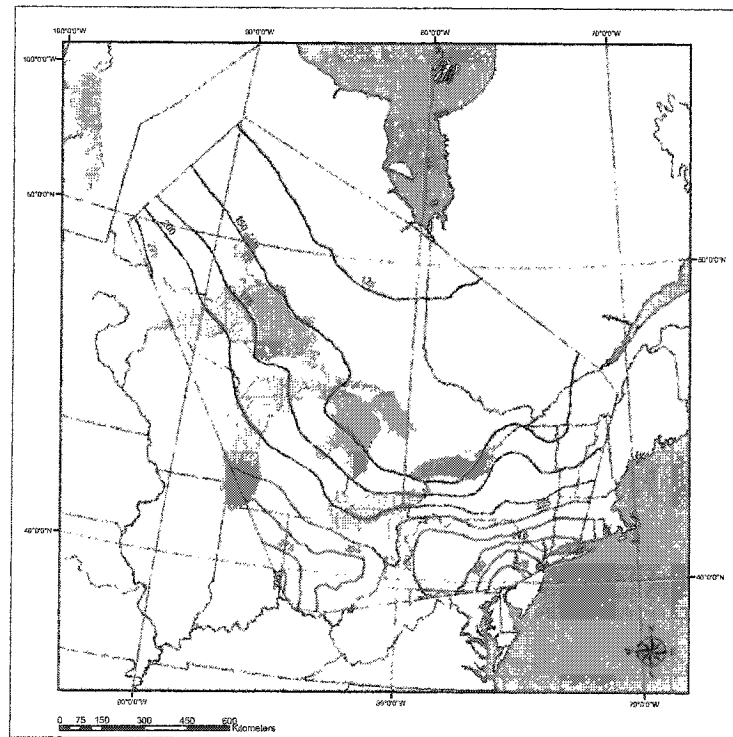


Fig. 14. Distribution of rainfall erosivity values (R) for the Great Lakes for the month of June calculated for 451 meteorological sites, interpolated using ordinary kriging (contours units - $\text{MJ mm ha}^{-1} \text{h}^{-1}$).

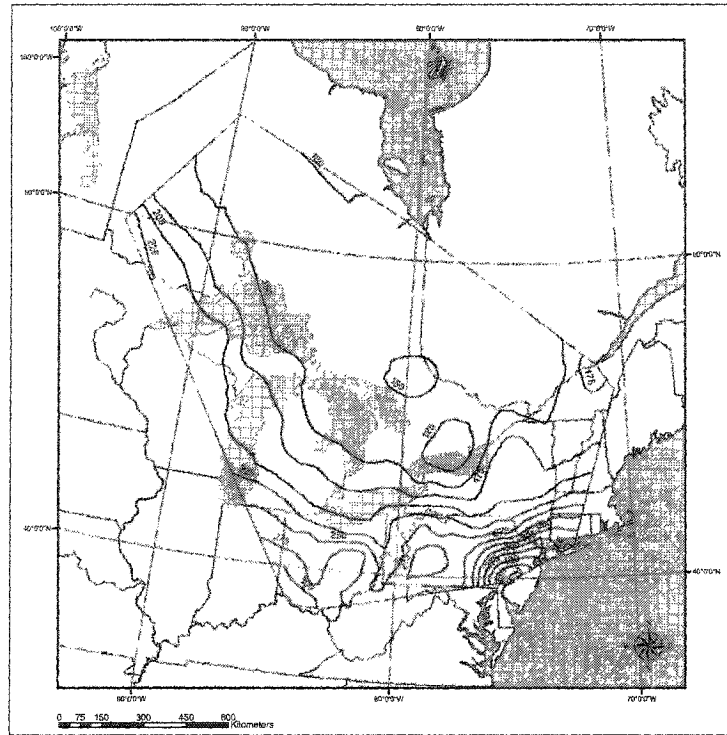


Fig. 15. Distribution of rainfall erosivity values (R) for the Great Lakes for the month of July calculated for 451 meteorological sites, interpolated using ordinary kriging (contours units - $\text{MJ mm ha}^{-1} \text{h}^{-1}$).

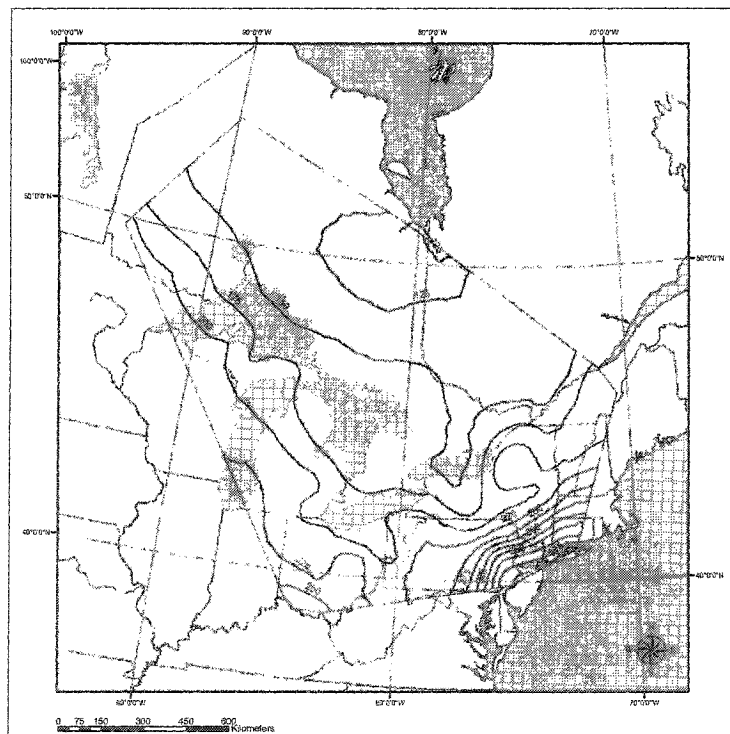


Fig. 16. Rainfall erosivity values (R) for the Great Lakes for the month of August calculated for 451 meteorological sites, interpolated using ordinary kriging (contours units - $\text{MJ mm ha}^{-1} \text{h}^{-1}$).

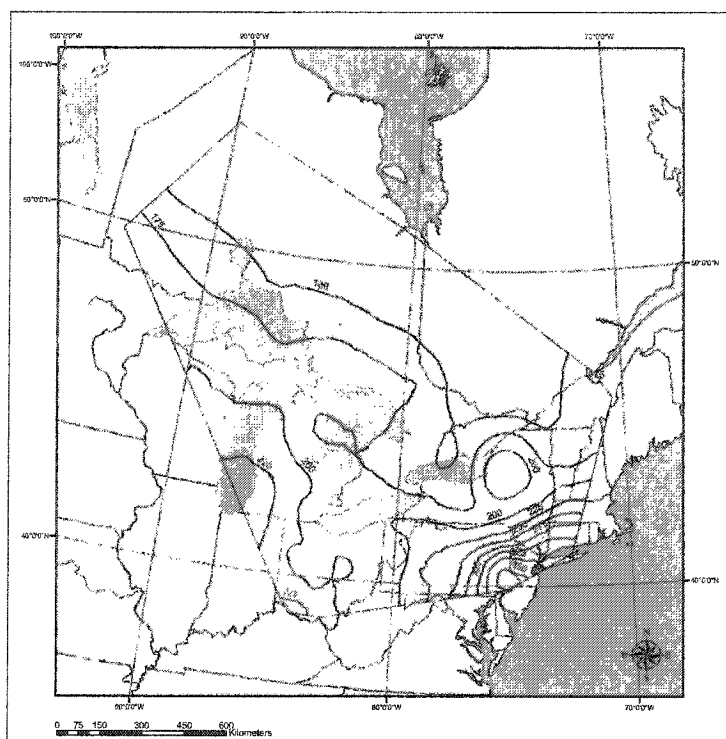


Fig. 17. Rainfall erosivity values (R) for the Great Lakes for the month of September calculated for 451 meteorological sites, interpolated using ordinary kriging (contours units - $\text{MJ mm ha}^{-1} \text{h}^{-1}$).

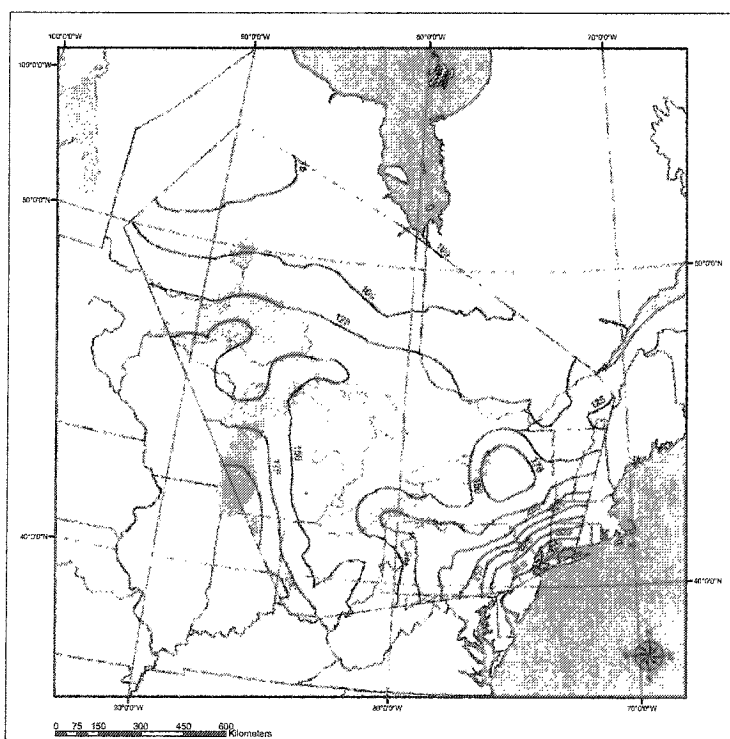


Fig. 18. Rainfall erosivity values (R) for the Great Lakes for the month of October calculated from 451 meteorological sites, interpolated using ordinary kriging (contours units - $\text{MJ mm ha}^{-1} \text{h}^{-1}$).

2.7 Discussion

Annual isoerodent values for Canada in Fig. 9 agree well with those published in Van Vliet *et al.* (1976), Wall *et al.* (1983), and Madramootoo (1988). Missing from Fig. 9, however, is the higher erosivity cell seen in the previous work east of southern Lake Huron. For the U.S., Fig. 9 is in general accord with isoerodent values found in Yoder *et al.* (2003). Interestingly, there is one significant deviation seen in Fig. 9 compared to Yoder *et al.* (2003) with an accentuation of erosivity on the Tug Hill Plateau of New York. The high values captured east of Lake Ontario in Fig. 9 are likely a result of higher lake effect precipitation in the fall months increasing the estimated once-in-two-year, 6-h extreme rainfall value used to calculate the R factor in this study.

Northern Ontario and southeastern Quebec share similar mean annual rainfall erosivity, between 700 and 800 MJ mm ha⁻¹ h⁻¹. To the south of this area there is an extension of higher isoerodent values east of Georgian Bay, into the Nipissing Ecoregion. Figures 15 through 17 indicate that this extension is a result of higher rainfall erosivity densities in the months of July, August, and September. Higher convective storm activity during these late summer months within and to the east of Lake Huron and Georgian Bay are likely increasing overall mean annual erosivity in this local. In agricultural regions of Canada rainfall erosivity seen in eastern Ontario and the eastern townships of Quebec are in the same range as those observed in Guelph, and surrounding region. However, a marked increase is evident from Guelph south to the Amherstburg/Windsor region of southern Ontario, which is expected due to the higher prevalence of thunderstorm activity in this area during summer months. A requirement for high energy and intensity rainfall is instability and layering of cool dry air over warm moist air. Southern Ontario receives an excellent source of warm and moist air from the Gulf of Mexico

during the summer months. Occurrence of cooler drier air aloft provides the perfect ingredients for thunderstorm activity and corresponding higher R factor values. Annual values seen in the Niagara are in line with those of locations northwest of London. Overall, there is a definitive northeast trend in isoerodent values west of Lake Ontario and Lake Erie.

Southeast of Lake Ontario and Lake Erie, one can see an extreme gradient in erosivity to the Atlantic. These great variations over short distances are predominantly due to large storms or Noreasters traveling up the east coast during fall months. One major deviation from this trend is a pronounced reduction of isoerodent values west of the Allegheny Mountains into the Ohio River valley. Lower values can be attributed to storm fronts incurring greater elevation once surpassing the Allegheny's and reaching the valley, providing less energy for soil movement on the leeward side of the mountains and valley. West of the Ohio, values increase substantially from 1700 to over 2300 MJ mm ha⁻¹ h⁻¹ of rainfall erosivity annually.

Monthly values follow some interesting trends. In March, values are high along the east coast of the U.S. and Ohio (Fig. 11). In contrast, values are low in Ontario and Quebec. In this month, warmer, moister air masses generally have not migrated far enough north to increase rainfall erosivity over a majority of the region. As the continent warms and solar radiation becomes more direct, April isoerodent values increase northward while remaining low in northwest Ontario (Fig. 12). Air masses from the Gulf of Mexico and Atlantic begin to influence the region and interact with air masses from the Arctic and Pacific. This interaction provides the instability needed for storm activity and rainfall erosivity to increase. In May, reductions in rainfall erosivity occur in northern Ontario with a shift in lower values eastward (Fig. 13). Erosivity values over Michigan reduce, while an increase is seen in Ohio, eastern Pennsylvania and New York. The Bermuda high begins to dominate at this time and associated cyclonic

activity provides warmer moist air for the region that has the potential to produce more energetic storms and higher rainfall erosivity.

Northern Ontario experiences lower erosivity, again with a progression in values eastward in June, juxtaposed by an intensification in northwestern Ontario (Fig. 14). During this same month there is a notable reduction in isoerodent values in mid-Ontario, with a general northward increase in the northern states. Little change is seen in July for Ohio, Pennsylvania and New York (Fig. 15), as cyclonic activity from the east coast normally decreases. However, other smaller-scale activity sustains high erosivity over the region at this time. Smaller-scale thunderstorm activity dominates, as convective cells resulting from daytime heating provide very intensive rainfalls and sustained isoerodent values. In August, September and October the R factor increases along the east coast, paralleled with an intensification of rainfall and runoff erosivity over the state of New York. At this time the Atlantic Ocean cools in the fall months, providing increased tropical storm activity along the coast and subsequently higher R factors. In this same period, reduced values expand over the Ohio River east of the Alleghany Mountains, which is likely a result of the Pacific high providing more stable, cooler and drier air in this area (Fig. 16, 17 and 18).

Plot soil loss most closely correlates with the rainfall erosivity factor when all other USLE parameters are held constant (Renard *et al.*, 1996). With the estimation of other factors individuals can determine sustainable methods of crop production in various locales and improve nutrient management plans. Comparison of coarse genesis rates with soil loss rates will improve the identification of unsustainable agriculture. R maps will provide guidance and focus to Rural Planners on what months are most prone to erosion and require residue and conservation tillage

adoption. Lastly, engineering personnel can use R factor maps for the design of drainage ditches, roads, lagoons, and earth dams.

For the researcher, rainfall erosivity maps provide us with the opportunity to visualize the spatial distribution of the primary factor effecting erosion over the region for better understanding of the spatial complexity of rainfall and its effect on erosion. Researchers can use R maps to identify lake(s) or embayments in agricultural areas that are more susceptible to siltation for comparative study. Analyses on various sediment yield reductions under specific land use modifications can be made (Williams and Berndt, 1972; see Fistikoglu and Harmancioglu (2002) for a GIS method). The maps produced in this current work are also essential for current mathematical modeling of soil loss in Geographic Information System science. We can also make the jump from quantifying and mitigating point source pollution to non-point source pollution. Another direction of research might investigate correlations between the Modified Fournier Index (Arnoldus, 1980) and the R factor values by month for estimating future erosion potential under various climate scenarios.

2.8 Conclusion

Universal soil loss equation annual rainfall and runoff indices (Ateshian, 1974) ranged from 550.34 to 3616.00 MJ mm ha⁻¹ h⁻¹ for meteorological sites in the Great Lakes region. Provided herein are the first isoerodent maps that cross Canada U.S. borders. A new approach was presented in this chapter for visualizing the progression of R in the most significant growing season months. Updated indices were computed for Michigan, Ohio, Pennsylvania, New York, Ontario and southern Quebec for use in land use planning, erosion and sedimentation control, and structural design.

Values correspond consistently with other published work but differ in that they capture some microclimatic features such as lake-effect precipitation seen in New York and reductions over the Ohio River likely due to a leeward orographic effect. The results indicate that March is a key month in which farmers and other land owners should provide cover to bare soil to protect against potential soil loss based solely on potential erosion due to rainfall events. Future work beyond the scope of this chapter should focus on the expansion of such continuous updated isoerodent maps over North American and the provision of adjusted erosivity values that account for soil loss on partially frozen ground.

Provided next is an examination of soil loss for eastern Ontario using rainfall erosivity values generated in this chapter. Annual and monthly isoerodent values were clipped for the study region and integrated with other USLE factor values to assess soil loss at a high precision and accuracy. Rainfall erosivity exhibits minimal variation over short distances warranting its use for precision agriculture and precision soil loss assessment.

CHAPTER 3

EVALUATION OF MITIGATION SCALE WARM SEASON EROSION POTENTIAL USING GISCIENCE FOR PRECISION FARMING: AN ANALYSIS IN EASTERN ONTARIO, CANADA

3.1 Abstract

Soil loss in Canada is costly in terms of dollars, soil productivity and the production of non-point source pollution. Based on coarse-scale data, current national estimates of soil erosion are inadequate for targeted regional and local mitigation through policy and farming practice. High-resolution environmental modeling has been confined to small areas due to processing and data constraints. There is a pressing need to develop models that provide both regional assessments of erosion while pinpointing soil loss at the field scale. Such model output identifies regional vulnerabilities that can impact on the economics of agricultural yields and at the same time fulfill the requirements for precision agriculture by allowing the implementation of farming practices that reduce erosion within individual fields. The increasing prevalence of higher-resolution environmental data provides the potential to produce mitigation-scale estimates of erosion in Canada. We present an application of the universal soil loss equation (USLE) modified in combination with the unit stream power erosion deposition (USPED) model and the universal soil loss equation 2 dimensional (USLE2D) model (a modification of the topographical factor of the USLE for use in GIS). These models utilize high-resolution field-level spatial data, satellite imagery, elevation, soil surveys, hydrography and meteorological data to produce sub-field-scale and finer erosion estimates over large regions. Results of the analysis include precise estimates of soil loss within agricultural field with associated error, scenario estimates of net soil

loss off of agricultural field excluding depositional areas, summaries of the various factors effecting loss grouped by hydrologic unit, maps of erosion and deposition locals, and a summary of the dominant factors in the region that are likely effecting erosion. The study area is 5,957 km², of which 2,878 km² is agricultural field in eastern Ontario, Canada.

3.2 Introduction

In this work the universal soil loss equation (USLE) (Wischmeier and Smith, 1965) modified for Canadian conditions (Wall *et al.*, 2002), the universal soil loss equation 2 dimensions (USLE2D) (Desmet and Govers, 1996a; 1997) and the unit stream power erosion deposition model (USPED) (Mitasova *et al.*, 1996) are utilized to assess soil loss for precision farming purposes in eastern Ontario, Canada. Eastern Ontario has been an agricultural area for the broader St. Lawrence Seaway region for many decades producing corn, mixed grains, soybean and wheat, amongst other crops. It is an area that has not been assessed for soil loss rates at fine spatial scales. Conservation problems have persisted in the region due to increased mechanization and intensification of agriculture with noticeable effects on water quality and availability. Due to the importance of soil erosion risk on agricultural productivity and the negative impacts it has on the environment, a broad scale GIS assessment of soil loss was undertaken. The analysis was performed in ArcGIS ® using ArcInfo within a Windows XP ® Operating System.

Erosion is a process which is accentuated by high agricultural activity. Traditional vegetative cover is removed and cropping practices usually result in the soil surface being exposed to the elements, which effect soil movement. This can be especially problematic in areas with large and long agricultural slopes, erodible soils, and where high intensity rainfalls are common. Soil erosion is becoming such a concern that it is now being recognized as a hazard

(Lee, 2004; Mati *et al.*, 2000) that must be dealt with in a rapid fashion (Boggs *et al.*, 2001). Soil loss is a major cause of soil degradation, with irreversible effects on water resources exterior to agricultural lands. Such problems include reductions in water clarity and quality, as well as recreational utility.

In the modeling of soil erosion over large areas, physically-based models are limited by their requirements for extensive continuous data in both space and time. Physically-based models are limited by the complexity of making precise in situ measurements of water flow (Renard, 1997). Interflow, perched groundwater contributions to runoff, and complex runoff run-on interactions are difficult to model physically (Woolhiser, 1996). Most momentum equations of physically-based models are one dimensional (Lane *et al.*, 1988) making significant abstractions of sheet and rill flow. Further, few physically-based models account for the seasonally and spatially changing infiltration characteristics of soil (Renard, 1997) which is one component expected of physical models. Additionally, there are many absences and limitations on the prevalence of appropriately scaled data for use with physically-based models over a large region such as eastern Ontario.

Empirically-based models like the USLE are relatively simple and are perceived by many researchers to be less susceptible to user error. As well, there is a larger amount of acceptable data for input into the USLE, USLE2D, and USPED for the region. In addition, USLE, USLE2D, and USPED processing restraints are limited and USLE sensitivity is less than that of some more complicated physically-based models. Therefore, the USLE modified for Canadian conditions, USPED and USLE2D for use in GIS were chosen for application in this study. Such model combination and integration is necessary to properly assess soil loss using the USLE for locations with net soil loss. Using the USLE without any account for deposition will

yield incorrect results about the quantity of soil loss occurring over the landscape due to the USLE's inability to model deposition.

Data inputs in this modeling study were soil surveys digitized from 1: 25,000 to 1: 63,360 scale maps obtained from Agriculture Canada (CANSIS, 2004), which can be accurately represented at resolutions of 12.5 to 31.7 meters in raster format. Land cover data were obtained from Agriculture and Agri-Food Canada from classifications made using Landsat 7 Enhanced Thematic Mapper Plus imagery for the year 2001 at a 25-meter resolution. A digital elevation model (DEM) in raster format at a 10-meter resolution and watershed boundary and watercourse data were obtained from the Ontario Ministry of Natural Resources (OMNR, 2002). Hourly rainfall data was obtained from Environment Canada's Ontario Climate Centre (OCC, 2003) and National Climatic Data Center (NOAA, 2003) for derivation of the rainfall erosivity factor (see Chapter 2). USLE, USLE2D, and USPED model parameters and outputs were extracted to a raster resolution of 10×10 meter DEM in ArcInfo grid format for analysis. Further, digitized field boundary data was obtained from Agriculture Canada and used to limit the analysis to fields. Fig 19 shows a small portion of the input data used in this analysis for a segment of the region. Modern technology has afforded us complex models, remote sensing and satellite imaging, GIS and professional systems to aid decision making for environmental management (Fistikoglu and Harmancioglu, 2002). The objectives of this study are to:

- a) apply GIS and professional systems to aid decision making for environmental management,
- b) model soil loss at the mitigation scale associated with precision farming in the region using GIS,
- c) quantify losses in areas only experiencing net soil loss,
- d) assess the reliability of the predictions,

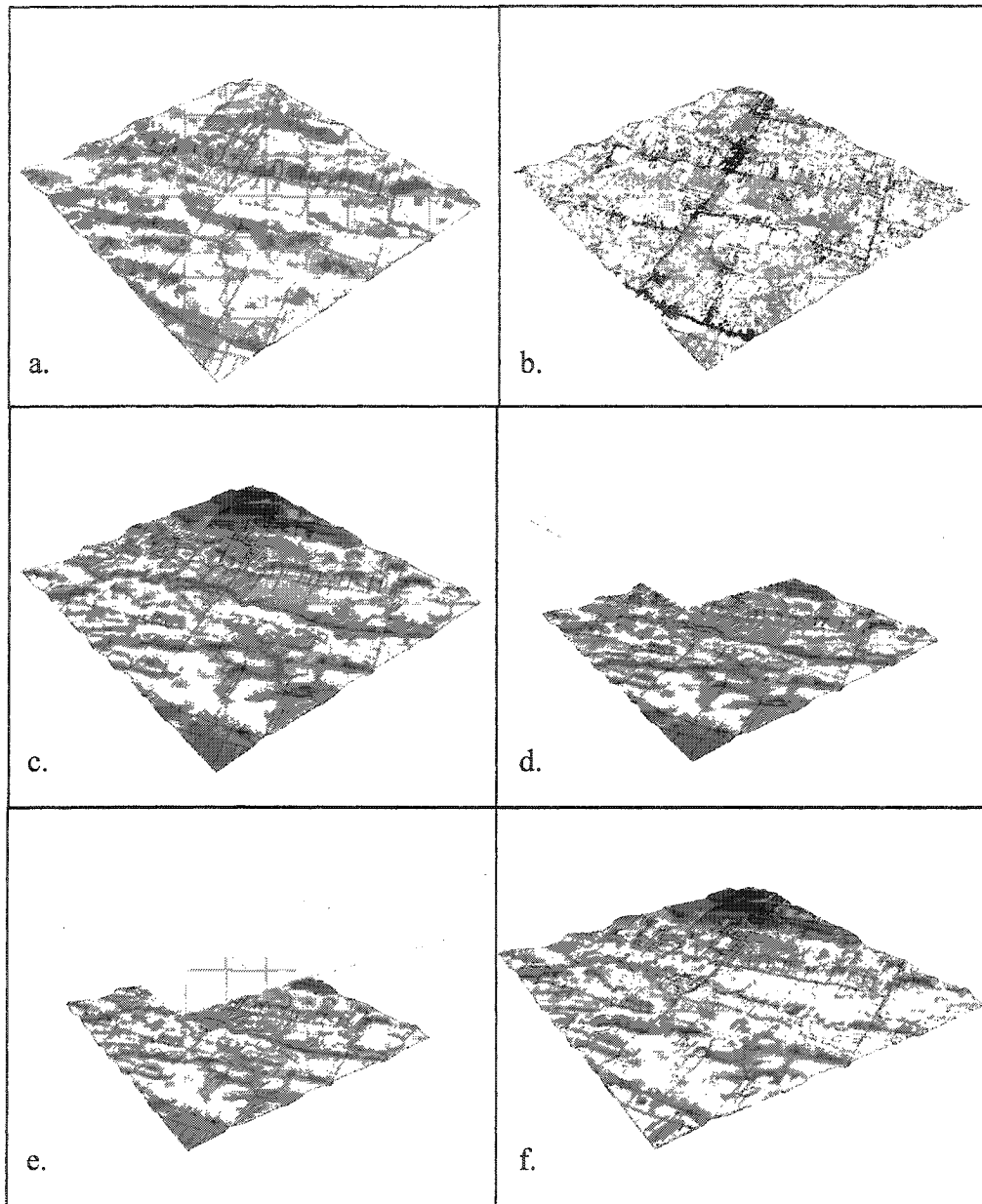


Fig. 19. Datasets utilized in the GIS analysis of soil loss assessment for eastern Ontario. The area shown above is a small portion of the Beaudette River watershed at the junction of Charlottenburgh, Lancaster, Kenyon, and Lochiel townships. a) a small subset of the soil survey data used to quantify the soil erodibility factor of the USLE, which is overlain with road and water datasets; b) Landsat 7 land use classification data for the summer of 2001 utilized to generate the crop management factor of the USLE; c) Natural Resources Value Information System (NRVIS) digital elevation data which was used to generate the slope length and steepness factor of the USLE2D; d) output of the rainfall erosivity factor generated from hourly input data for meteorological stations within and surrounding the region. The R factor is extruding from the primary elevation data layered below the R factor; e) extruded portion of the NRVIS watershed boundary data for the region juxtaposed by the elevation data in panel c; f) a small portion of the field boundary data obtained from Agriculture and Agri-Food Canada used to constrain the USLE analysis.

- e) model at spatial resolutions more coincident with the USLE's development,
- g) determine the most dominant factor effecting erosion regionally.

The following products were generated to meet these objectives.

- 1) Rainfall erosivity (R) maps through the various growing months (March, April, May, June, July, August, September, October) were computed for eastern Ontario to provide input into USLE/RUSLE modeling analysis (see Chapter 2).
- 2) A mean annual erosivity map for the eastern Ontario was generated to demonstrate the spatial distribution of rainfall erosivity over the landscape. This was accompanied by a prediction standard error map for mean annual rainfall erosivity for the study region.
- 3) A soil erodibility map was produced for eastern Ontario generated from county soil survey and associated attribute data accompanied by a standard error map.
- 4) Two slope length and steepness (LS) susceptibility maps were produced for eastern Ontario, one which calculates the LS factor by accounting for 25% connectivity between field boundaries, while the second calculates the LS factor with exclusion of any field boundary limitation (100% field boundary connectivity).
- 5) Three crop management factor (C) maps were generated to exhibit how crop cover affects soil loss under conventional tillage, conservation tillage, and no tillage farming systems for the summer of 2001. Six annual soil loss estimate summaries were generated for the various LS and C factor scenarios.
- 6) The previous were accompanied by standard error summaries depicting the probable error associated with the soil loss estimates calculated in 5.
- 7) Further, eight monthly estimates of soil loss were generated for 25% parcel connectivity between fields under conventional tillage to display the susceptibility of soil to erosion over the major growing season months.
- 8) Subsequently, two maps were generated that depict the most dominant factor effecting erosion on a cell by cell analysis. One examines all USLE factors while the second only compares the slope length and steepness and crop management factor.
- 9) Finally, output grids depicting net deposition or erosion were developed using the unit stream power erosion deposition model (USPED) for masking purposes and assessment of soil loss.

Coarse scale national soil loss model outputs are ineffective for targeting of regional scale to field scale soil loss mitigation. Further, the coarse resolution of input data utilized and the accompanying generalization of parameters spatially results in the underestimation of the severity of erosion. The current resolution of soil erosion modeling that is being applied on Canadian farmland (Fig. 20) indicates that there are no intolerable rates of erosion occurring in the region. We will show in this study that such results are incorrect.

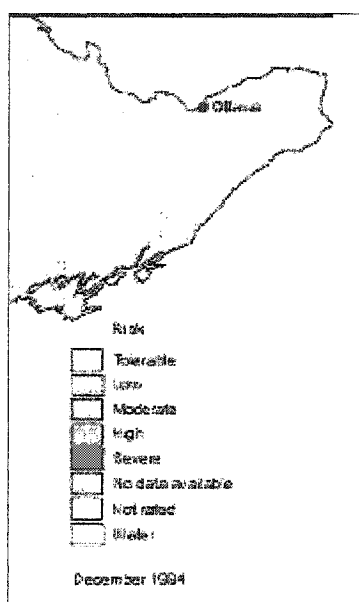


Fig. 20. Risk of water erosion in southern Ontario (Federal-Provincial Crop Insurance Program, 1998).

3.3 Background

Climate, topography, soil, crop and anthropogenic factors are quantified and modeled within the USLE (Wischmeier and Smith, 1978). The process of water related erosion within the USLE is in the form of uniform sheet and rill erosion. Water related erosion on a field slope is first initiated when raindrops impact the land surface causing splash detachment and ejection of small soil particles in various directions. Some of the raindrops will convalesce on the surface, sealing the surface. If the surface soil is presently saturated due to antecedent soil conditions, surface pooling and subsequent flow may occur if a slope is present. Runoff will also occur when infiltration is exceeded by water addition. At this point pooling of water and flow will occur under infiltration excess conditions. If the surface water envelope is thin enough, raindrops will continue to detach soil particles for transport. Further, sheets of runoff progress to form rills, subsequently converge forming larger rills and ultimately gullies. The USLE models the loss of soil during the first steps of the detachment limited state of erosion and groups the many factors effecting erosion in this state.

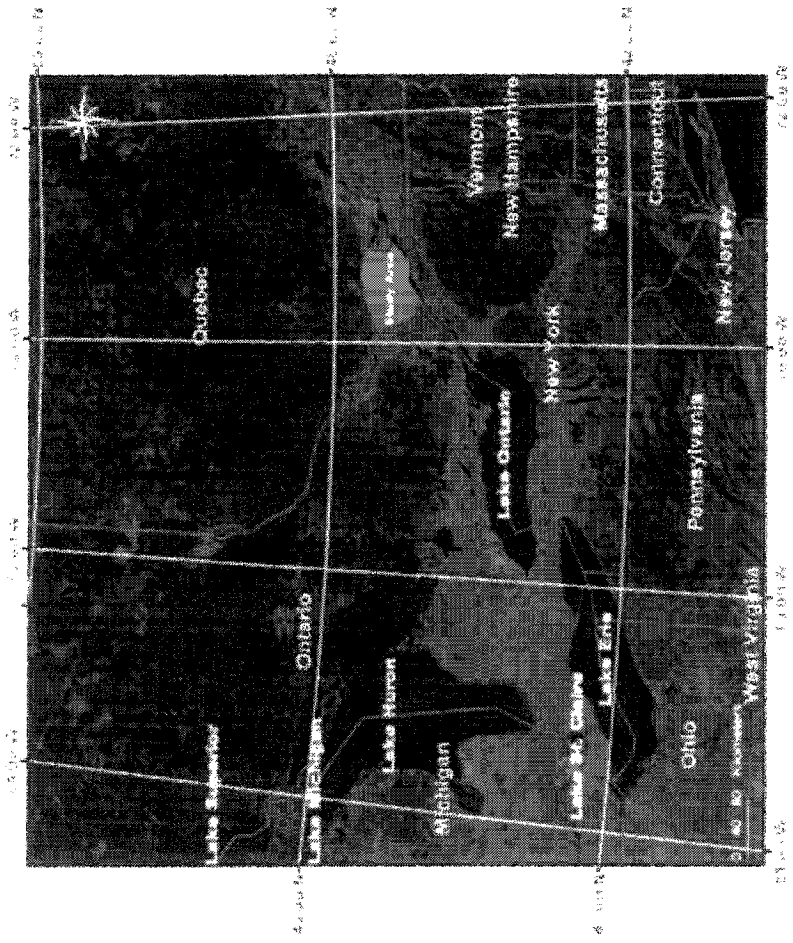
Some of the main misuses or misconceptions of the USLE must be established. First, the USLE does not provide any values for sediment yield and only provides soil loss off of a particular slope segment represented by a particular topographic factor (Wischmeier, 1976). Secondly, the estimates should not be viewed as absolute, as all empirical relationships are subject to experimental errors and lack of completeness due to the exclusion of unmeasured variables. Thirdly, the USLE is limited in application as it should only be applied where one can

accurately quantify the factors of the equation in the same environmental conditions for which the original relationships were derived.

In this study, the previously mentioned misconceptions are addressed. Areas that are likely experiencing net loss are delineated using the USPED and then the USLE is applied only in these regions. Secondly, the values are not assumed as absolute and error propagation (Burrough and McDonnell, 1998; page 248) is applied to quantify the error in the USLE at each of the cellular units on which the USLE is applied. Thirdly, the factor values used as input have been derived for Canadian conditions in the study region (Wall *et al.*, 2003) and the examination has been limited to warm season soil loss.

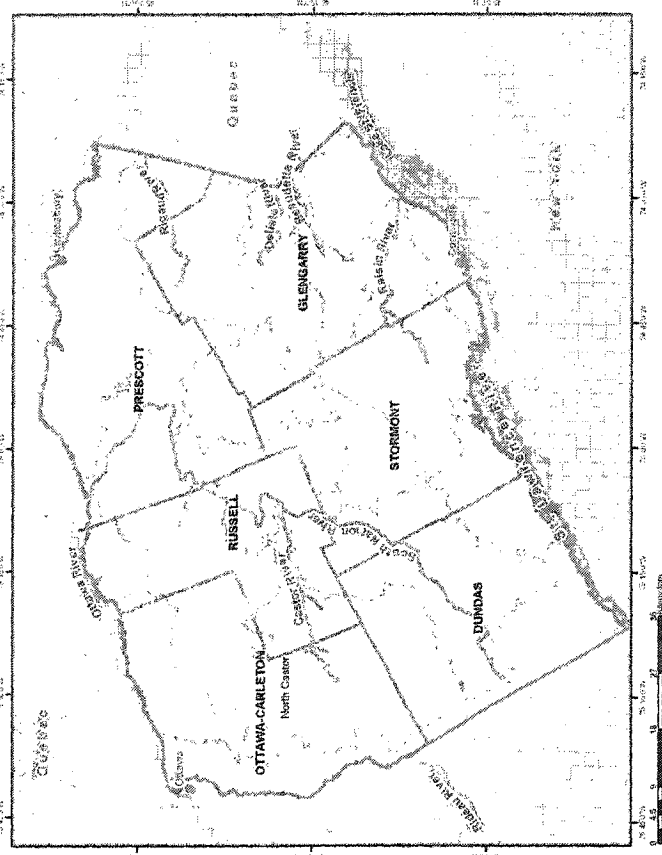
3.3 Study Region

The study region (74.33° - 75.67°W, 44.90° - 45.64°N) is located in eastern Ontario adjacent to the St. Lawrence Seaway. The study area is bounded by the Ottawa, Rideau, and St. Lawrence Rivers extending east to the Quebec-Ontario border. Major rivers of the area include the South Nation and Raisin River. Minor rivers include the Castor, Rigaud, Delisle, Beaudette, and Payne. The region being analyzed comprises all fields (approximately 2,878 km²) within fourteen watersheds in Eastern Ontario. The United Counties of Prescott and Russell cover a large portion of the northern extent of eastern Ontario and Stormont, Dundas and Glengarry Counties cover the southern extent (Fig. 21b).

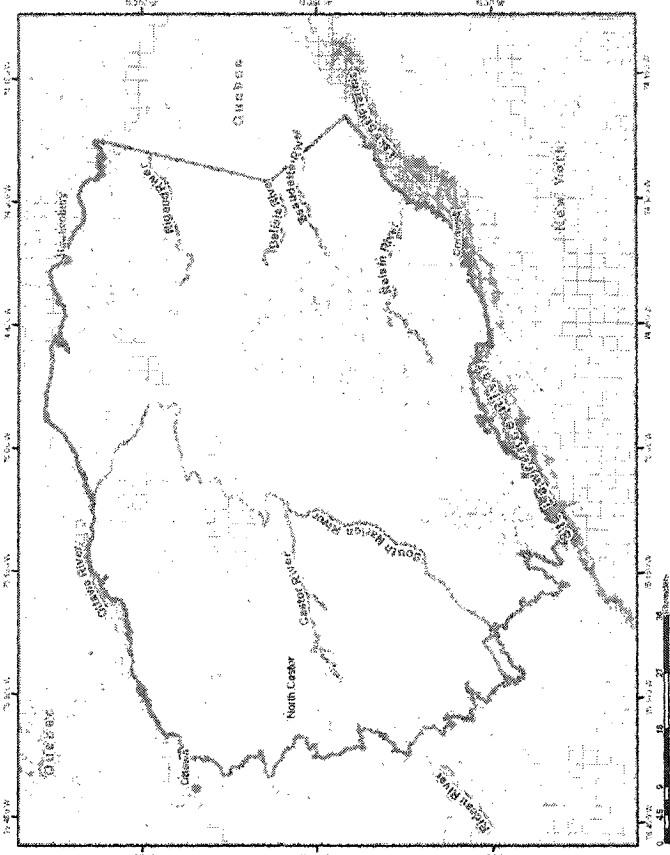


a.

Fig. 21. a) Study region inset map (Fig. 21a); b) study region depicted in yellow relative to the administrative counties intersecting its boundaries; c) fields on which the soil loss analysis was performed.



b.



c.

The highest agricultural production in the region is for hay, grain corn, and fodder corn (OMAFRA, 2004). Hay is seeded most commonly, followed by grain corn and soybeans. Spring wheat is sown in larger volumes than winter wheat.

The area is generally flat, with some slightly rolling topography in the south and east. Before colonization eastern Ontario was covered in deciduous forest. Most if not all of these forests were cleared and the remaining stands that are left are those situated on soil that is too rocky or too agriculturally poor to farm or in areas where they have been protected for conservation purposes. Unproductive acidic soils situated on Precambrian Shield lie to the west of the region. Soils of the region are underlain by sedimentary rock and are in most cases neutral to alkaline. Most of the Raisin, Beaudette, Delisle River, and Fraser Creek watersheds are overlain with strongly calcareous soils. As well, the region has a high prevalence of mineral soils. The majority of the southern watersheds are covered in Melanic Brunisols, with the exception of Sutherland Creek which is overlain with Gleysolic soils. Humo-Ferric Podzols occur at the lower portion of the South Nation and surrounding sheds. Mesisols are found in a relatively small abundance in isolated locals.

The temperature regime of the region is continental and peaks in July with low January temperatures. Mean daily temperature does not show great variation over the region, with mean daily temperature ranging from 5.4 to 7.2 °C over the entire year, January mean daily temperature ranging from -8.8 to -11.3°C, and July mean daily temperature ranging from 18.7 to 21.4°C (Environment Canada, 2000). Mean annual rainfall ranges between 729.5 and 820.6 mm (Environment Canada, 2000).

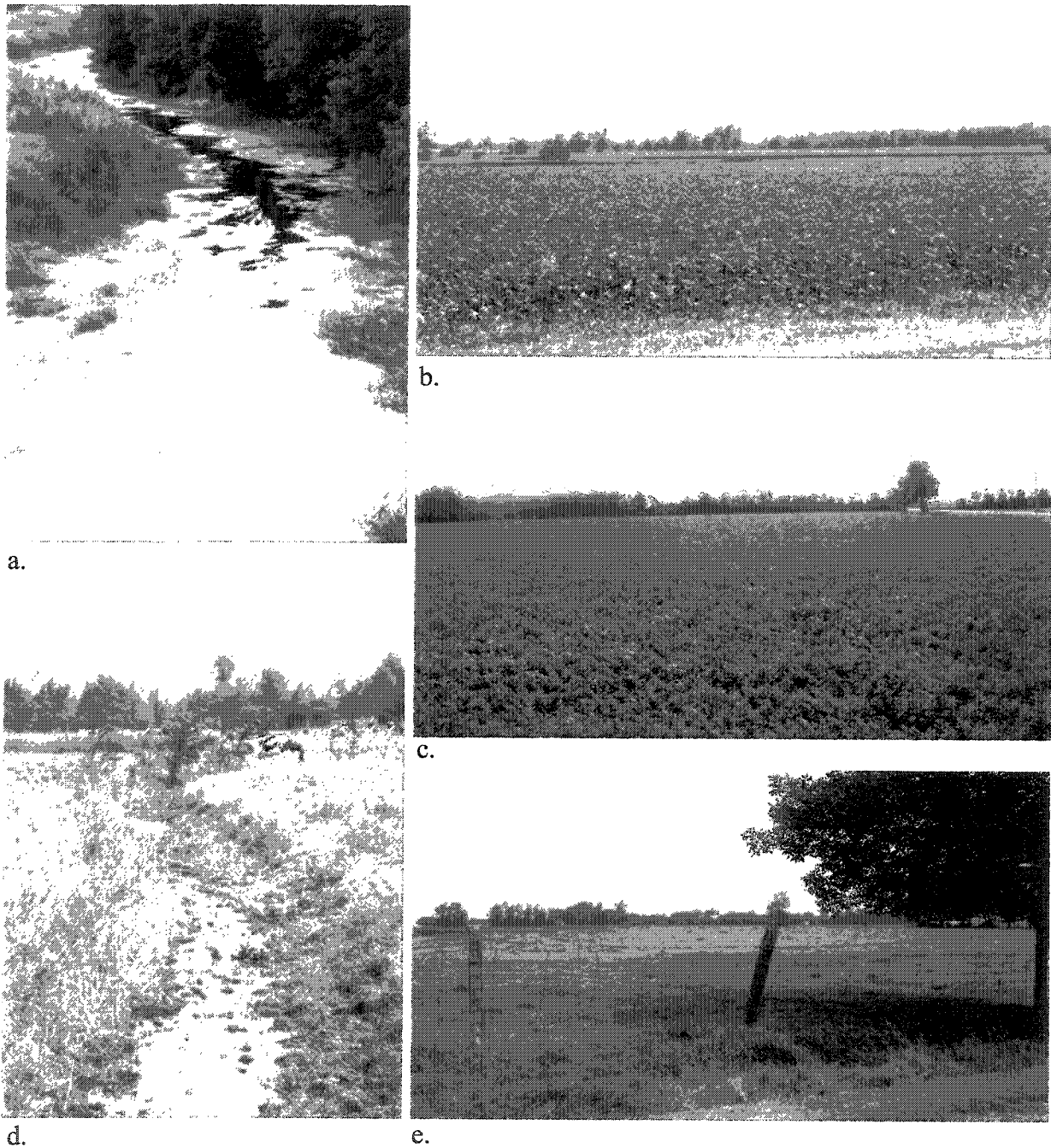


Fig. 22. Images of the eastern Ontario landscape (summer of 2003); a) small watercourse located in an intensively farmed agricultural area in Winchester Township, Ont., July 21st, 2003. To the left of the watercourse is an agricultural field with no riparian zone buffer stripping; b) a typical soybean field in the region; c) a typical alfalfa field, note the generally flat landscape; d) cow grazing next to open water, illustrating a major land use problem in the region (Mountain Township, July 23rd, 2003); e) a typical pastured field in the region.

3.4 Introduction to the USLE, USLE2D, and USPED Models

3.5 USLE (Universal Soil Loss Equation) Described

USLE models the potential long term annual soil loss in tonnes per hectare per year ($\text{t ha}^{-1} \text{yr}^{-1}$), originally derived in tons per acre per year ($\text{t a}^{-1} \text{yr}^{-1}$), which can be compared to tolerable soil loss limits ($< 6 \text{ t ha}^{-1} \text{yr}^{-1}$) (Wall *et al.*, 2002). The model computes the loss of soil at the outlet of some plot or catchment on an annual basis and it is assumed that the eroded material is collected from the whole plot. The USLE is an index that computes the average soil loss from a field slope over a number of continuous and consecutive years. The USLE is given by:

$$A = RKLSCP \quad (3.1)$$

where:

- A = potential long term annual soil loss ($\text{t ha}^{-1} \text{yr}^{-1}$),
- R = rainfall and runoff erosivity factor ($\text{MJ mm ha}^{-1} \text{h}^{-1} \text{yr}^{-1}$),
- K = soil erodibility factor ($\text{t h MJ}^{-1} \text{mm}^{-1}$),
- L = slope length coefficient which is unitless,
- S = slope gradient coefficient which is unitless,
- C = cropping management coefficient which is unitless,
- P = support practice coefficient which is unitless.

Each of the factors in equation (3.1) was derived from data inputs displayed in Fig. 19 within GIS. Factors were set in a consistent raster format. Map algebra was utilized to compute the quantity of potential long term annual soil loss at the centroid of each raster cell. Factor values vary considerably from storm to storm but this variation is ideally reduced as R and related factors are averaged over twenty-two years or more.

The rainfall erosivity index is composed of two variables shown to be most closely related to a storm's ability to cause soil loss, a storm's energy and maximum thirty-minute

intensity (Renard *et al.*, 1996). Storm energy (E) and maximum thirty-minute intensity (I_{30}) must be calculated for storms over a twenty-two year or greater period. A storm is defined as a continuous period of rainfall recordings with a total rainfall amount greater than 12.7 mm that is separated by at least six hours of non-recordings. Storm's with less than 12.7 mm of total rainfall are not included unless 6.35 mm of rainfall fell in fifteen minutes as these storms have been determined to not significantly contribute to soil loss (Renard *et al.*, 1996). The result of one storm calculation is an energy times thirty minute intensity value denoted as EI_{30} . Storm EI_{30} 's are averaged per year and subsequently averaged over the length of record to produce the R factor (refer to Chapter 2 for more information on the calculation of the rainfall erosivity factor).

In the USLE, soil loss is next understood to be a function of the erodibility of soil (K), the soils inherent compositional/structural ability to withstand the energy and intensity of rainfall and runoff. The soil erodibility factor is ideally calculated from measurements made on study plots over time for a soil within a given study region. This data is difficult to collect for specific sites and for many soils, especially within large regions. An alternate method of determining K is to approximate the erodibility of soil based on relationships found for similar soils in different locations. One formula has been developed that summarizes the results of plot studies based on percentages of sand, silt, clay, as well as texture and permeability (saturated hydraulic conductivity), rockiness and organic matter below a certain percentage to provide an erodibility value for soil (Wischmeier and Smith, 1978). Limitations to the soil erodibility equation of Wischmeier and Smith (1978) include the need for soil data including the percentage of sand between 0 and 90% (0.10 – 2.0 mm), percentage organic matter between 0 and 4 %, soil structure rated from 1 to 4, and permeability rated from 1 to 6. Properties should be provided for the horizon or soil layer closest to the surface, apart from permeability which should be defined

for the most impermeable layer in the soil profile. In absence of such information, soil erodibility factor can also be estimated using surface texture (Ontario Centre for Soil Resource Evaluation 1993; Wall *et al.* 2002). Soil erodibility in this analysis was calculated using the Wischmeier and Smith (1978) approximation modified for rock fragments in the soil profile (Römkens *et al.*, 1996) based on soil survey attribute data, and in those cases where appropriate soil attributes are unavailable erodibility was estimated based on soil texture alone provided within individual soil surveys (Richards *et al.*, 1949, Mathews and Richards, 1952, Mathews and Richards, 1954, Mathews *et al.*, 1957, Wickland and Richards, 1962, Jarvis and Shutt, 1998).

The second and third functions that contribute to soil loss are slope length (L) and steepness (S). Slope length and steepness are closely related to runoff velocity which increases with slope gradient and length when other factors are held constant. The slope length and steepness factor in this analysis is calculated in GIS using the USPED method described by Mitsova *et al.* (1996). The LS factor is an intrinsic property of the landscape and thus quantifies the morphology of the surface and its effect on drop impact and stimulation of runoff.

Land use and cropping practices are summarized by the crop and vegetation management factor (C), an additional parameter of the USLE. The C factor summarizes a variety of variables including crop canopy, surface cover, soil biomass, and tillage (Shelton, 2002). These variables are budgeted for individual impact, relative impact over the growing season, and variable interrelation throughout the growing season. Generalized annual C factors are the combination and summation of the above variables, and their relative and compounding influences over time (Shelton, 2002). Cropping management coefficients have been developed for a variety of Canadian tillage and soil management systems for major agricultural regions, including eastern Ontario (Shelton, 2002). Annual coefficients for eastern Ontario were assigned to raster imagery

classified in the study region for the year 2001 for a variety of land use and cropping scenarios on a cell by cell basis. These C factors for various scenarios afford us a coefficient of how surface soil is protected from the force of raindrop impact due to crop cover and tillage practices.

The support practice coefficient (P) is one of the most difficult factors to account for in the USLE, especially in a broad scale analysis such as the present. The P factor is the soil loss ratio with the specified support practices to soil loss with up and down slope tillage or straight row farming (Renard *et al.*, 1996). The major sub-practices of the P factor for Canadian conditions are cross slope farming, contour farming, stripcropping, and terracing (Van Vliet, 2002). The support practice factor was set to 1 on a cell by cell basis and was not included as an influencing variable in this analysis. The assignment of 1 to the support practice factor models soil loss with no implementation of mitigation strategies to reduce soil loss in the region. From field work observations made during the summer of 2003 in eastern Ontario we believe this scenario is warranted.

3.6 USLE2D Described

The USLE2D originates from the work of Desmet and Govers (1996a), Desmet and Govers (1997), and Desmet and Govers (2000). Desmet and Govers (1997) show that the best approximation of the USLE slope length factor (L) in GIS is the physical assessment of topography using a digital elevation model (DEM) and a calculation of slope length based on unit contributing area. The major components of their method are given below.

We first assume the numerical form of the LS factor proposed by Wischmeier and Smith (1978) and that provided by Mitasova *et al.* (1996) as:

$$LS = \left(\frac{\lambda}{22.13} \right)^i (65.4 \sin^2 \beta + 4.56 \sin \beta + 0.0654) \quad (3.2)$$

where:

LS = slope length and steepness factor of the equation (3.1),

λ = the horizontal projection of the slope length in meters,

t = length exponent dependent on slope,

β = the slope angle in degrees.

Equation (3.1) can be rewritten to include equation (3.2) to provide the mean annual erosion rate for an elementary unit of slope length (λ) in meters by ignoring the derivation of other factors as (Desmet and Govers 1996a):

$$A_m = RKSCP \left(\frac{\lambda}{22.13} \right)^t \quad (3.3)$$

where:

A_m = the mean annual erosion rate for an elementary unit of slope length (λ) ($\text{t ha}^{-1} \text{ yr}^{-1}$),

λ = the horizontal projection of the slope length in meters,

t = length exponent dependent on slope.

If one applies the mean annual erosion rate over a surface with a given width D , equation (3.3) can be rewritten as equation (3.4) to compute the mean annual erosion rate for an elementary unit of slope length with a given width and length (Desmet and Govers 1997).

$$A_m = RKSCP \left(\frac{\lambda}{22.13} \right)^t (\lambda D) \quad (3.4)$$

where:

A_m = the mean annual erosion rate for slope length (λ) and width (D) ($\text{t ha}^{-1} \text{ yr}^{-1}$),

λ = the horizontal projection of the slope length in meters,

D = width of the elementary unit,
 t = length exponent dependent on slope.

The horizontal projection of the slope length in meters and the width of the elementary unit are demonstrated in Fig. 23 (from Desmet and Govers, 1997).

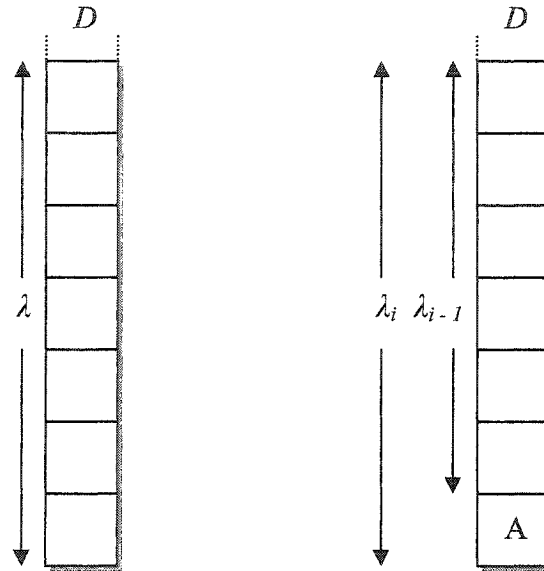


Fig. 23. Demonstration of the slope length factor of the USLE2D provided by Desmet and Govers (1997). One first applies equation (3.4) to the entire slope length (λ). Next, the same equation is applied to slope length (λ_{i-1}). Slope length calculated for segment (λ_{i-1}) is subtracted from that calculated at (λ) to determine the L factor at cell A. The process is repeated for all cells on the slope length.

The length factor of the USLE2D in one dimension for a particular cell is the difference between the length factor calculated for the entire length and the length factor calculated for the slope excluding the cell in question. These two differing lengths are demonstrated in Fig. 23. The total erosion on a slope segment is shown in equation (3.5).

$$A_i = A_{\lambda_i} - A_{\lambda_{i-1}} \quad (3.5)$$

where:

A_i = the mean annual soil loss on the segment in question ($\text{t ha}^{-1} \text{ yr}^{-1}$),

$$A_{\lambda_i} = \frac{RKSCP}{(22.13)^i} (\lambda_i)^i (\lambda_i D) \quad (3.6)$$

$$A_{\lambda_{i-1}} = \frac{RKSCP}{(22.13)^i} (\lambda_{i-1})^i (\lambda_{i-1} D) \quad (3.7)$$

i = slope segment.

Also, the length of slope at a particular cell is that of the length above that cell and the resolution of that particular cell being examined. The notation for this relationship is $\lambda_i = \lambda_{i-1} + D$, where D (meters) represents the raster resolution and λ_{i-1} represents the length of slope above the cell in question. One can then substitute λ_i into equation (3.7) leading to (3.8).

$$A_{\lambda_i} = \frac{RKSCP}{(22.13)^i} (\lambda_{i-1} + D)^i ((\lambda_{i-1} + D) D) \quad (3.8)$$

Substitution of equation (3.7) and (3.8) into equation (3.5) produces equation (3.9) which can be further reduced (Desmet and Govers 1997).

$$A_i = \left(\frac{RKSCP}{(22.13)^i} (\lambda_{i-1} + D)^i ((\lambda_{i-1} + D) D) \right) - \left(\frac{RKSCP}{(22.13)^i} (\lambda_{i-1})^i (\lambda_{i-1} D) \right) \quad (3.9)$$

$$A_i = \left(\frac{RKSCP}{(22.13)^i} \right) \left(((\lambda_{i-1} + D)^i ((\lambda_{i-1} + D) D)) - ((\lambda_{i-1})^i (\lambda_{i-1} D)) \right) \quad (3.10)$$

$$A_i = \left(\frac{RKSCP}{(22.13)^i} \right) \left(D ((\lambda_{i-1} + D)^{i+1} - (\lambda_{i-1})^{i+1}) \right) \quad (3.11)$$

One requirement is that A_i be converted to the surface area of the segment to receive units relative to the raster resolution for computation of soil loss. This can be done by dividing the L side of equation (3.11) by the raster resolution of one cell's area to provide the mean erosion on segment i in $\text{t ha}^{-1} \text{ yr}^{-1}$ shown in equation (3.12).

$$A_{m,i} = \left(\frac{RKSCP}{(22.13)^t} \right) \left(\frac{D \left((\lambda_{i-1} + D)^{t+1} - (\lambda_{i-1})^{t+1} \right)}{D^2} \right) \quad (3.12)$$

In the previous examples, equations (3.2) through (3.12) of the slope length factor in one direction fail to account for unit contributing area which is understood to be a better approximation of the topographic factor affecting soil loss (Desmet and Govers 1997; support referenced by Kirkby and Chorley 1967; Carson and Kirby 1972; Ahnert 1976; Moore and Birch 1986a; Bork and Hensel 1988; Moore and Nieber 1989). This complicates the calculation of the slope length factor of the USLE. However, in raster GIS the 'unit contributing area' or the area of upslope contribution divided by the raster resolution can be calculated to satisfy this need. Essentially one substitutes the unit contributing area into the length factor of the USLE. Contributing area formulae are shown in equations (3.13) and (3.14) (Desmet and Govers 1997).

$$\lambda_{i-1} = \left(\frac{a_{i-1}}{D} \right) \quad (3.13)$$

$$\lambda_i = \left(\frac{a_i}{D} \right) \quad (3.14)$$

where:

λ_{i-1} = contributing area at the outlet of cell $i - 1$ (m^2),

λ_i = contributing area at the outlet of cell i (m^2),

a = contributing area,

i = segment of upslope area.

The unit area at the outlet of the cell is the area input into the cell plus the actual area of the cell being examined. This relationship can be written as:

$$\lambda_i = \left(\frac{a_{in} + D^2}{D} \right) \quad (3.15)$$

where:

a_{in} = the total area contributing into the cell,

D^2 = the area of the cell,

D = the resolution of the digital elevation model.

Substitution of λ_{i-1} calculated for contributing area into equation (3.12) provides us equation (3.16).

$$A_{m,i} = \left(\frac{RKSCP}{(22.13)^t} \right) \left(\frac{D \left(\left(\left(\frac{a_{in}}{D} \right) + D \right)^{t+1} - \left(\left(\frac{a_{in}}{D} \right) \right)^{t+1} \right)}{D^2} \right) \quad (3.16)$$

Substitution of λ_i calculated for contributing area into equation (3.16) provides us with equation (3.17).

$$A_{m,i} = \left(\frac{RKSCP}{(22.13)^t} \right) \left(\frac{D \left(\left(\frac{a_{in} + D^2}{D} \right)^{t+1} - \left(\left(\frac{a_{i-1}}{D} \right) \right)^{t+1} \right)}{D^2} \right) \quad (3.17)$$

Elimination of D provides us with:

$$A_{m,i} = \left(\frac{RKSCP}{(22.13)^t D^t} \right) \left((a_{in} + D^2)^{t+1} - (a_{in})^{t+1} \right) \quad (3.18)$$

What intuitively follows is the L factor after isolation in equation (3.19), with the grid based notation given in equation (3.20). The LS factor is given in equation (3.21) after combination with the slope steepness factor (S) found in equation (3.2) (Desmet and Govers 1997).

$$L = \left(\frac{(a_{in} + D^2)^{t+1} - (a_{in})^{t+1}}{(22.13)^t D^t} \right) \quad (3.19)$$

$$L_{(k,l)} = \left(\frac{(a_{(k,l)-in} + D^2)^{t+1} - (a_{(k,l)-in})^{t+1}}{(22.13)^t D^t} \right) \quad (3.20)$$

$$LS_{(k,l)} = \left(\frac{(a_{(k,l)-in} + D^2)^{t+1} - (a_{(k,l)-in})^{t+1}}{(22.13)^t D^t} \right) (65.4 \sin^2 \beta_{(k,l)} + 4.56 \sin \beta_{(k,l)} + 0.0654) \quad (3.21)$$

where:

$L_{(k,l)}$ = L factor accounting for contributing area of the USLE in raster GIS for cell (k,l) ,

$LS_{(k,l)}$ = LS factor accounting for contributing area of the USLE in raster GIS for cell (k,l) ,

β = slope angle ($^\circ$) for grid cell (k,l) ,

$a_{(k,l)-in}$ = contributing area at the input of grid cell (k,l) .

The slope steepness factor in equation (3.21) from Wischmeier and Smith (1978) has been improved into one continuous function by Nearing (1997) which has been examined for slopes up to 50%. Other more recent versions developed for the revised universal soil loss equation

(RUSLE) are limited to slopes less than or equal to 18%. The experimentally and numerically improved formulation was used in the analysis and is given in equation (3.22).

$$S = -1.5 + \frac{17}{\left(1 + e^{2.3 - 6.1 \sin \beta}\right)} \quad (3.22)$$

where:

S = is the slope steepness factor applied in this analysis,
 e = natural logarithmic base ($e \approx 2.718\ 281$),
 β = slope angle ($^\circ$).

Equation (3.20) was utilized for the calculation of the slope length factor of the USLE while the exponent of the length factor (t) was that defined by McCool (1987 and 1989) and is given in equation (3.23).

$$M = \frac{\gamma}{(1 + \gamma)} \quad (3.23)$$

where:

M = is the exponent used to adjust the slope length factor,
 γ = ratio of rill to interrill erosion.

The ratio of rill to interrill erosion can be approximated by slope angle given in equation (3.24) (McCool *et al.*, 1996).

$$\gamma = \frac{\left(\frac{\sin \beta}{0.0896}\right)}{\left(3.0(\sin \beta)^{0.8} + .56\right)} \quad (3.24)$$

To summarize, slope length was calculated using equation (3.20), with the exponent of the length factor derived from equation (3.23) and (3.24). The steepness factor was calculated using Nearing's (1997) numerical improvement provided in equation (3.22).

3.7 USPED (Unit Stream Power Erosion Deposition Model) Described

The unit stream power erosion deposition (USPED) model of Mitasova *et al.* (1996) estimates the spatial distribution of erosion and deposition for steady-state overland flow in uniform rainfall excess conditions. In this study the USPED is used to identify those areas that are experiencing only a net loss of soil for application of the USLE. One benefit of the USPED model is that it can predict the spatial distribution of deposition so that these areas can be masked (excluded from analysis) in further final USLE modeling. The work of Mitasova *et al.* (1996) stems from the earlier work of Moore and Burch (1986b) and Moore and Wilson (1992) who proposed an index to model erosion and deposition based on change in transport capacity of water in relation to topography. A given transport capacity is calculated based on slope, water flow rate, and transportability based on soil erodibility (K factor) and cover (C factor). Once this transport capacity is exceeded deposition is assumed. Mitasova *et al.* (1996) and Mitas and Mitasova (1998) assume the sediment flow rate is at the sediment transport capacity (see equation (3.25)):

$$|q_s(r)| = T(r) \quad (3.25)$$

Sediment transport capacity can be approximated using equation (3.26).

$$T(r) = K_t(r) |q(r)|^m \sin b(r)^n \quad (3.26)$$

where:

$b(r)$ = is the slope ($^{\circ}$),

$q(r)$ = water flow rate,

$K_t(r)$ = transportability coefficient dependent on soil and cover,

m and n = are dependent on flow type and soil properties.

Constants m and n are usually set to $m = 1.6$ and $n = 1.3$ (Mitasova *et al.* 1996; Mitas and Mitasova 1998). Steady-state overland flow can be assumed a function of upslope contributing area (A) with a given uniform rainfall intensity (i) (see equation (3.25)). This assumption fails to account for changes in flow rates due to vegetative cover and soil properties (Mitasova *et al.* 1996; Mitas and Mitasova 1998). However, it does provide an approximation of depositional areas that is a necessity for delineating appropriate areas for the application of the USLE. This relationship is shown in equation (3.27).

$$|q(r)| = A(r)i \quad (3.27)$$

where:

$q(r)$ = flow rate,

A = upslope contributing area (m),

i = rainfall intensity (m).

Relative erosion and deposition can be approximated using a divergence from equation (3.27) given by the form provided by Pistocchi *et al.* (2002) (see equation (3.28)) which calculates the relative amount of stream power across a particular landscape unit in GIS, shown as:

$$\nabla T = \left(\frac{d(T(r) \cos a)}{dx} \right) + \left(\frac{d(T(r) \sin a)}{dy} \right) \quad (3.28)$$

where:

∇T = divergence in transport capacity,

$T(r)$ = sediment transport capacity given in equation (3.26),

a = aspect angle.

Equations (3.26) through (3.28) were utilized in this study in combination with raster elevation, cropping coefficient, and soil susceptibility data to determine depositional and erosion areas.

3.8 Error Assessment of the USLE and Associated Models

As Millward and Mersey (1999) stress, USLE soil erosion estimates are subject to error due to data inaccuracies and the method limitations used to derive component factors. Errors propagate in the USLE because of the multiplicative nature of the equation. Wang *et al.* (2001) assessed the error in the soil erodibility factor taken from published values from the USDA-Natural Resources Conservation Service (NRCS) national soil survey and that from soil erodibility obtained from sampling and erodibility measurement. They found that published values differed from samples values by as much as 10 to 15%. Further, Burrough and McDonnell (1998) provide a conservative estimate of 20% error in the C factor and a 2 – 10% error in the LS factor. Additionally, error in R factor surfaces can be estimated using geostatistical techniques (see Chapter 2). However, errors estimated from geostatistical techniques represent errors in the estimate and assume that the sampled values are true values from a stationary field. As such, R factor error estimates are first approximations to the uncertainty in the R factor itself and strictly held as methodological errors.

Burrough and McDonnell (1998) provide an error propagation relation that can be applied on multiplicative models such as the USLE. If we consider the dependent variable of soil loss as a function of several other independent variables or factors y_1 , y_2 , y_3 , and so on, the relation can be written as equation (3.29).

$$u = f(y_1, y_2, y_3, \dots, y_j) \quad (3.29)$$

Each of the factors is listed as y_j , with j representing the unique occurrence of that factor. Knowing this relationship, we can calculate the standard error of the dependent variable. Standard errors of our outputs indicate the dependability of our soil loss estimates. It is a way of estimating the precision of our output. In this study standard error was calculated using equation (3.30) and is denote as s_{eu} :

$$s_{eu} = \sqrt{u^2 \sum_{i=1}^n \left(\frac{s_{ey_i}}{y_i} \right)^2} \quad (3.30)$$

where, for a given modeled cell output:

s_{eu} = standard error of the prediction in output units,

u = model estimate,

s_{ey_i} = standard error of the factor value,

y_i = the factor value,

i = factor value index,

n = number of factors.

Where terms are as defined in equation (3.1), and for the USLE with factors R, K, LS, C, and P, the expansion of equation (3.30) is thus:

$$A_{eu} = \sqrt{u^2 \sum_{i=1}^n \left(\frac{s_e LS}{LS} \right)^2 \left(\frac{s_e K_i}{K} \right)^2 \left(\frac{s_e LS}{LS} \right)^2 \left(\frac{s_e C}{C} \right)^2 \left(\frac{s_e P}{P} \right)^2} \quad (3.31)$$

where:

A_{eu} = standard error of the soil loss assessment,

s_eR = standard error map of rainfall erosivity generated by a Ordinary kriging interpolation,

s_eK = conservative assumption that soil erodibility values deviate from calculated values in Ontario to the same extent as they in the U.S., by an average of 12.5% (Wang *et al.*, 2001),

s_eLS = assumption that LS factor values are in error to a maximum of 10% as found by Burrough and McDonald (1998),

s_eC = where C values deviate by as much as 20% from that calculated in Ontario,

s_eP = was held constant and thus equal to zero in equation (3.31).

This error model (equation (3.31)) can be considered a first approximation to the prediction errors and while a step forward in the USLE methodology does not itself take into account the spatial correlation (spatial autocorrelation) present in a predictive map such as that produced in the application of the USLE. As such, the prediction errors are likely larger and thus more conservative than they would be otherwise be if more elaborate spatial methods of error calculation were employed.

3.9 Quantifying the dominant factor of the USLE

Determination of the dominant factor of a multiplicative model is easily accomplished in GIS. It requires the assessment of model output with true factor values and model output with a single parameter held constant. Essentially, one should calculate the USLE equation with each factor non-existent and determine the difference between the original and the output derived with a constant factor. The most influential of the factors on a cell by cell basis will cause the greatest difference from the original USLE estimate. Dominant factor analysis was performed for annual rainfall erosivity, with annual soil erodibility, crop and management factor coefficients for conventional tillage, and a USLE2D slope length and steepness factor estimate based on 25%

land unit connectivity. Assessment of the most dominant factor was undertaken for R, K, LS, and C combined and for LS and C independently.

3.10 Methods

3.11 Calculating the Rainfall Erosivity Factor

The rainfall erosivity factor quantifies the impact that climate, and more precisely precipitation, has on inducing soil loss on a field.

In this study the R factor was approximated using Ateshian's (1974) relationship between R and the once-in-two-year 6 hour storm (see Chapter 2). Variable width recordings of rainfall are not distributed by Environment Canada in digital format. R can be approximated using the following (Ateshian,1974):

$$R \approx 0.417(P^{2.17}) \quad (3.32)$$

where:

R = rainfall erosivity factor approximated ($\text{MJ mm ha}^{-1} \text{h}^{-1}$),

P = once-in-two-year, 6-h duration extreme rainfall (mm).

Observations of hourly precipitation at 453 sites in Ontario, southeastern Quebec, Michigan, Ohio, Pennsylvania, and New York were used to interpolate the annual rainfall erosivity factor over the study region. Further, the quantity of rainfall occurring at each site per month was calculated to provide a density of precipitation over the major growing season months (March to October). Essentially, monthly erosivity is a product of the percentage of rainfall occurring in any given month and the annual R factor for the station. Implied in this calculation is a direct relationship between quantity of rainfall and the erosivity of rainfall. Cook *et al.* (1985) provide a method for calculating R by the percentage of R occurring in each season using the original R

factor of Wischmeier and Smith (1978). Further, Renard *et al.* (1996) suggest computing a bi-monthly R factor based on a 15 day period percentage of R throughout the year. Limitations in the computation form of equation (3.32) do not allow for the calculation of R using the method of Cook *et al.* (1985) or the bimonthly method of Renard *et al.* (1996). Thus, the monthly R was calculated as a percentage of monthly precipitation multiplied by the annual erosivity factor, which was calculated using the once-in-two-year, 6-h duration extreme rainfall.

Ordinary kriging was utilized to interpolate the results due to its ability to capture global trends and relaxed assumption of normality. This method is common and replicable in general geostatistical software. Figures 24 following is the mean annual erosivity computed for eastern Ontario. Figure 25 is the associated error of the mean annual erosivity (R) factor interpolation. Figure 26 (shows the distribution of rainfall erosivity in the month of March, and was interpolated using records from 372 sites), and Figures 27 through 38 provide erosivity through successive growing season months in the region.

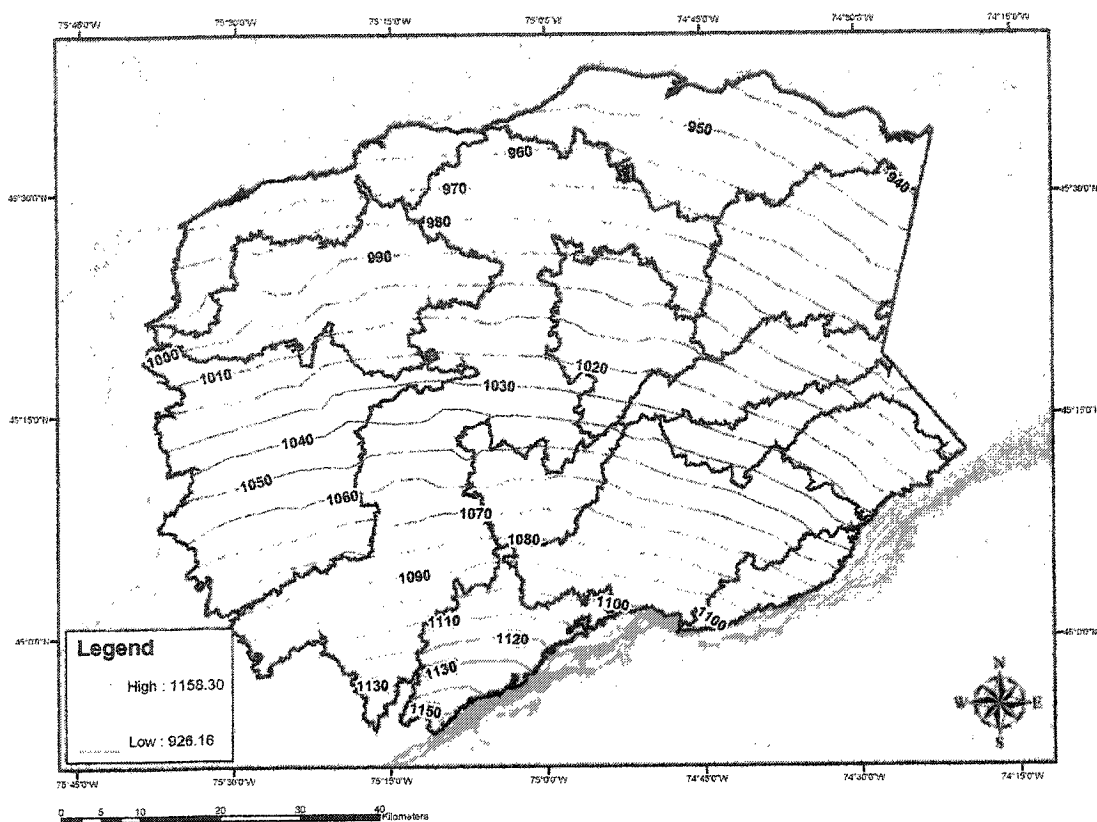


Fig. 24. Mean annual erosivity factor (R) for eastern Ontario (453 sites) (units - $\text{MJ mm ha}^{-1} \text{ h}^{-1}$). Contours are in 10 unit intervals.

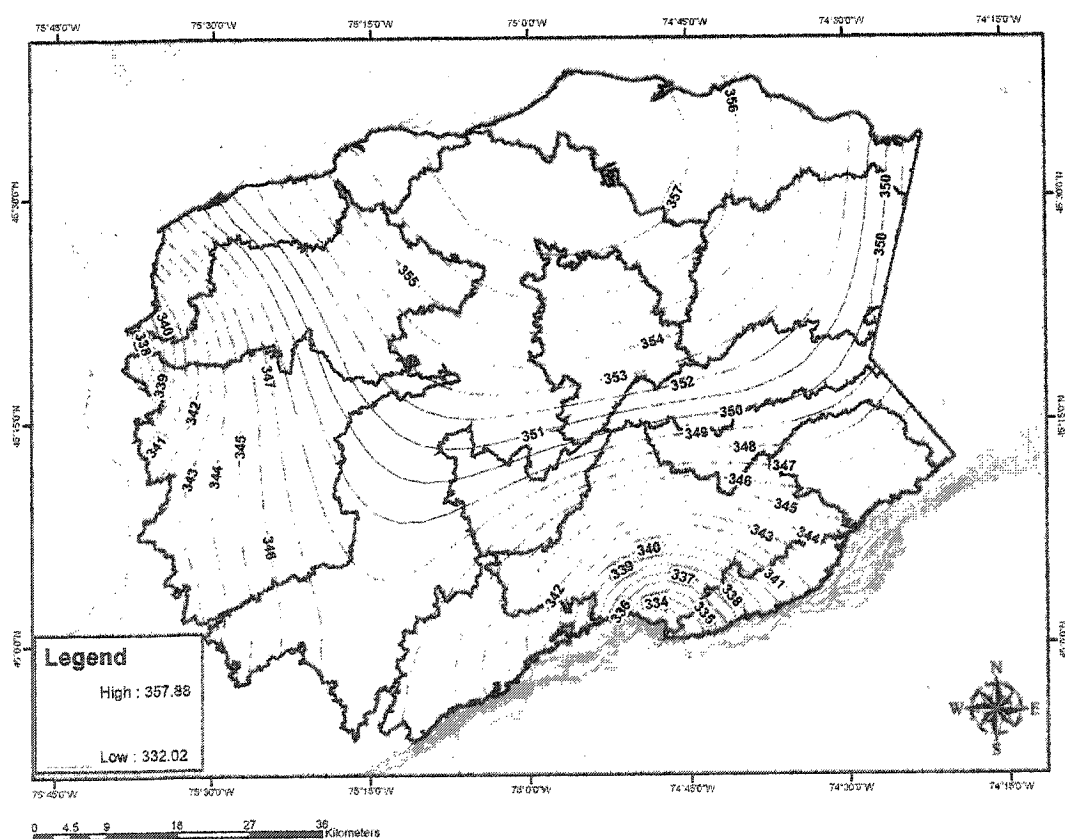


Fig. 25. Standard error of the mean annual erosivity factor (R) (453 sites) for eastern Ontario given in Fig. 22 (units - $\text{MJ mm ha}^{-1} \text{ h}^{-1}$). Contours are in 1 unit intervals. Bullseye effect is a result of errors being less around station erosivity values.

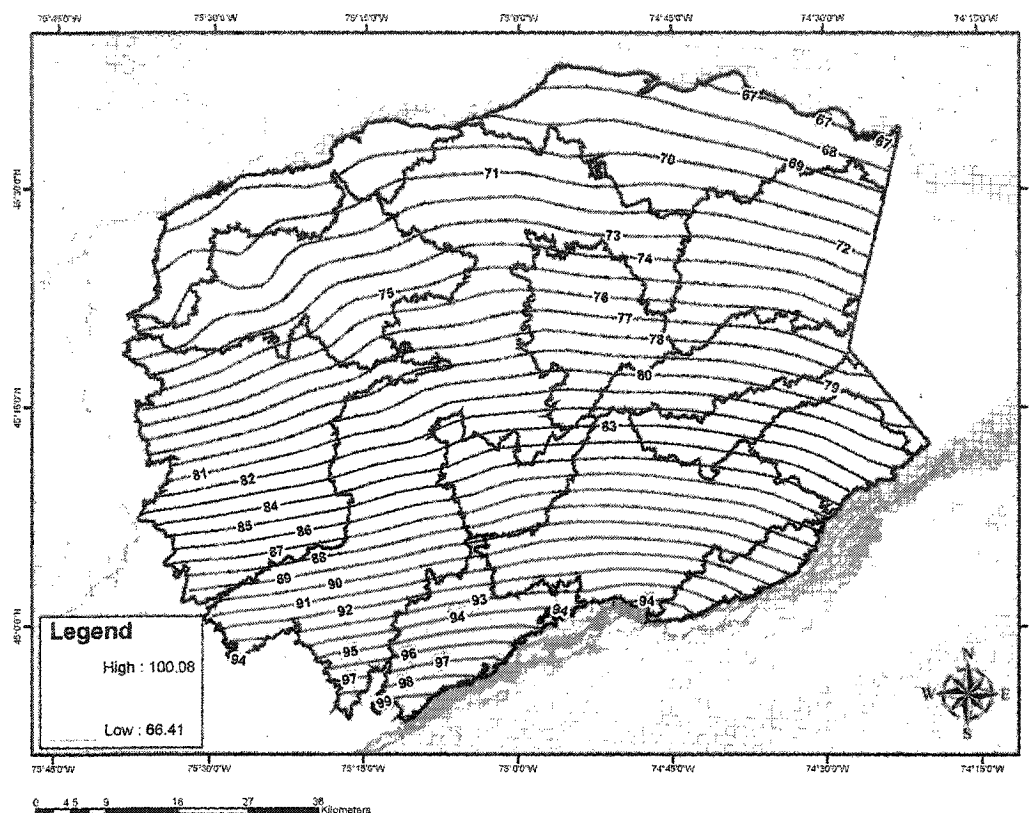


Fig. 26. Rainfall erosivity factor (R) for the month of March (372 sites) for the eastern Ontario region (units - $\text{MJ mm ha}^{-1} \text{h}^{-1}$). Contours are in 1 unit intervals.

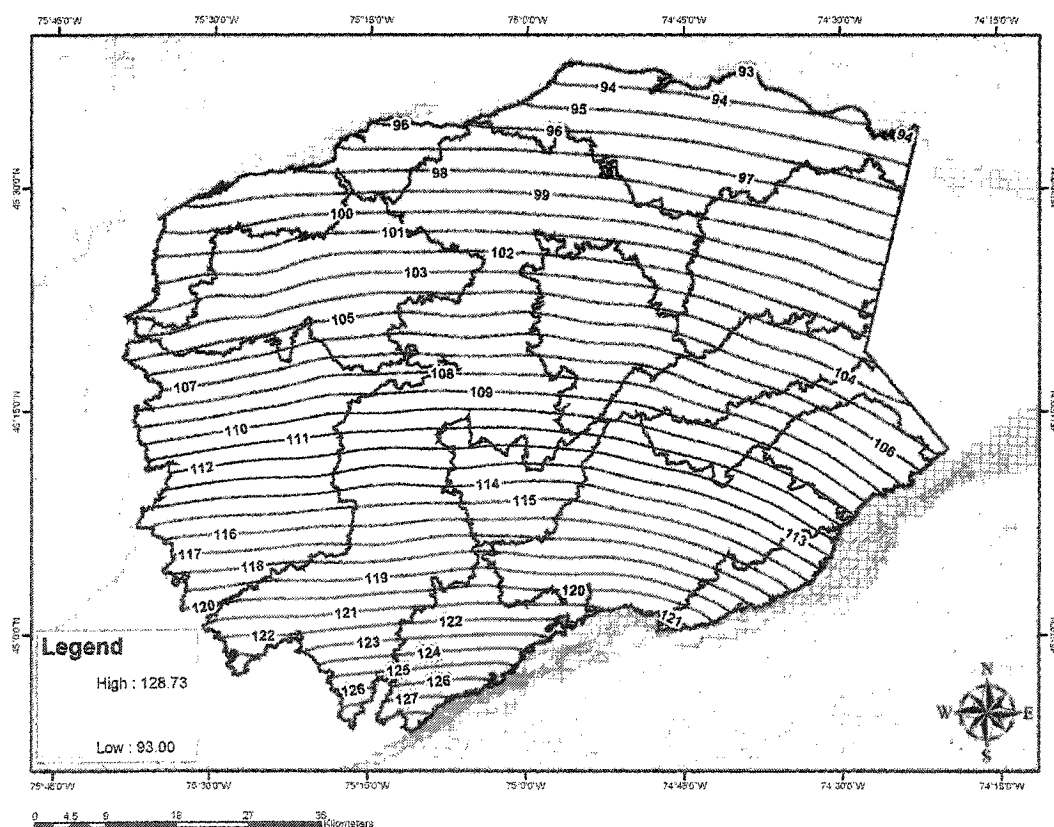


Fig. 27. Rainfall erosivity factor (R) for the month of April (435 sites) for the eastern Ontario region (units - $\text{MJ mm ha}^{-1} \text{h}^{-1}$). Contours are in 1 unit intervals.

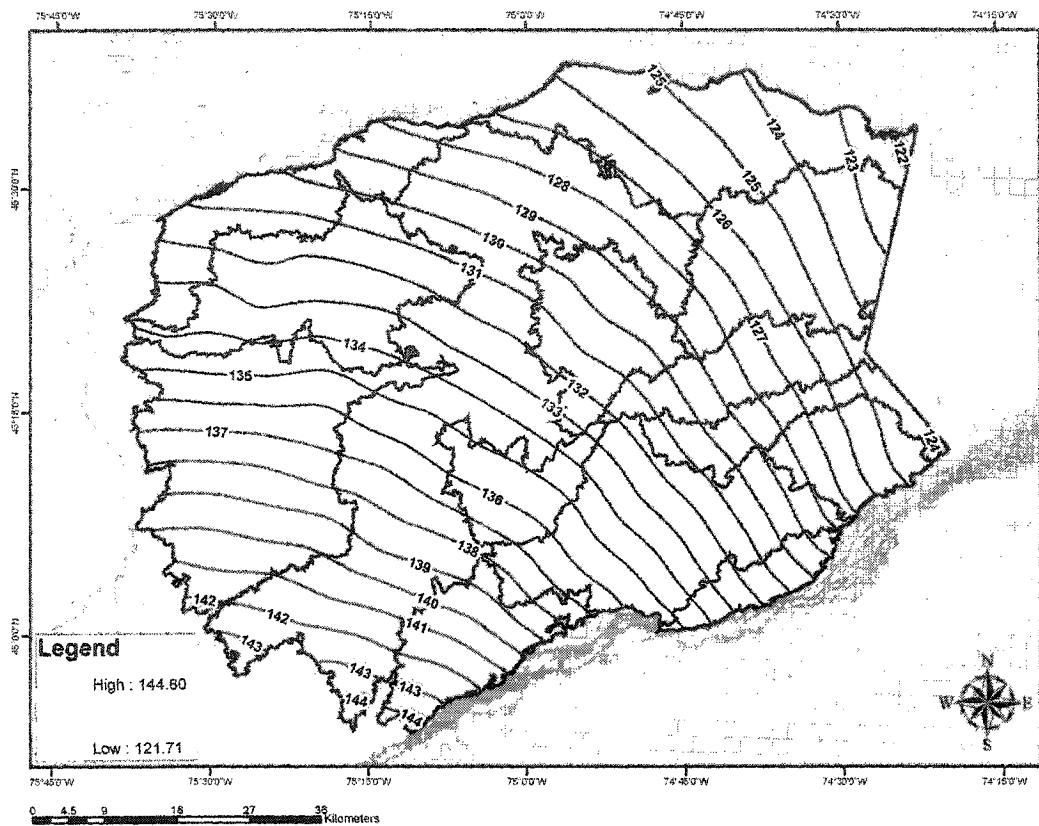


Fig. 28. Rainfall erosivity factor (R) for the month of May (451 sites) for the eastern Ontario region (units - MJ mm ha⁻¹ h⁻¹). Contours are in 1 unit intervals.

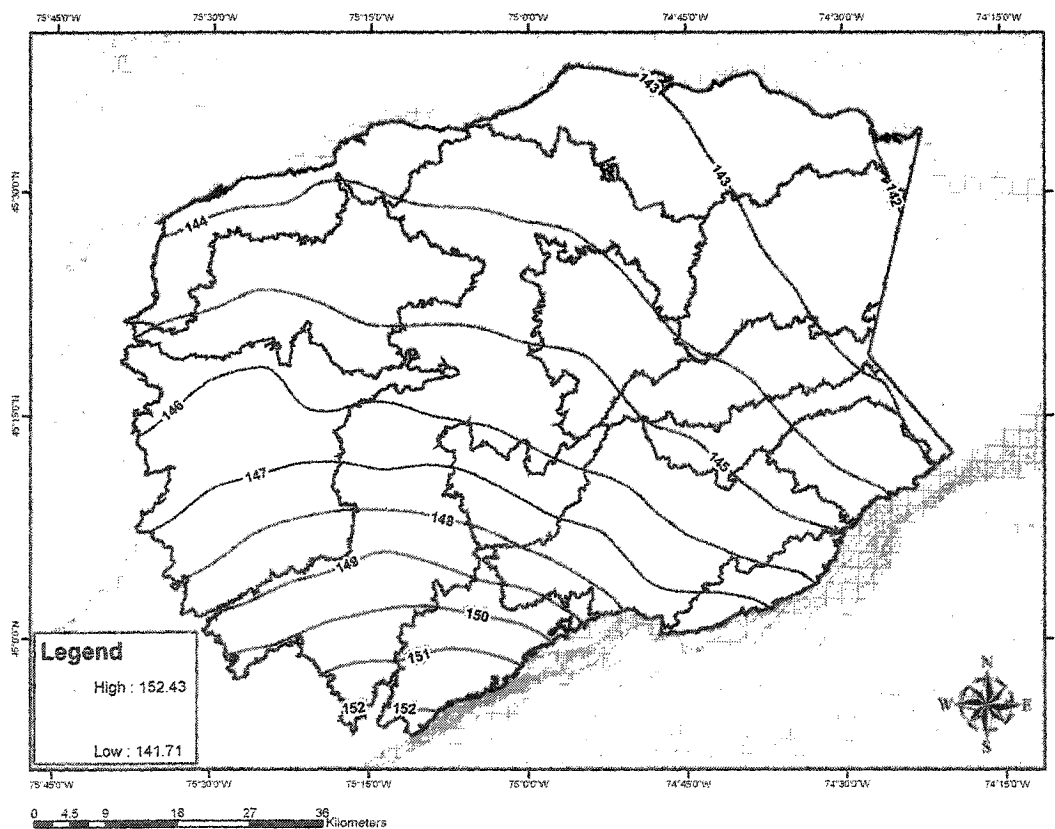


Fig. 29. Rainfall erosivity factor (R) for the month of June (451 sites) for the eastern Ontario region (units - MJ mm ha⁻¹ h⁻¹). Contours are in 1 unit intervals.

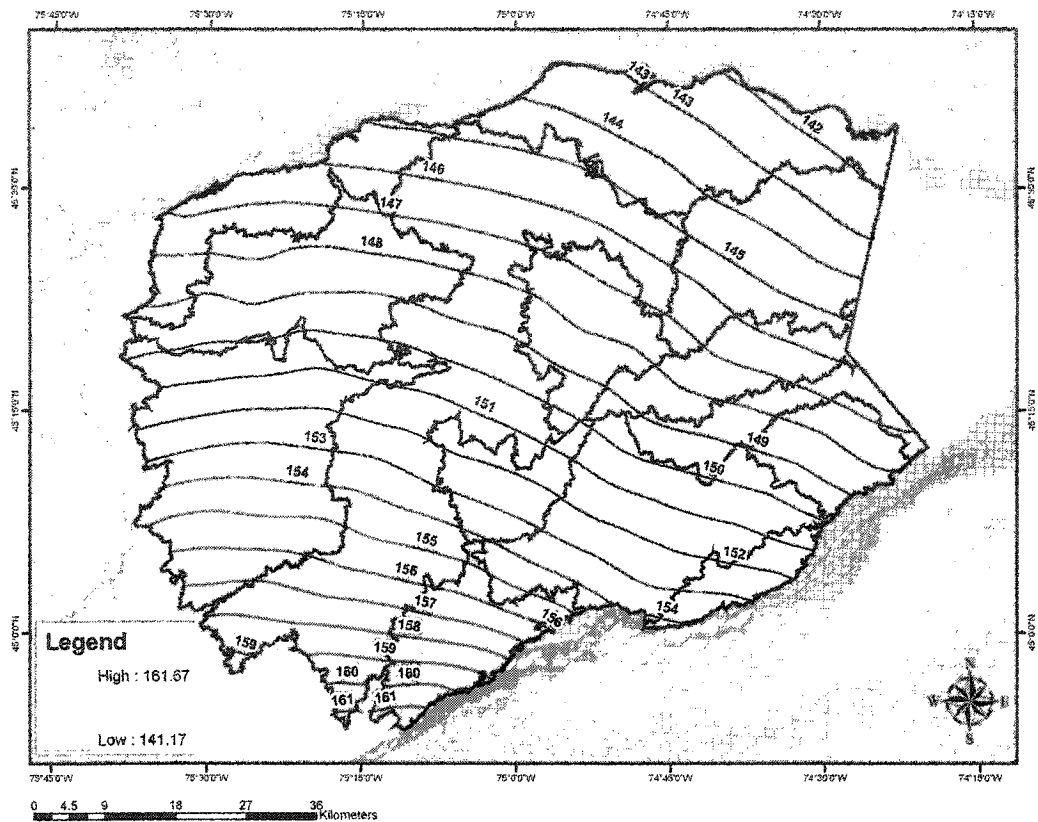


Fig. 30. Rainfall erosivity factor (R) for the month of July (451 sites) for the eastern Ontario region (units - $\text{MJ mm ha}^{-1} \text{h}^{-1}$). Contours are in 1 unit intervals.

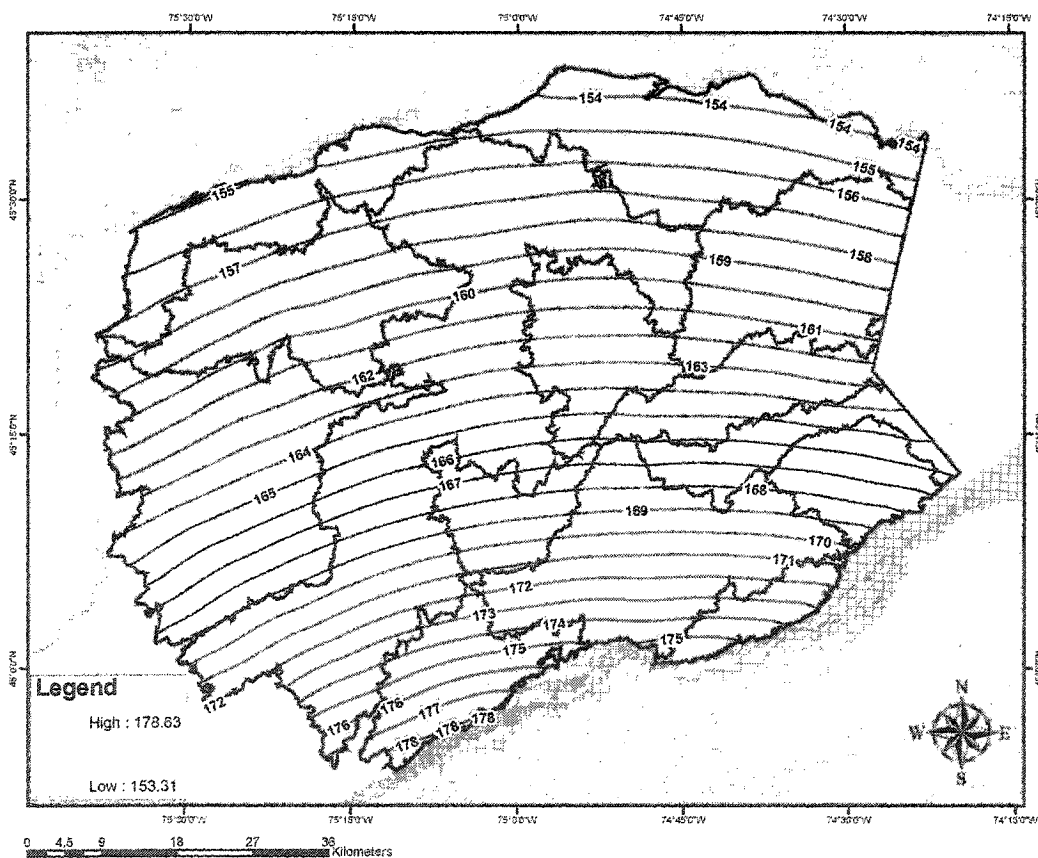


Fig. 31. Rainfall erosivity factor (R) for the month of August (451 sites) for the eastern Ontario region (units - $\text{MJ mm ha}^{-1} \text{h}^{-1}$). Contours are in 1 unit intervals.

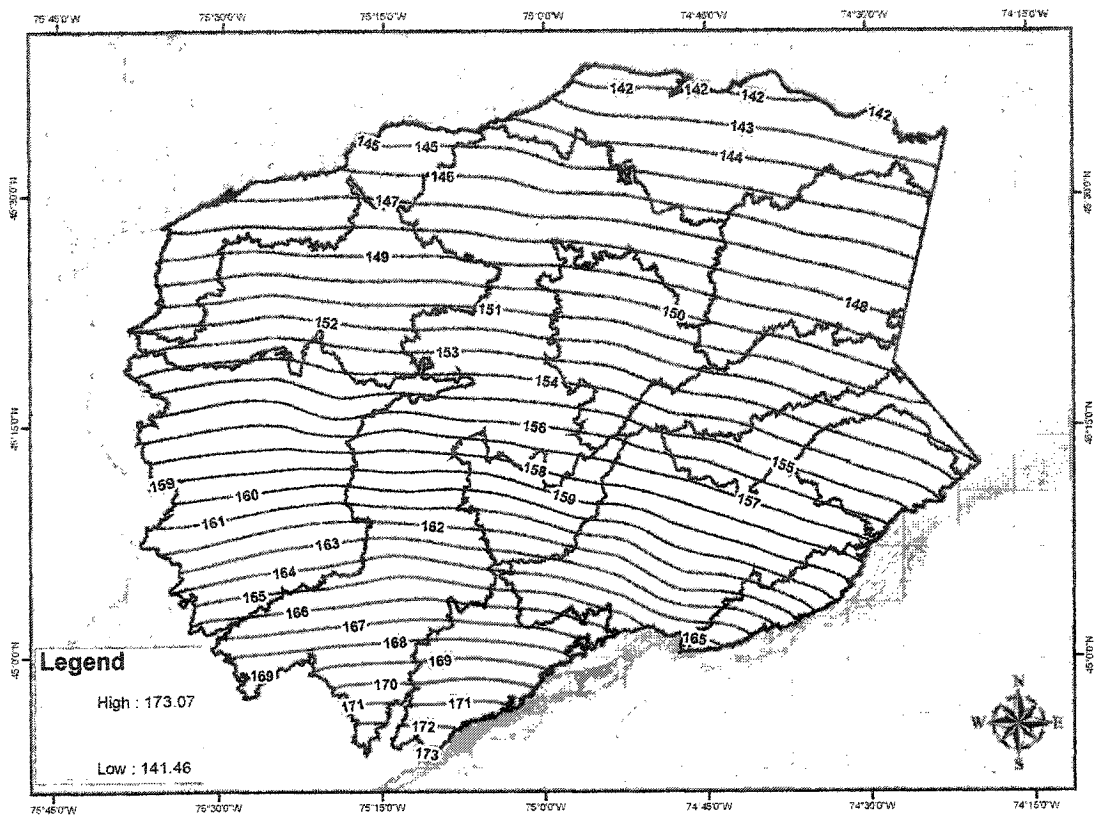


Fig. 32. Rainfall erosivity factor (R) for the month of September (451 sites) for the eastern Ontario region (units - $\text{MJ mm ha}^{-1} \text{h}^{-1}$). Contours are in 1 unit intervals.

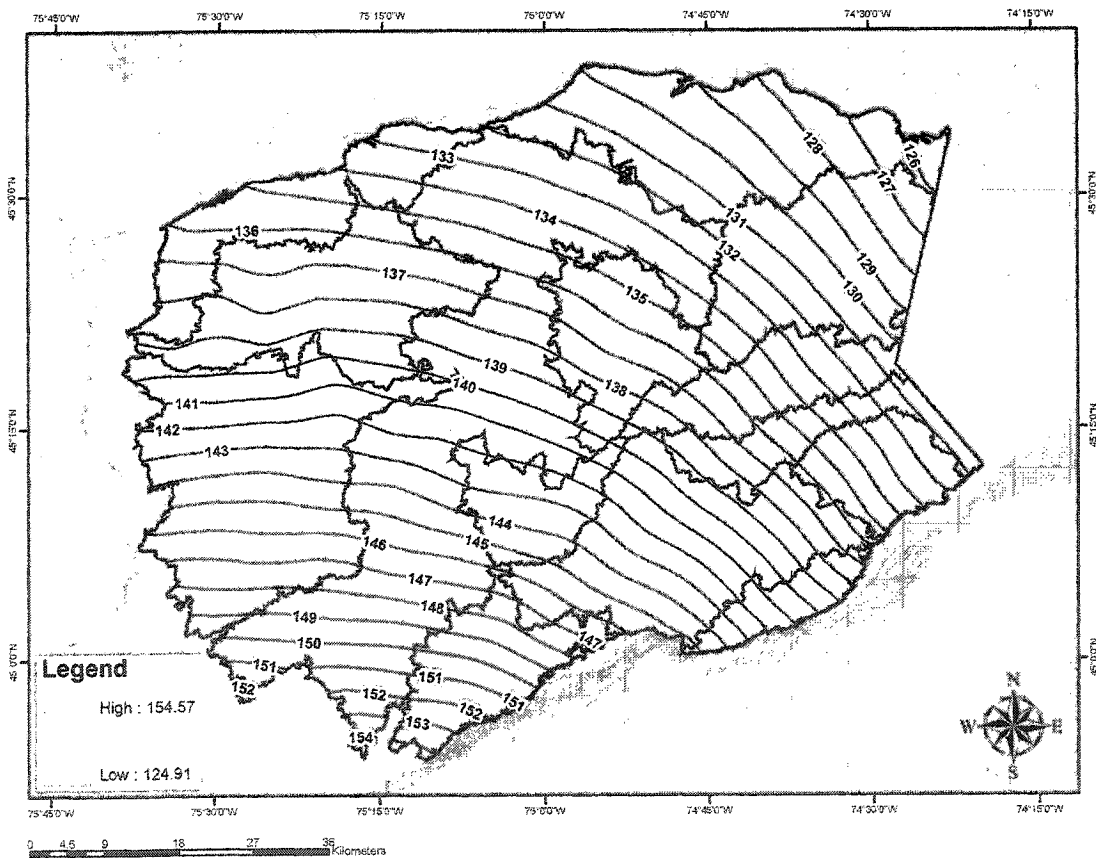


Fig. 33. Rainfall erosivity factor (R) for the month of October (451 sites) for the eastern Ontario region (units - $\text{MJ mm ha}^{-1} \text{h}^{-1}$). Contours are in 1 unit intervals.

3.12 Computing the Soil Erodibility Factor

The soil erodibility factor proved the most difficult to compute. First, soil attribute data for several soil types and soil layers had various missing attributes. Secondly, the dataset (CANSIS, 2004) represents a merger of several surveys from various time intervals (1949 to 1998) and surveyors (Richards *et al.*, 1949, Mathews and Richards, 1952, Mathews and Richards, 1954, Mathews *et al.*, 1957, Wickland and Richards, 1962, Jarvis and Shutt, 1998) making the integration of the data open to incongruence. Assumptions made in this study are that the data are compatible spatially and temporally. One must further question whether soil attributes and characteristics have changed since the last examination and scientific analysis of their properties. However, as discussed in section 3.8, uncertainty can be addressed using an approximation of error for soil erodibility in equation (3.31). The results of the calculation of erodibility between counties indicate good agreement using visual inspection of the spatial and temporal differences of soil erodibility as calculated from these attributes (see Fig. 34a and 34b for examples).

Soil erodibility can be approximated first by percent silt and very fine silt, percent sand, and percent organic matter (Foster *et al.*, 1981). Estimates are then refined using soil structure and permeability of the soil profile. Soils that have surface textures of very fine sand, loamy very fine sand, and silt loam tend to be the most erodible (Wall *et al.*, 2002 page 56). Soils that have surface textures of sand, loamy sand, and coarse sandy loam tend to be the least erosive (Wall *et al.*, 2002 page 56). Sandy soil tends to have lower K values due to their higher infiltration capacities that allow for movement of water through the profile providing less excess runoff and subsequent erosion. Clays normally have lower soil erodibility due to their ability to resist

detachment. Silts are generally highly erodible due to surface crusting during rain events which promotes overland flow and ensuing erosion.

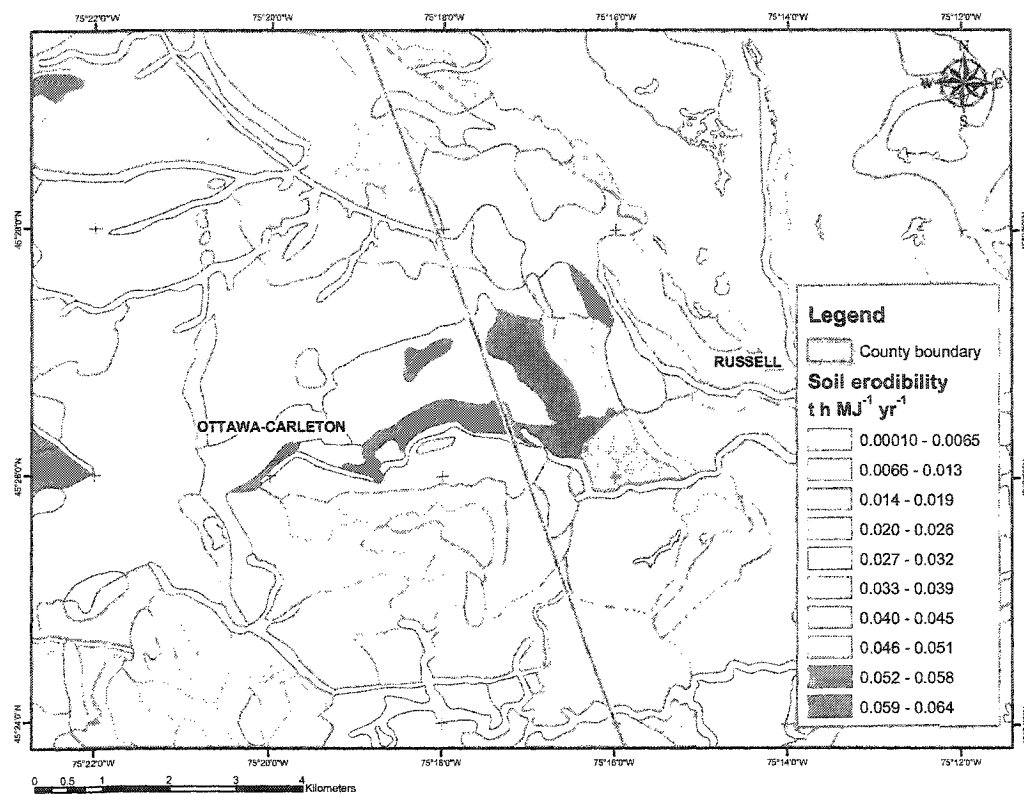


Fig. 34a. Soil erodibility value congruency between Ottawa – Carleton and Russell County.

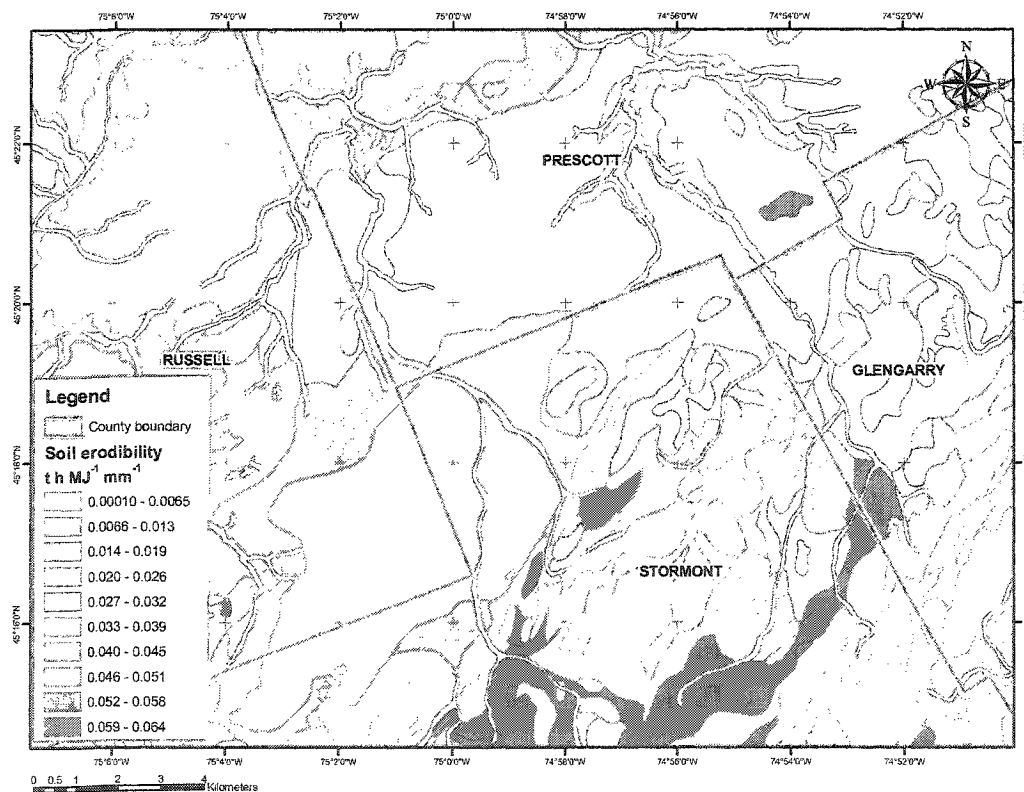


Fig.34b. Soil erodibility value congruency between Russell, Prescott, Stormont, and Dundas County.

Erodibility was calculated where possible using the numerical approximation of the Wischmeier and Smith (1978) nomograph. The approximation applied was that provided in equation (3.33) (Wischmeier and Smiths, 1978; Wall, 2002) for those soils with appropriate attribute data. Soil erodibility is calculates as:

$$K = \frac{2.1M^{1.14}(10^{-4})(12 - g) + 3.25(b - 2) + 2.5(c - 3)}{100} \quad (3.33)$$

where:

K = soil resistance to erosion ($t\ h\ MJ^{-1}\ mm^{-1}$),
 $M = (d + e) \times (100 - f)$,
 g = % organic matter,
 b = soil structure ranging from 1 to 4,
 c = profile permeability code ranging from 1 to 6,
 d = % silt,
 e = % very fine sand,
 f = % clay.

The inputs needed for equation (3.33) are supplied by properties of the top layer of soil except for permeability which requires an assignment for the least impermeable layer in the soil profile. Percent organic matter was calculated using an estimation based on percentage organic carbon (Mitchell, 1995; Plank, 2001), given as:

$$g = (h) \times 1.724 \quad (3.34)$$

where:

h = % organic carbon.

Percent organic carbon was present as a soil attribute and was used directly in equation (3.34) to determine percent organic matter. Soil attribute data of percent silt, very fine sand and clay were used directly in equation (3.33). Soil structure and profile permeability were attributes not included in the digital data and had to be calculated indirectly. Where silt and very sand percentages are greater than 70%, or where soil layers are missing attributes essential for use in equation (3.33), K values were flagged for calculation of soil erodibility using the hard-copy soil survey textural classes (see Table 6). In the case where organic matter percentages beyond 4% occurred, factor g was set to 4.1 %.

Profile permeability (*c*) was not included as an attribute in the digital data and had to be calculated via textural class using percentage of sand, silt and clay contained in the final component table. Textural class for each layer was estimated using an ArcInfo® Macro

Language (AML) script applied to the layer file to generate a textural class for each layer (Appendix K). For each textural class associated to a soil layer a permeability rating was generated. Permeability was assigned by textural class as found in Wall *et al.* (2002), page 59 using logical operators in ArcMap® GIS with Visual Basic script. Next, the least impermeable layer was found for each soil type in

<i>Texture Class</i>	<i><2% Organic Matter</i>	<i>>2% Organic Matter</i>	<i>Mean</i>
Clay	0.032	0.028	0.029
Clay loam	0.044	0.037	0.040
Coarse sandy loam	-	0.009	0.009
Fine sand	0.012	0.008	0.011
Fine sandy loam	0.029	0.022	0.024
Heavy clay	0.025	0.020	0.022
Loam	0.045	0.038	0.040
Loamy fine sand	0.020	0.012	0.015
Loamy sand	0.007	0.005	0.005
Loamy very fine sand	0.058	0.033	0.051
Sand	0.001	0.003	0.001
Sandy clay loam	-	0.026	0.026
Sandy loam	0.018	0.016	0.017
Silt loam	0.054	0.049	0.050
Silty clay	0.036	0.034	0.034
Silty clay loam	0.046	0.040	0.042
Very fine sand	0.061	0.049	0.057
Very fine sandy loam	0.054	0.044	0.046

Table 6. Soil erodibility for some common surface textures (units - $t h MJ^{-1} mm^{-1}$) (Wall *et al.*, 2002). The estimates are based on 1600 samples collected in southern Ontario by the Ontario Institute of Pedology surveyors.

the layer table using a program written in Visual Basic (VB) (Appendix L). The program loops

through the layer table and finds the least permeable layer per soil type and outputs this in tabular format. Program output is a table of soil types and associated permeability classes from one through six, where class six is the least permeable class. Further, permeability was adjusted to conform to RULSE based guidelines of reduced permeability due to rock fragments inhibiting water movement through the soil profile. These corrections were made where coarse fragment data existed. Soils with less than 25% coarse rock fragments experienced no change in permeability class. Soils with 25 to 60% coarse rock fragment were raised one permeability class, while soils with 60% or coarse rock fragments were raised two permeability classes.

Regarding soil structure (b), four classes ranging from very fine granular to blocky/platy/massive were not present as an attribute in the original soil data. This parameter was also computed on the layer file using a second AML (Appendix M). The AML assigns structural codes to the soil type based on the 1 to 14 textural classes given in Wall *et al.* (2002), page 58. Textural class is again assigned by the percentage of sand, silt, and clay found in the layer. Once the computation of permeability and soil structure were complete, soil erodibility was calculated for each type of soil using equation (3.33).

For those soil types that were flagged as containing inappropriate or missing attributes, soil erodibility was estimated using the surface textural classifications and organic matter content provided in hard copy soil surveys (Richards *et al.*, 1949, Mathews and Richards, 1952, Mathews and Richards, 1954, Mathews *et al.*, 1957, Wickland and Richards, 1962, Jarvis and Shutt, 1998). In cases where organic matter data was lacking, average K were assigned based on texture class (refer to Table 6).

The assignment of erodibility to the soil polygon was made for the soil that occupies the greatest percent (largest share) of the polygon for each map unit. Averaging of soil susceptibility

(K) within polygons can be misleading and may not represent the inherent erodibility of any soil type in a map unit (Wall, 2002). A utility was developed to select the most dominant soil type per polygon (Appendix N). In situations where two soil types occupy the same percentage of the map unit, the soil type with the dominant or highest K value was chosen. If the K values are found equal, the last ordered soil type is assigned to the map unit. Alternate formulations such as random assignment or assignment based on K values of neighboring polygons could also be conceived but were not used here and represent an avenue of further study.

The soil erosivity (Fig. 35) and error data (Fig. 36) in vector format, after calculation of the K factor, were converted to a 10 m $\times$ 10 m raster to match elevation data used to calculate the slope length and steepness factor. Results agree well with unpublished erodibility maps of the region provided by researchers at Agriculture Canada, Eastern Cereal and Oilseeds Research Centre. Conversions of these maps to grid format were made using a nearest neighbor approach. K values were then masked to field boundaries limits for further analysis.

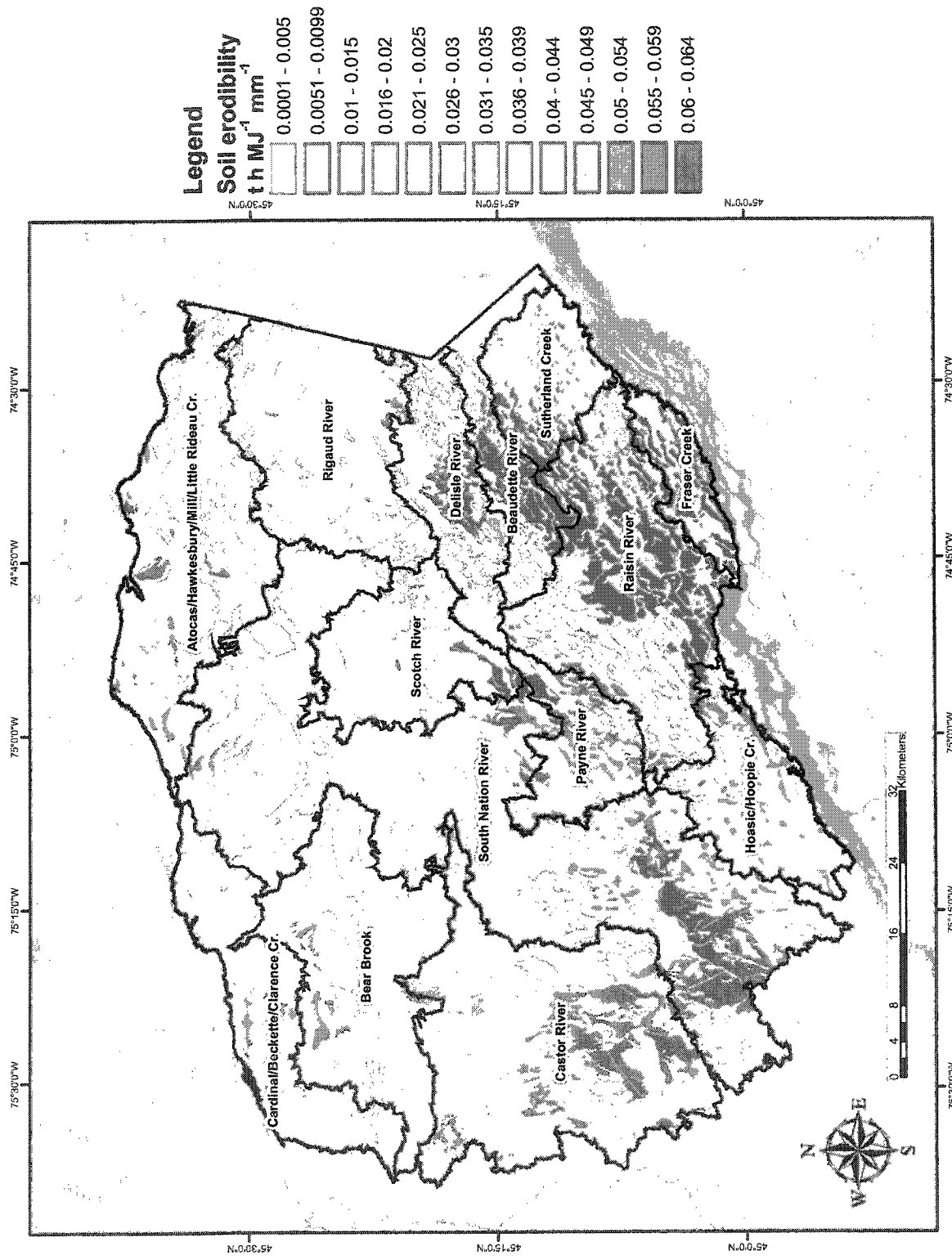


Fig. 35. Soil erodibility in the eastern Ontario region based on surface soil attributes ($t\ h\ MJ^{-1}\ mm^{-1}$).

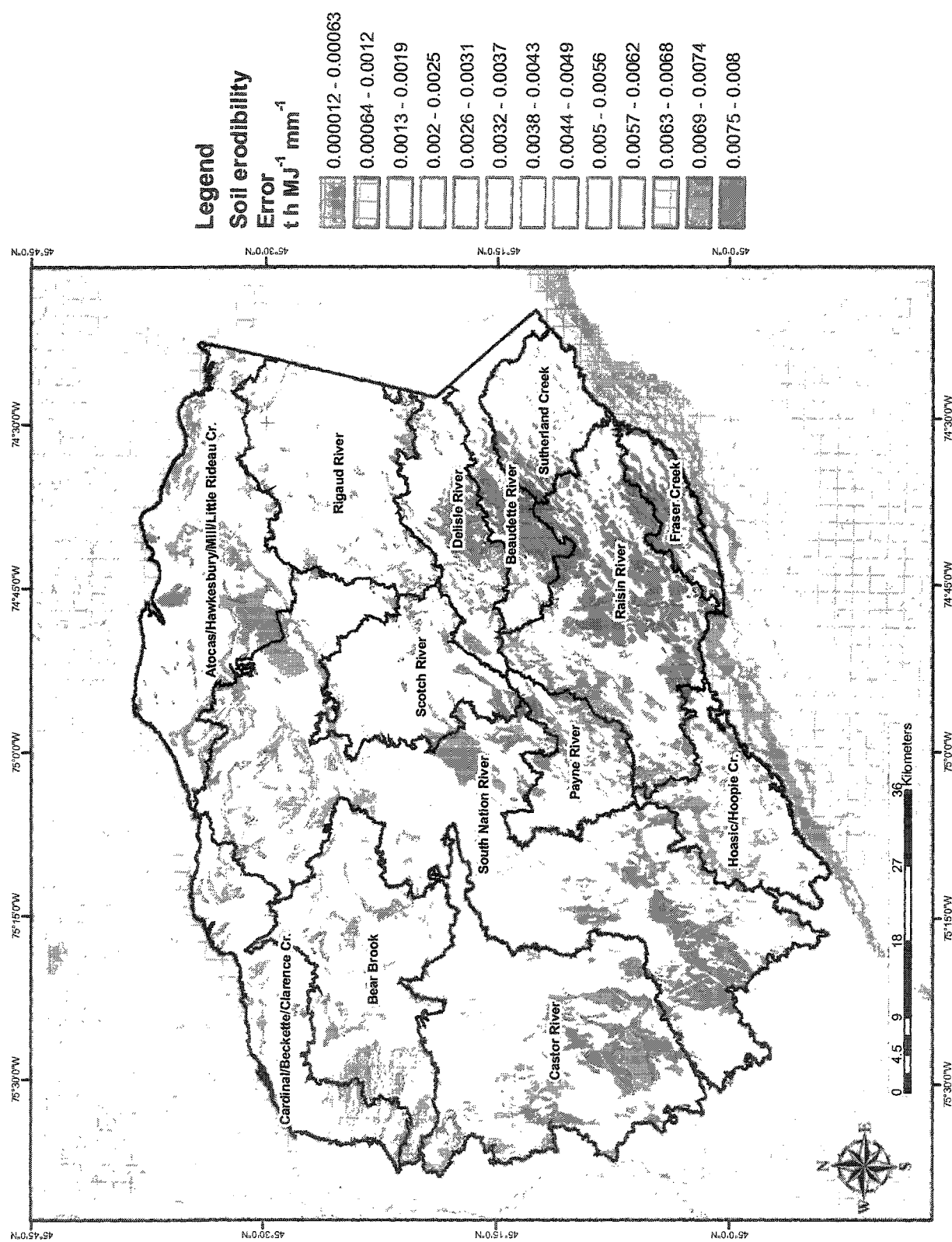


Fig. 36. Soil erodibility standard error map, eastern Ontario region based on surface soil attributes ($t\ h\ MJ^{-1}\ mm^{-1}$).

It is slightly misleading to represent the soil erodibility data at a 10 m resolution, as this data in raster format should ideally be scaled at resolutions of 12.5 to 31.68 meters. However, for integration with LS factors values this resolution was chosen out of practicality.

An, alternate formulation of the K factor using fuzzy boundary theory is a promising line of investigation which should be followed in the future. Such analysis would require that only the boundaries between polygonal units be filtered using a kernel which averages soil erodibility values across polygon boundaries. However, one could argue that an averaging of soil erodibility across soil polygon boundaries may not actually represent the erodibility of any of the soils contained within the polygons, or may not represent soil erodibility at boundary limits. The results could be misleading, as are the results if one averages erodibility values within soil polygons. The use of the fuzzy boundary theory would assume that erodibility varies continuously in space and that there are no abrupt boundary transitions between types of soil unlike the spatial model that soil scientist use to represent soils on paper maps, where map units and internal soil types are depicted usually as discrete entities. As such debate is open, the K factor was not averaged at polygonal boundaries. One additional problem with the application of fuzzy boundary theory in this analysis would be the difficulty of quantify the error in erodibility between map units. One question such work would pose is whether you can actually average error between two soil types. Given these limitations, erodibility was maintained in its discrete spatial form.

3.13 Computing the Slope Length and Steepness Factor Using the USLE2D

Topographic data, or a digital elevation model (DEM) was obtained from the Ontario Ministry of Natural Resources (OMNR) (OMNR, 2002) in tile format for analysis of the slope length (L) and steepness factor (S). The dataset covers Ontario to the 51st parallel. Tiles 142, 143, 135 and 136 cover the study region and were used to compute the LS factor. The tiles were developed on a tile by tile basis using base data at a scale of 1:10,000. Tiles are distributed with 200 m overlap. Therefore, given the 1:10,000 scale of input data, DEM elevations can be accurately represented at a 5 m resolution. Elevations, however, are generated and distributed at a resolution of 10 m by the OMNR.

The DEM was generated using Natural Resources Value Information System (NRVIS) contour and water virtual flow data. This data is housed under the Water Resources Information Project of the Ontario government (WRIP). WRIP is a cooperative project by several Ontario ministries to integrate and standardize water information for Ontario for effective knowledge based water management. Contours stored in NRVIS represent isolines at fixed intervals and virtual flow path data represent the direction of flow of water courses, both of which are stored in vector format. The original isolines were generated in 5 m increments with a vertical accuracy of 2.5 m. Both the contour and virtual flow path inputs used to generate the elevation tiles vary in currentness from January 1976 to January 2002. From 1976 to 1988, all contours were generated photogrammetrically. In 1988, elevation contours were generated using point datasets of digital terrain model elevation points using automated software utilities (OMNR, 2002). Since 1998, automated utilities have been developed that search for errors in the DEM tiles and make appropriate corrections. The water flow data originates from drainage lineage derived from aerial

photography at a 1:30,000 scale and has been corrected for proper direction of flow and connection of broken arcs.

Using water flow and contour data, Water Resources Information Project (WRIP) (OMNR, 2002) generated elevation estimates via ANUDEM 4.6.3 that adhere to drainage topology. The Australian National University Digital Elevation Model (ANUDEM) program has a drainage filling component where sinks or pits (areas which have no outward flow) are filled if they intersect the water flow lineage or are identified as sinks independent of the waterline data. Elevation is developed so drainage is enforced. ANUDEM results from the work of Hutchinson (1989) in which interpolations are imposed using a morphological approach with an iterative finite difference interpolation method. Grids at successively finer intervals are generated iteratively until the user specified resolution is obtained, during which a roughness penalty is imposed so that the grid cells are smoothed to adhere to user tolerances specified. Metadata for the input DEM is provided in Table 7. The constraints of drainage enforcement and sink filling were applied on the DEM utilized in the LS analysis.

The tiles were combined using a Hermite cubic spatially weighted average (Franke, 1982). The Ontario Ministry of Natural Resources (OMNR) generated the elevation tiles independently, which causes one major limitation, in that, due to edge effects during the interpolation of individual tiles, coincident cells in overlapping regions were not identical. These differing values are averaged using Hermite cubic spatially weighted averaging to provide a smooth transition between tile boundaries.

<i>Map projection</i>	Universal Transverse Mercator
<i>Zone</i>	18
<i>Horizontal Geodetic Datum</i>	Nad83
<i>Vertical Datum</i>	CGD28 – CDN
<i>Horizontal Precision</i>	+/- 10 m
<i>Vertical Precision</i>	+/- 5 m

Table 7: Metadata for digital elevation model.

Contributing area is determined using a repeated 3×3 moving window which calculates the direction of flow from the central cell and the proportion of flow contributing to each adjacent cell. In this analysis a multiple flow algorithm is utilized which divides the flow out of a cell over several receiving cells. Multiple flow algorithms can accommodate divergent flow which is not accounted for in steepest descent and related algorithms. The use of a single flow algorithm to route water over complex landscapes is problematic as minor topographic accidents as a result of elevation interpolation may cause the misallocation of main drainage direction (Desmet and Govers, 1996a).

Failure of non-inclusion of multi-flow water movement may underestimate the actual flow being contributed to a specific cell over time. Other available methods of flow distribution using USLE2D are steepest decent and flux decomposition. A steepest decent algorithm normally examines the gradient between all cells and a center cell and attributes flow to the cell with the largest decent. A flux decomposition algorithm takes a flux vector, a vector having a magnitude equal to the upslope area to be distributed, increased with the area of the cell itself, and directs movement according to aspect direction which is split in two ordinal components (Desmet and Govers, 1996b). The magnitude of each component is proportional to the sine or cosine of the aspect value (Desmet and Govers, 1996b). Quinn *et al.* (1991) and (Desmet and Govers, 1996b) proposed the multiple flow direction algorithm given in equation (3.35). The receiving fraction of upslope flow is transferred to each cell down slope of the central cell using a sub-matrix approach where the transference is proportional to a product of the distance-weighted drop and a geometrically weighted factor dependent on the direction, shown as (Desmet and Govers, 1996b):

$$a_i = a \frac{\tan \theta_i T_i}{\sum_{j=1}^k (\tan \theta_j T_j)} \quad (3.35)$$

where:

a_i = fraction draining through neighbor i (m^2),

a = upslope area available for distribution (m^2),

θ_i = slope gradient towards neighbor i ,

i = lower neighbor,

T_i = weight factor (0.5 for a cardinal and 0.354 for a diagonal direction),

k = number of lower neighbors,

$\sum_j^k$ = summation over all lower neighbors.

The relationship (equation (3.35)) above can be modified for boundaries which inhibit flow, a component of the USLE2D. Landscape objects and structure affect erosion due to the impact of field boundaries and fence and ditch objects on sediment and/or runoff transfer between different land units (Van Oost and Govers, 2000). This inhibition assumes a predetermined percent of contributing area is trapped at field boundary locations over consecutive years (Van Oost and Govers, 2000).

Two scenarios were applied to understand how LS may be altered by the USLE2D model connectivity parameters applied. Scenario 1 computes LS with 25% connectivity between land units when routing water using the multi-path algorithm. A conservative estimate in this study is that 25% of contributing flow is moved through land unit boundaries. Scenario 2 assumes no obstruction of contributing area in the LS factor determination between field boundaries and can be viewed as the extreme opposite case of Scenario 1 (Table 8).

The raster outputs of slope length and steepness and error associated with these estimates conform to the same spatial scale as the soil erodibility data that was re-sampled to a 10 m × 10 m grid. Fig. 37 is the LS coefficient map for the entire region including areas external to field boundary with 25% parcel connectivity. Fig. 38 depicts the LS factor for 100% parcel connectivity for the same area. Error estimates of soil erodibility associated to Fig. 38 and Fig. 39 are given in Fig. 40 and Fig. 41.

<i>Parameter</i>	<i>Scenario 1</i>	<i>Scenario 2</i>
Routing algorithm	Multiple flow (3.35)	Multiple flow (3.35)
Parcel connectivity	25%	100%
Slope steepness	Nearing (1997) (3.22)	Nearing (1997) (3.22)
LS slope length exponent	McCool (1987) (3.24)	McCool (1987) (3.24)

Table 8. Parameters for LS factor scenarios calculated using USLE2D.

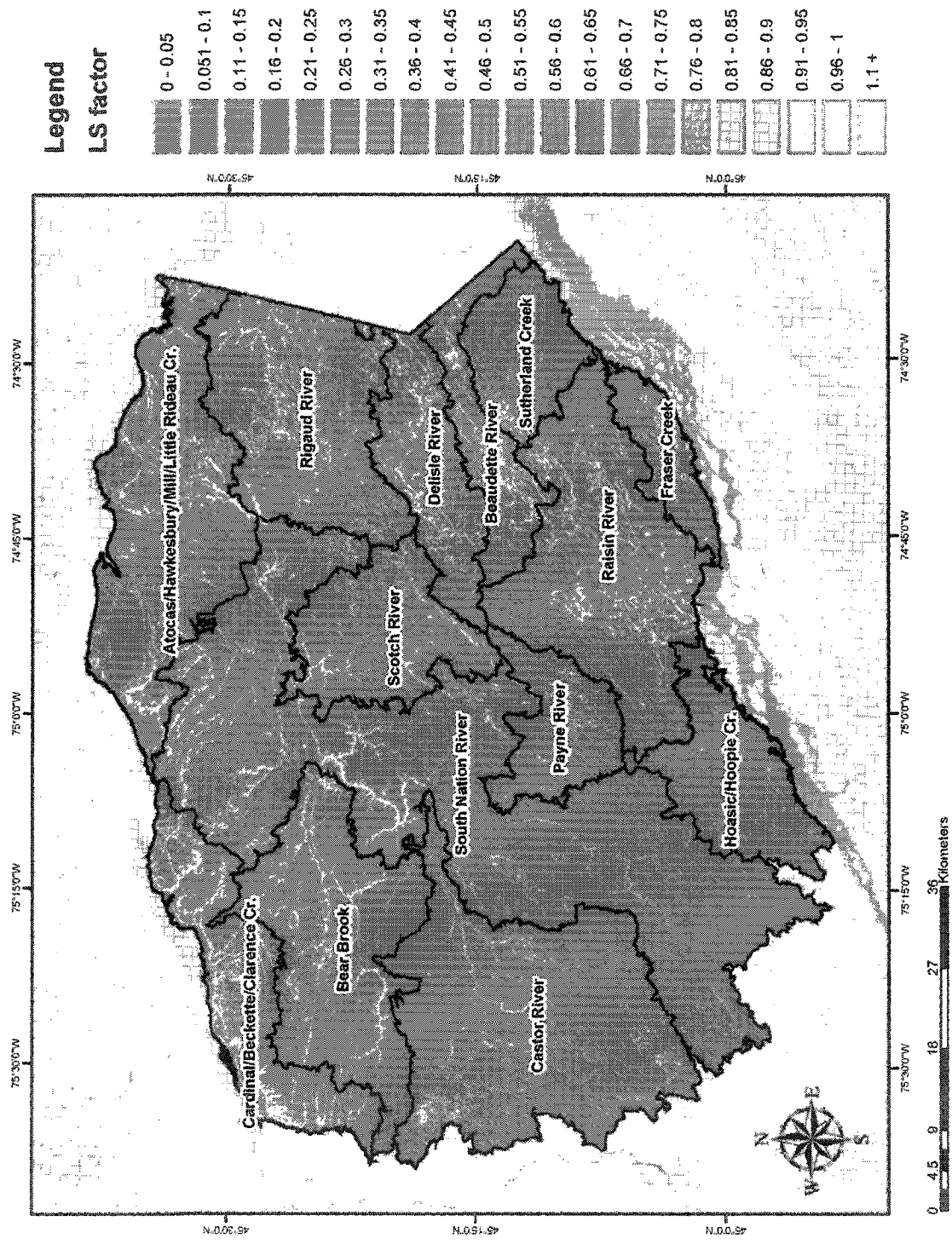


Fig. 37. Slope length and steepness coefficient map, eastern Ontario, 10 m resolution DEM, calculated using multi-flow algorithm (3.35), 25% parcel connectivity, slope steepness (3.22), and slope length coefficient from (3.24).

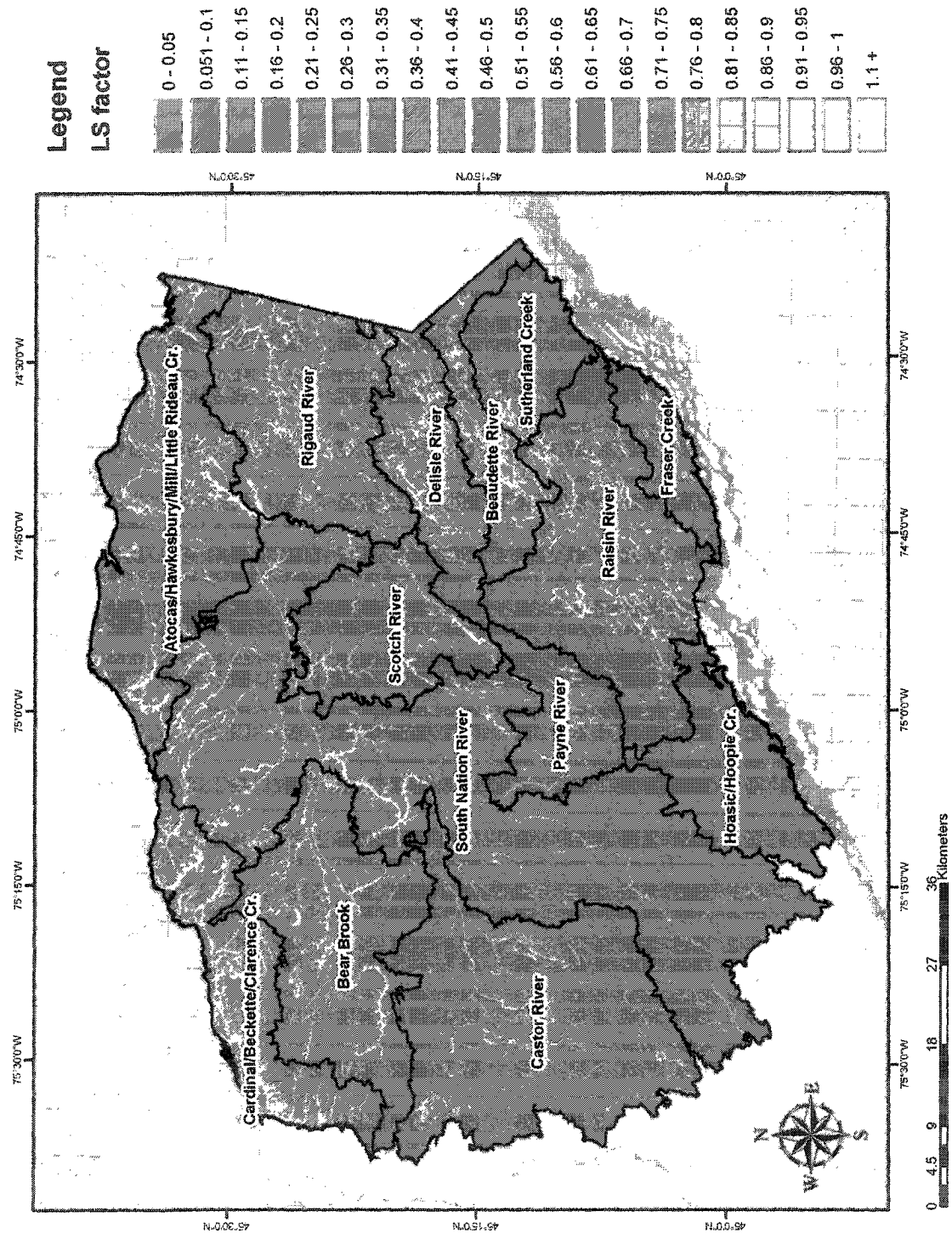


Fig. 38. Slope length and steepness coefficient map, eastern Ontario, 10 m resolution DEM, calculated using multi-flow algorithm (3.35), 100% parcel connectivity, slope steepness (3.22), and slope length coefficient from (3.24).

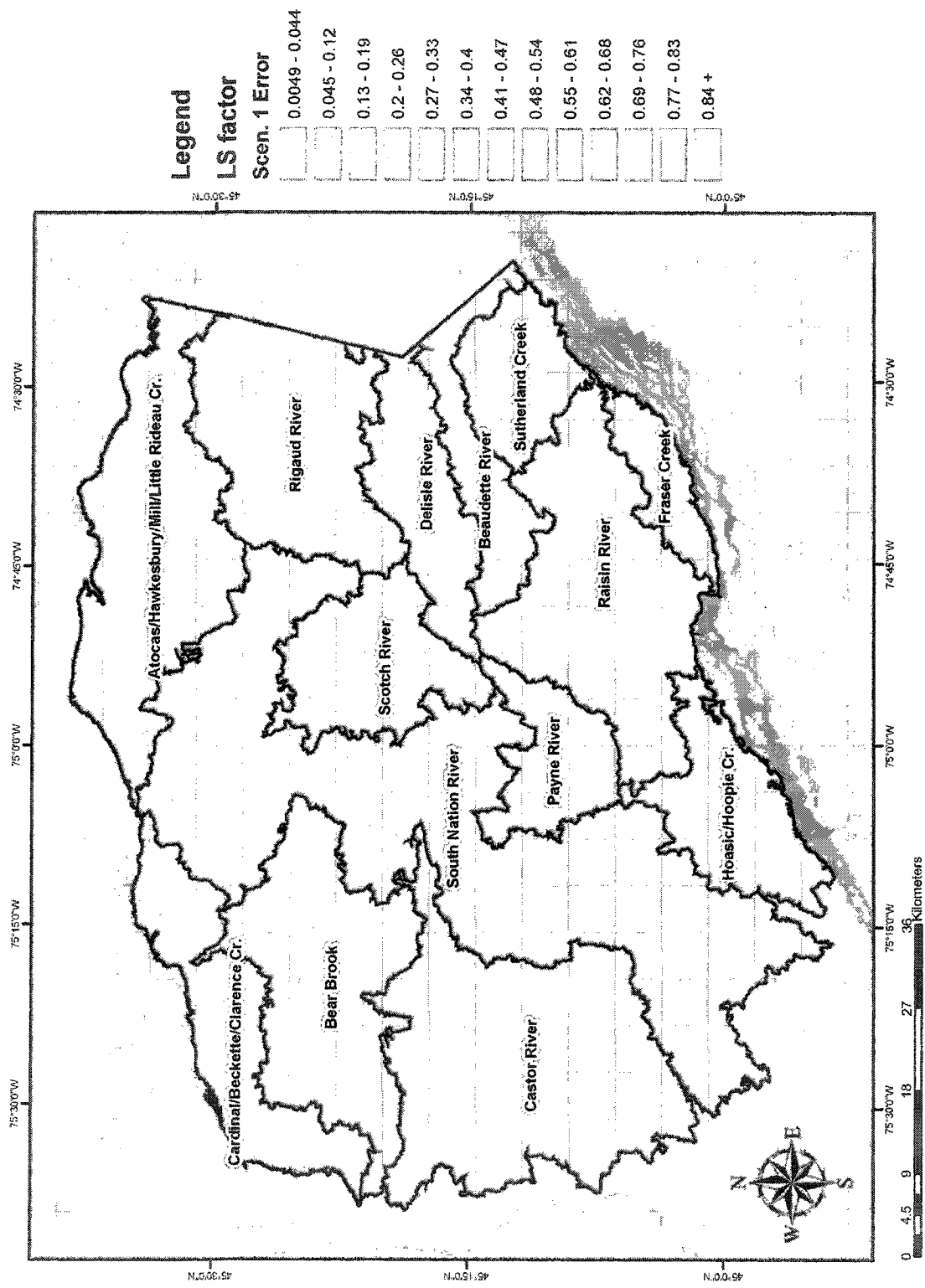


Fig. 39. Slope length and steepness coefficient error map, eastern Ontario, 10 m resolution DEM, calculated using multi-flow algorithm (3.35), 25% parcel connectivity slope steepness (3.22), and slope length coefficient from (3.24).

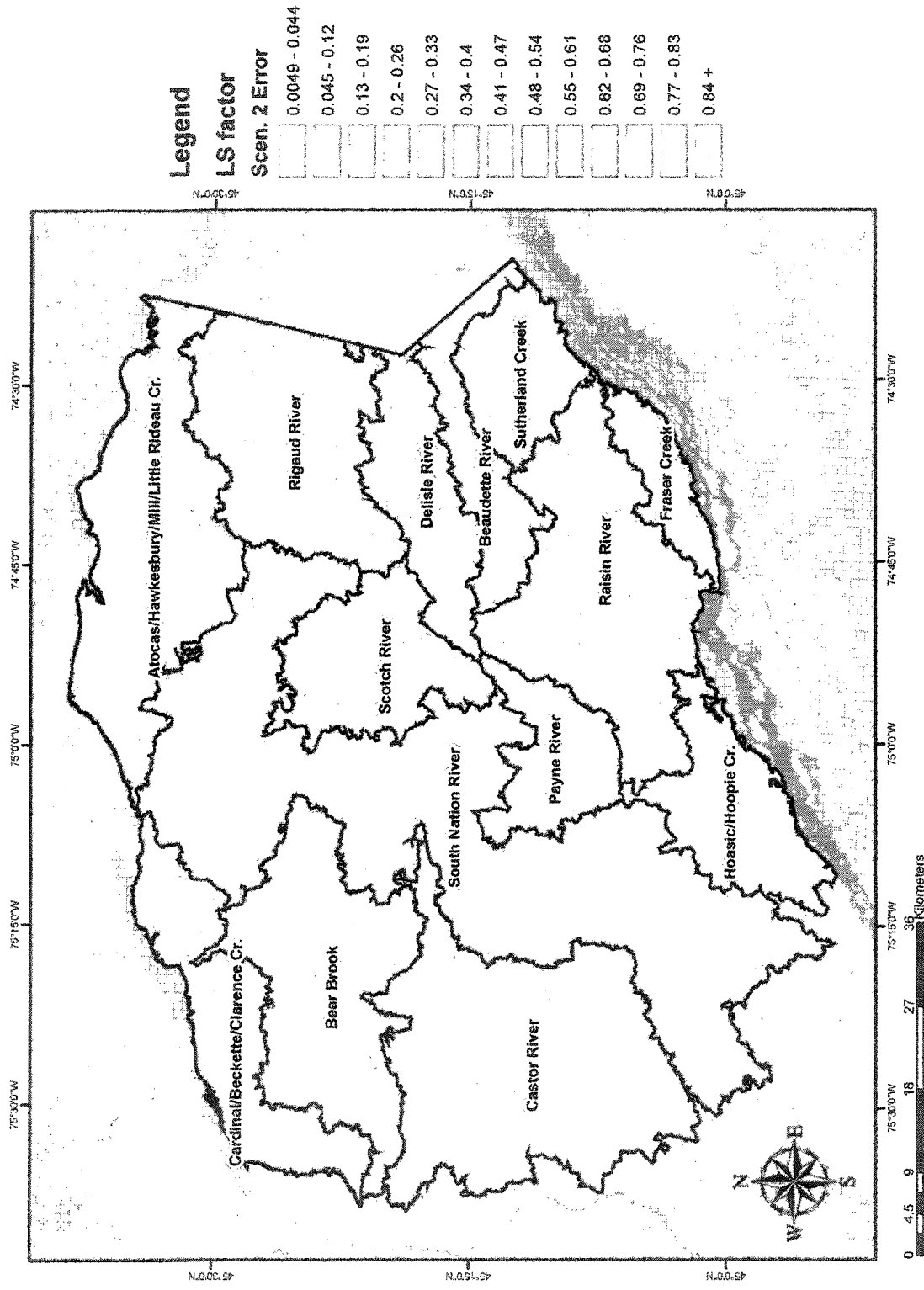


Fig. 40. Slope length and steepness coefficient error map, eastern Ontario region based on 10 m resolution DEM, multi-flow algorithm (3.35), 100% parcel connectivity slope steepness (3.22), and slope length coefficient from (3.24).

3.14 Deriving the Crop Cover and Management Factor

Classifications were produced by a remote sensing specialist at Agriculture Canada using Landsat Enhanced Thematic Mapper Plus (ETM+) imagery obtained on April, 27, 2001 and July 17, 2001. Given the acquisition time, the estimates of overall soil loss are limited to the summer of 2001 in that the C factor only represents crop management conditions for this time. The data were made available through research arrangements with Agriculture and Agri-Food Canada. The land use and land cover classifications were made using a supervised maximum-likelihood classifier. The input classes provided for the analysis were urban, wetland, forest, water, cropland (when it was not feasible to differentiate between crop type), hay/pasture, alfalfa, corn, cereals, and soybean. A confusion matrix is provided which depicts the accuracy of the crop classification (Table 9). Using field boundary data, 50% of the pixels inside each field were used as training sites while the other 50% within fields were used for accuracy assessment.

	class	Reference Class									Total
		Urban	Wet-land	Forest	Water	Hay pasture	Pure alfalfa	Corn	Cereals	Soybean	
Classification Class	Urban	5567	33	0	1	51	0	16	48	3	5719
	Wetland	2	5451	8	0	7	0	3	2	0	5473
	Forest	0	176	5935	0	2	0	3	0	0	6116
	Water	0	7	0	658	1	0	0	0	0	666
	Hay/ pasture	23	0	10	0	1175	53	26	65	25	1377
	Pure alfalfa	0	0	39	0	14	189	1	9	1	253
	Corn	8	6	35	1	46	3	951	65	35	1150
	Cereals	18	0	30	0	9	11	19	861	24	972
	Soybean	1	0	0	0	26	0	23	3	1161	1214
	Total	5619	5673	6057	660	1331	256	1042	1053	1249	22940

Table 9. Confusion matrix for land cover dataset derived from a supervised maximum likelihood classifier, 50% training within field boundaries, 50% testing within field boundaries.

Omission (exclusion) errors, show pixels that should have been included in class but were not and were classified in some other class incorrectly. Errors of commission (inclusion) represent the number of pixels in each class that were improperly included in the row class. Producer's accuracy is represented by the number of correctly classified pixels per column class divided by the total number of training set pixels for the column category and provides a value of how well training set pixels of a given category are classified (Table 10). User's accuracy, the probability that a pixel classified in a given category actually represents the category on the ground (Lillesand and Kiefer, 2000; page 570), is computed by dividing the number of correct classifications per category by the row total (Table 10). The error matrix (Table 9) and the accuracy table (Table 10) are provided as a guide for presenting the accuracy of those areas and classes used in the training and testing stage of class model building. Positive results indicate only that the training areas are homogeneous, the training classes are spectrally separable, and the classification strategy employed works well in the training areas (Lillesand and Kiefer, 2000; page 570). The statistics provide no indication of how well the classification performs exterior to the training and testing sites. Overall accuracy reflects the percentage of positively identified pixels to the total number of reference pixels and is the bold diagonal value in Table 9 divided by the sum of row or column totals. Further, one can differentiate the degree to which a given classification deviates from a random classification using the KHAT or kappa statistic which represents how much better a given classification is compared to one resulting from chance alone. The formula for the Kappa statistic is (Lillesand and Kiefer, 2000):

$$\hat{k} = \frac{N \sum_{i=1}^r x_{ii} - \sum_{i=1}^r (x_{i+} \bullet x_{+i})}{N^2 - \sum_{i=1}^r (x_{i+} \bullet x_{+i})} \quad (3.36)$$

where:

$\hat{k}$ = the percentage improvement of the classification beyond a randomly generated classification,

N = total number of observations made in the matrix,

x_{ii} = the number of observations in row i and column i (the major diagonal),

x_{i+} = total observations in row i (marginal total of row),

x_{+i} = total observations in column i (marginal total of column).

The Kappa statistic given in Table 10 of ~0.95 or 95% indicates that the classification is much better than a random classification and provides us with good confidence in the classifications made based on spectral signature in comparison to a randomly generated classifier.

Class	Producer's Accuracy	User's Accuracy
Urban	99.07%	97.34%
Wetland	96.09%	99.60%
Forest	97.99%	97.04%
Water	99.70%	98.80%
Hay/ pasture	88.28%	85.33%
Pure alfalfa	73.83%	74.70%
Corn	91.27%	82.70%
Cereals	81.77%	88.58%
Soybean	92.95%	95.63%
Overall accuracy	95.68%	
Kappa statistic	0.9458	

Table 10. Accuracy table of the classifications of crop type and land cover for the crop/vegetation and management factor (refer to Table 9).

Class	Conventional tillage	Conservation tillage	No Till
Urban	-99999	-99999	-99999
Wetland	-99999	-99999	-99999
Forest	-99999	-99999	-99999
Water	-99999	-99999	-99999
Hay/ pasture	0.02*	0.02*	0.02*
Pure alfalfa	0.02*	0.02*	0.02*
Corn (grain)	0.37	0.30	0.16
Cereals	0.41	0.25	0.18
Soybean	0.46	0.33	0.32

Table 11. Reclassification table applied to the crop classification grid generated from Landsat Thematic Mapper Imagery, summer 2001. Values of -99999 represent of no data. *Tillage practice does not vary for crop class in the region.

This higher Kappa statistic value, however, does not signify the confidence in our C factor applied to a particular class in this analysis. Thus, we further assign an approximation of 20% standard error for each of the crop class C factor values as discussed in Section 3.8.

In this study, the crop classification grid was re-sampled to a 10 m resolution, to the same extent as the K, and LS factors using a nearest neighbor assignment. It is slightly misleading to represent the crop management factor data at a 10 m resolution, as this data in raster format should ideally be scaled at its original 25 meter resolution. However, for integration with LS factor values, this resolution was chosen out of practicality. In the discussion and results section, the accuracy of the spatial predictions is discussed. The grid was then re-classed to conform to generalized C factor values for eastern Ontario (Wall *et al.*, 2002; page 91, Region 4). Three different C factor scenarios were applied, 1) conventional tillage, 2) conservation tillage, and 3) no till. The re-class table for the analysis is provided in Table 11. The classifications were then clipped to the extent of the field boundaries within the study region for USLE analysis and integration. Fig. 41 to Fig. 46 are the scenario C factor outputs and associated standard errors applied in this analysis.

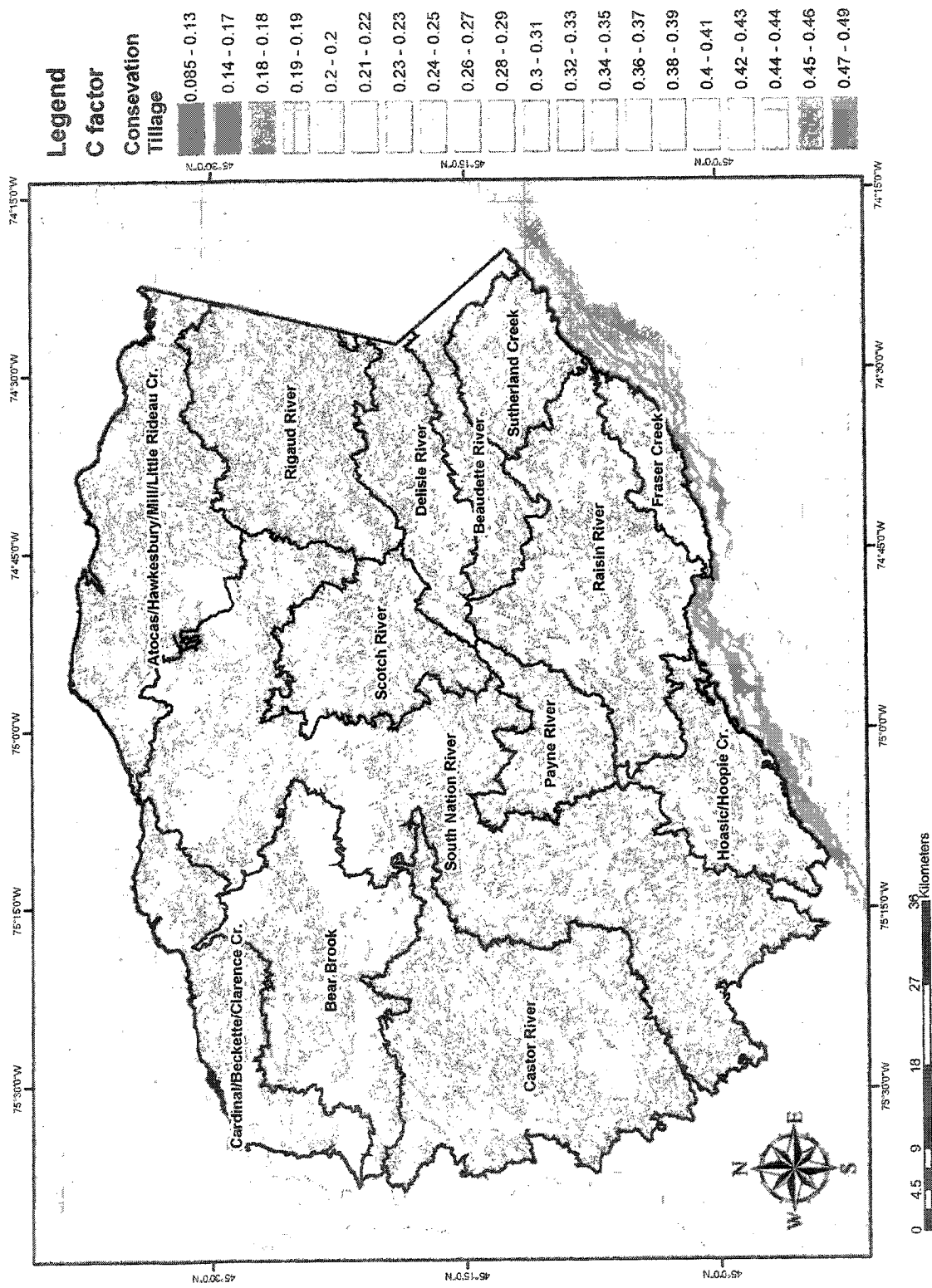


Fig. 41. The crop and management factor for eastern Ontario, summer 2001, under conventional tillage.

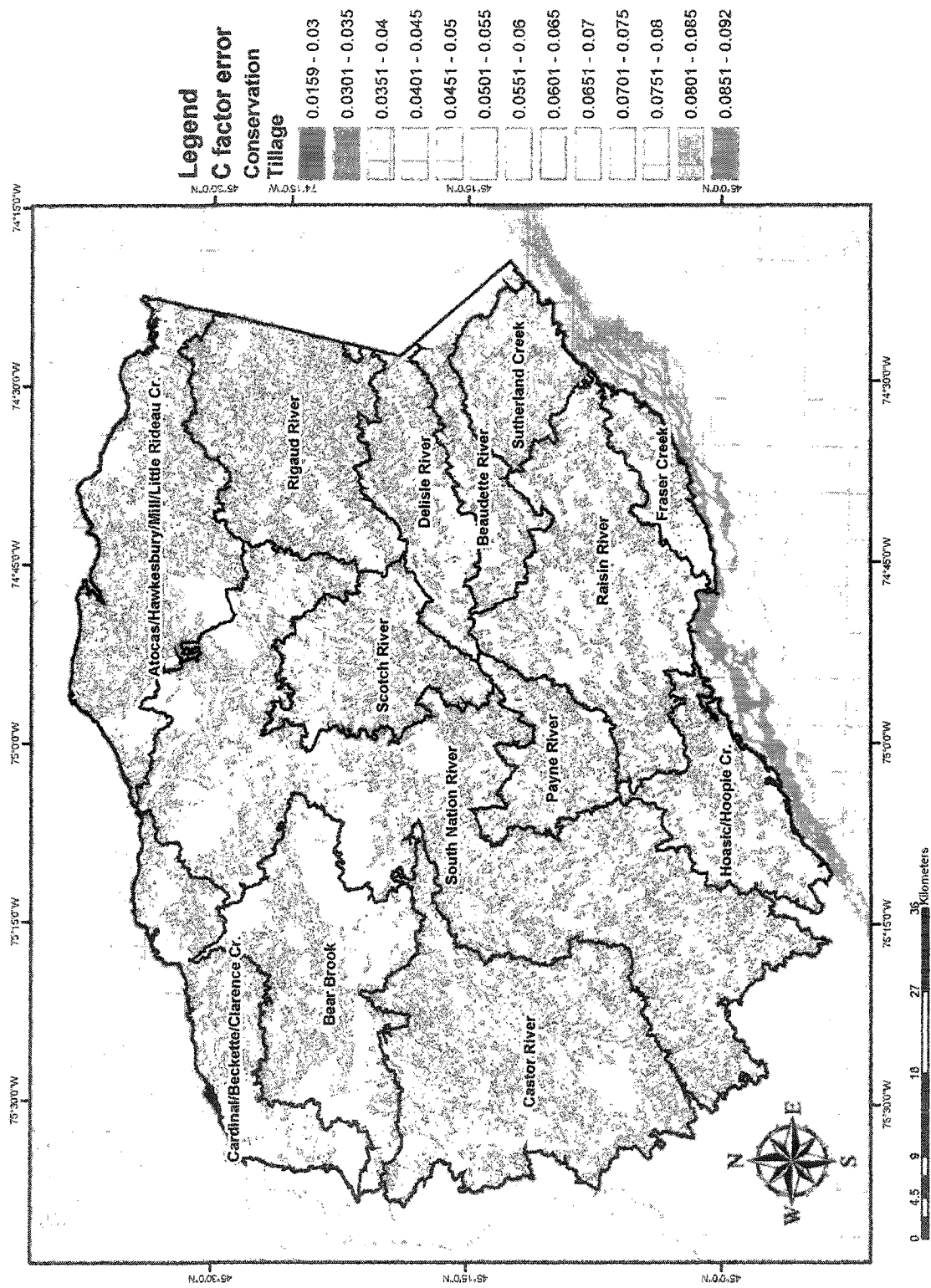


Fig. 42. The estimated standard error for the crop and management factor in eastern Ontario, summer 2001, under conventional tillage.

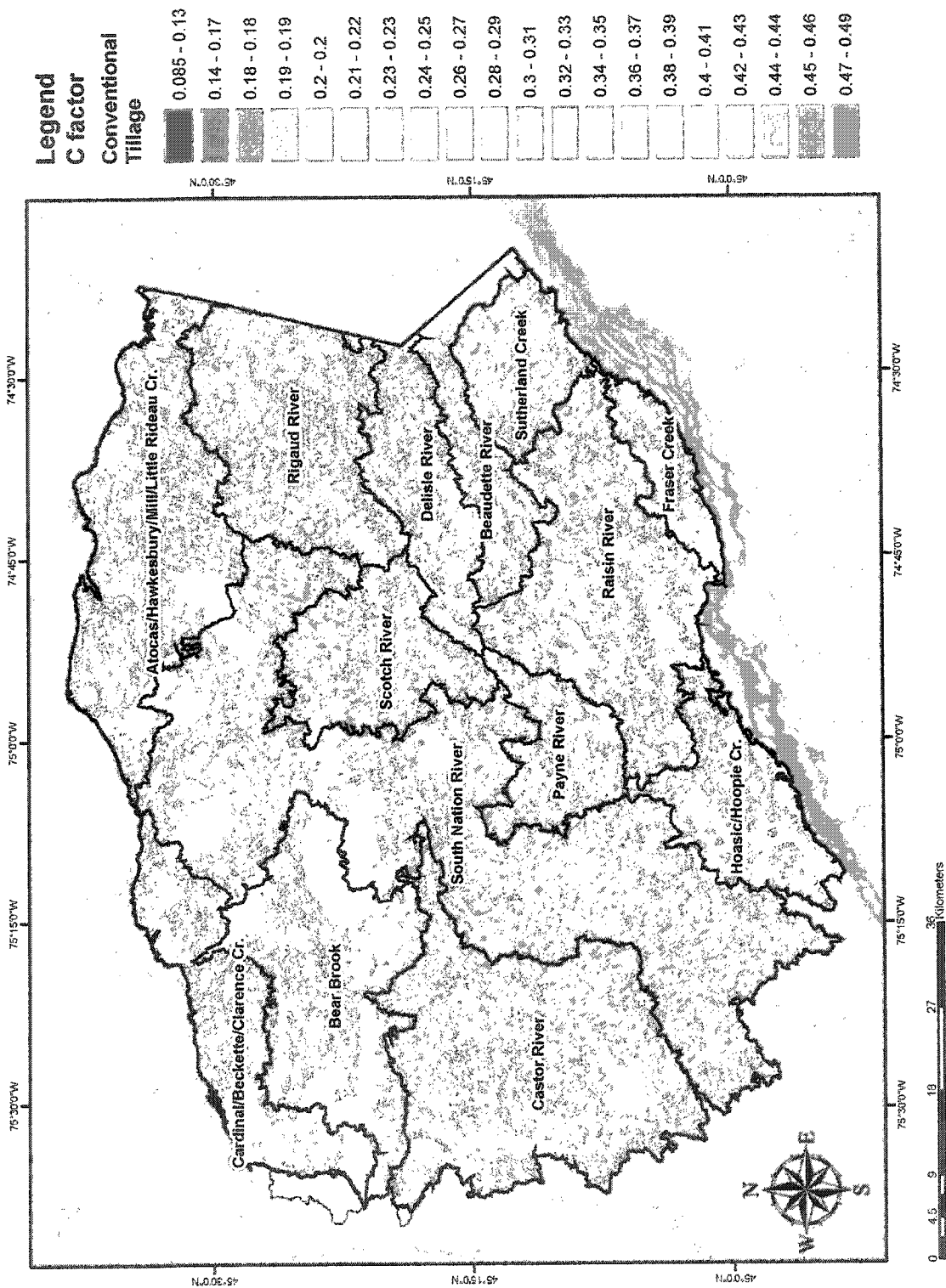


Fig. 43. The crop and management factor for eastern Ontario, summer 2001, under conservation tillage.

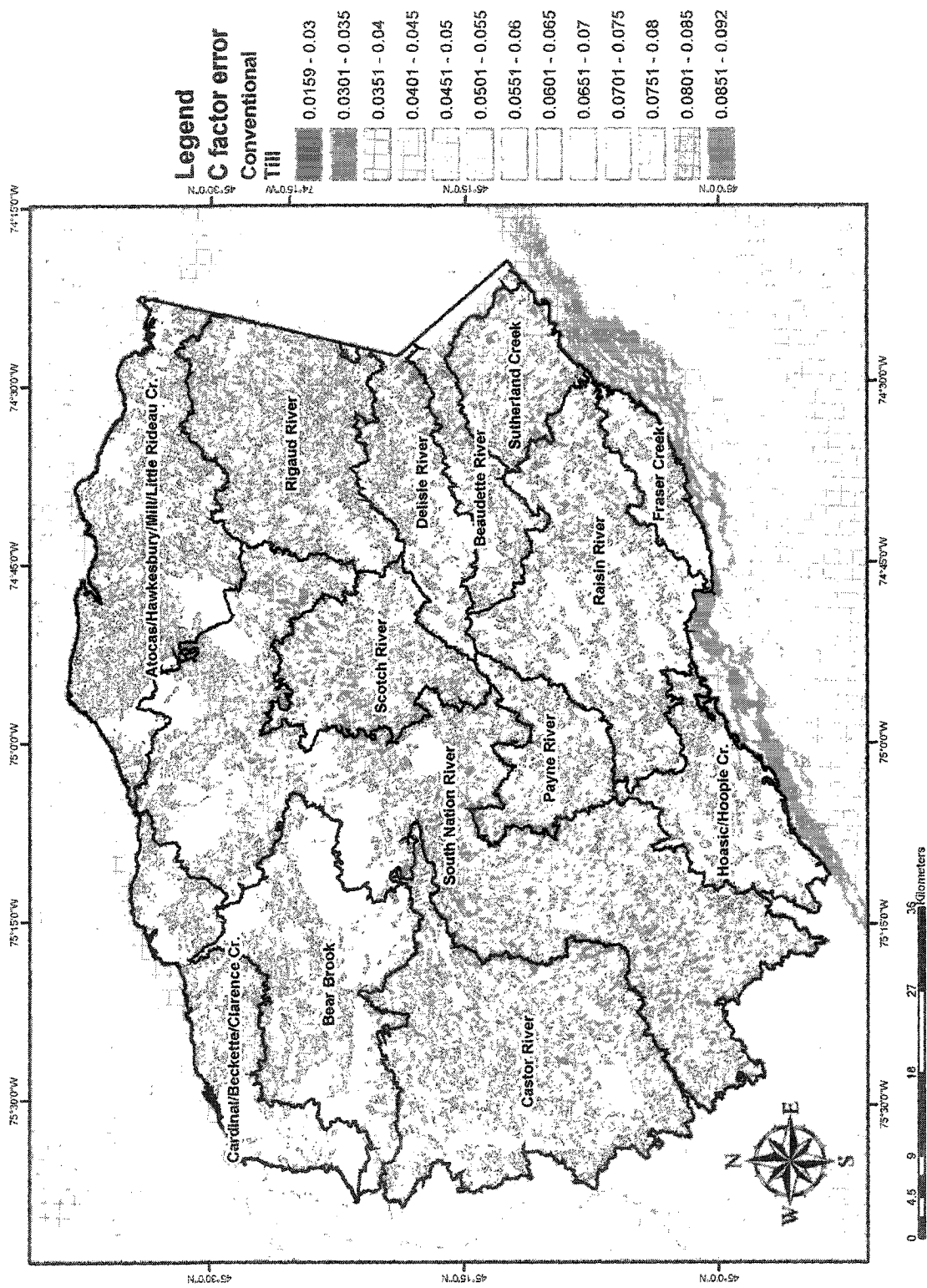


Fig. 44. The estimated standard error for the crop and management factor in eastern Ontario, summer 2001, under conservation tillage.

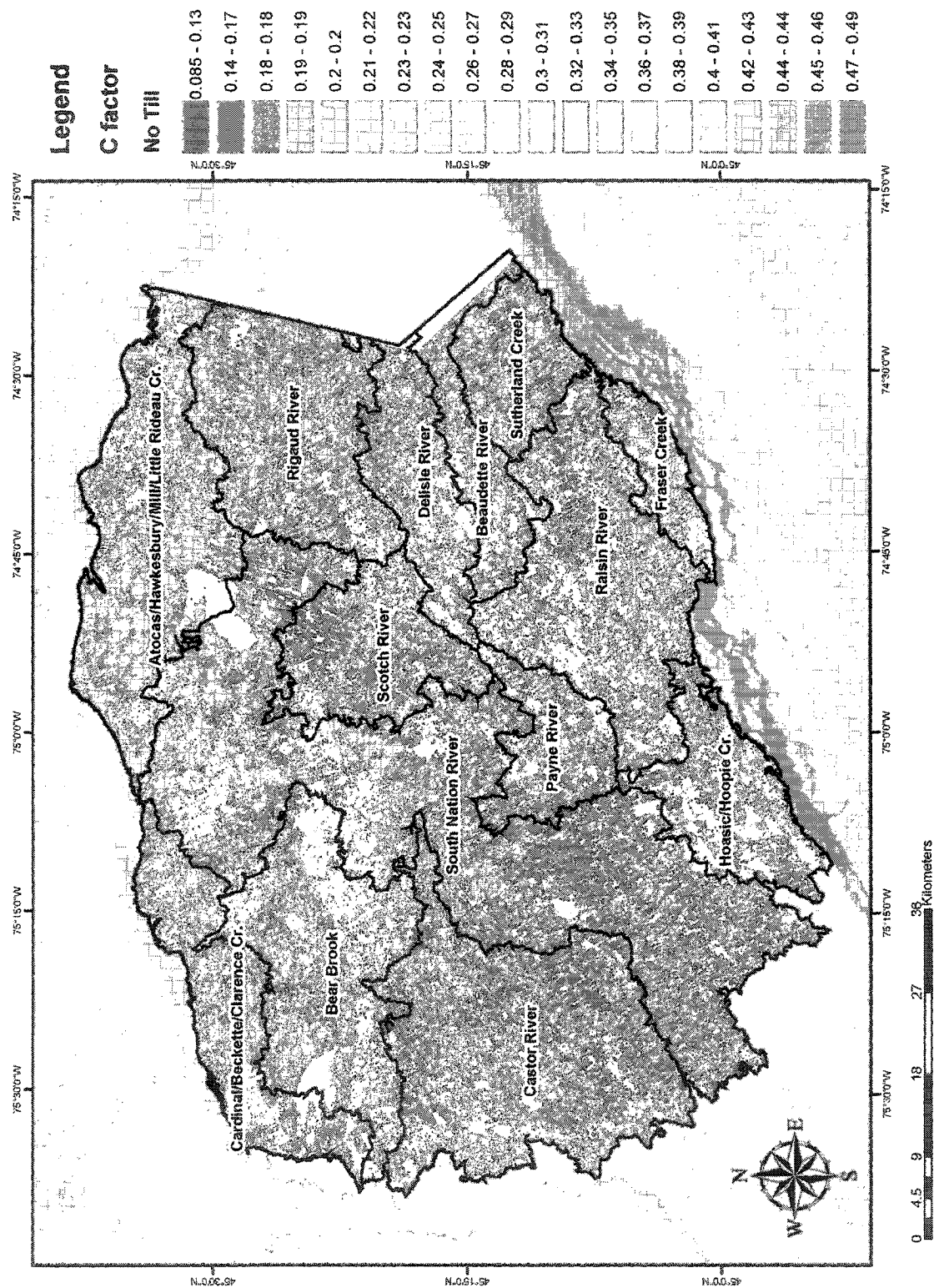


Fig. 45. The crop and management factor for eastern Ontario, summer 2001, under a no tillage farming system adoption.

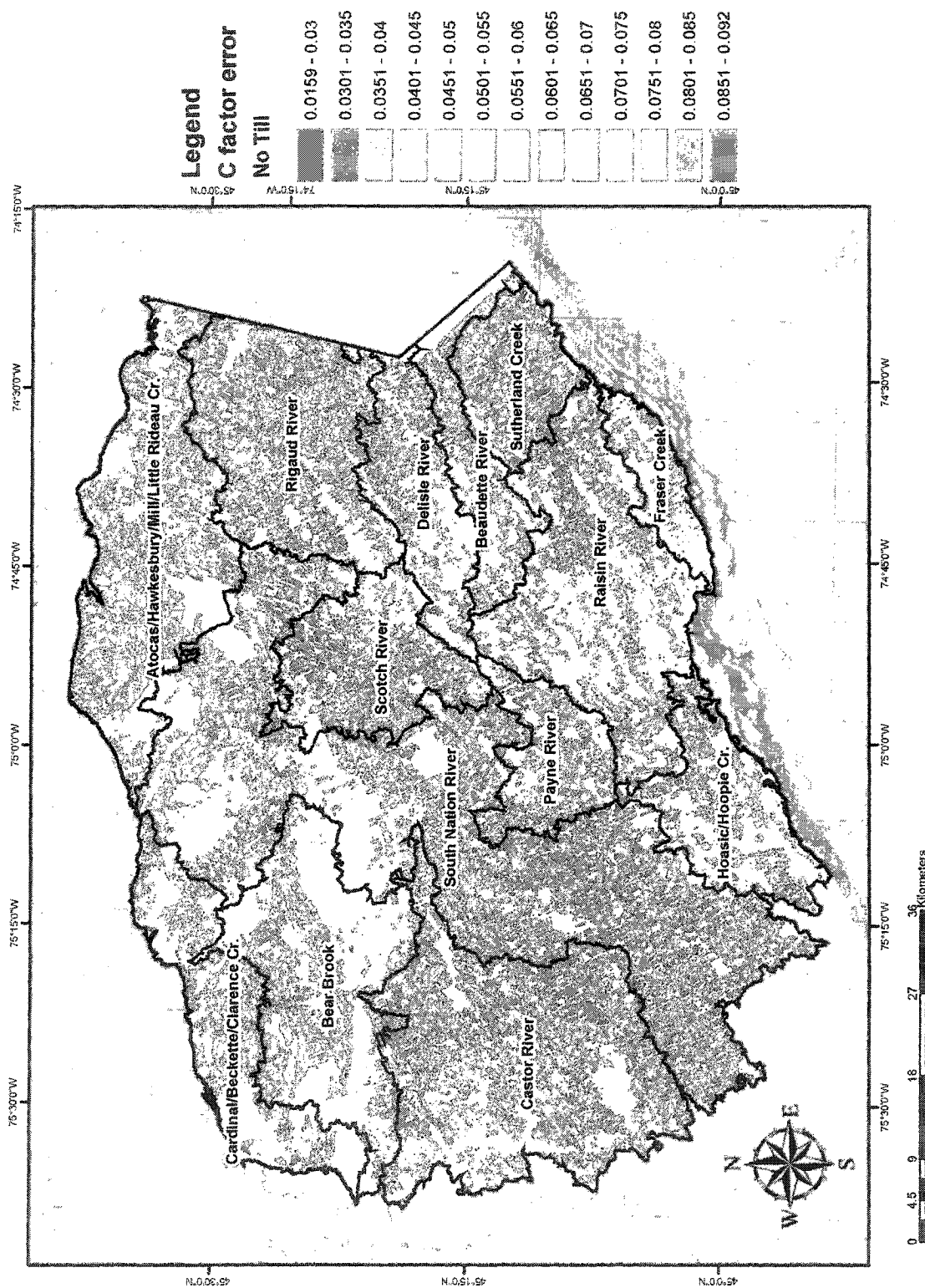


Fig. 46. The estimated standard error for the crop and management factor in eastern Ontario, summer 2001, under a till farming system adoption.

3.15 USPED Outputs

The unit stream power erosion deposition model (USPED) was applied based on the method described by Mitasova and Mitas (1999). See section 3.8 for explanation of the components and equations related to the USPED. The USPED in this analysis is not used to estimate the quantity of erosion over the landscape. The greatest benefit of the USPED is that it shows areas of net deposition and thus where erosion is not a problem.

The inputs for the USPED model include the elevation DEM used in the USLE2D analysis (Section 3.13), soil erodibility inputs (Section 3.12), and cropping and management inputs derived in Section 3.14. The results of the USPED identification are provided in Fig. 47, Fig. 48 and Fig. 49.

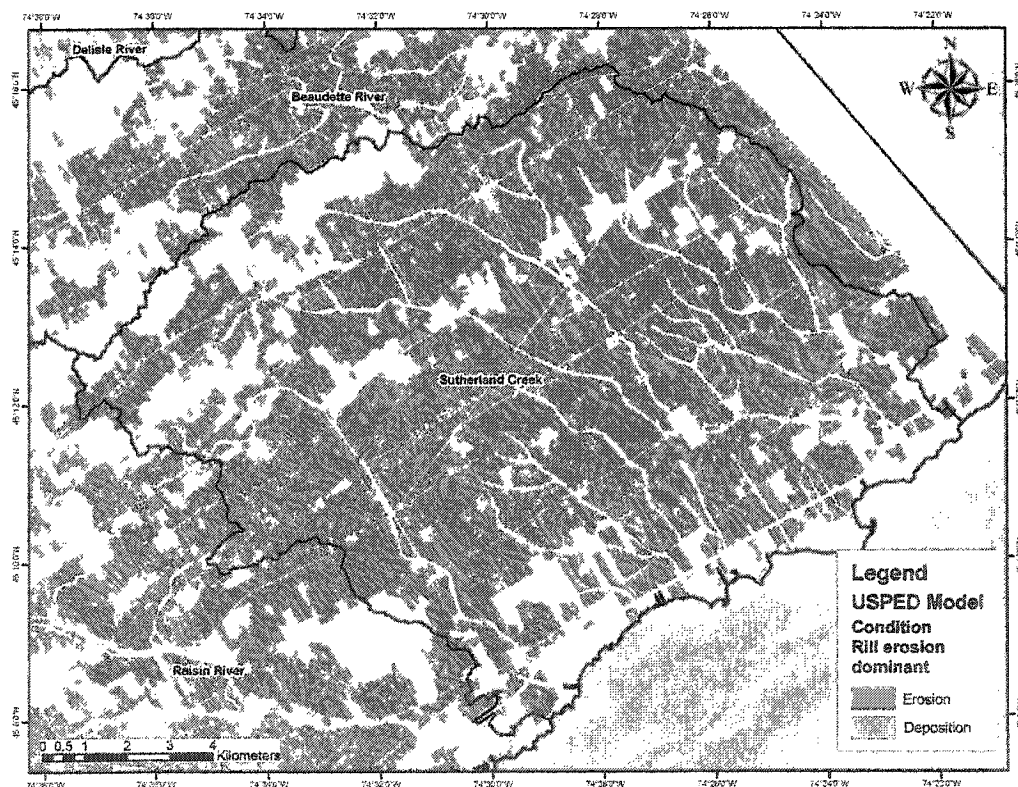


Fig. 47. Identification of deposition and erosion areas using the USPED model, Sutherland Creek (rill erosion dominant).

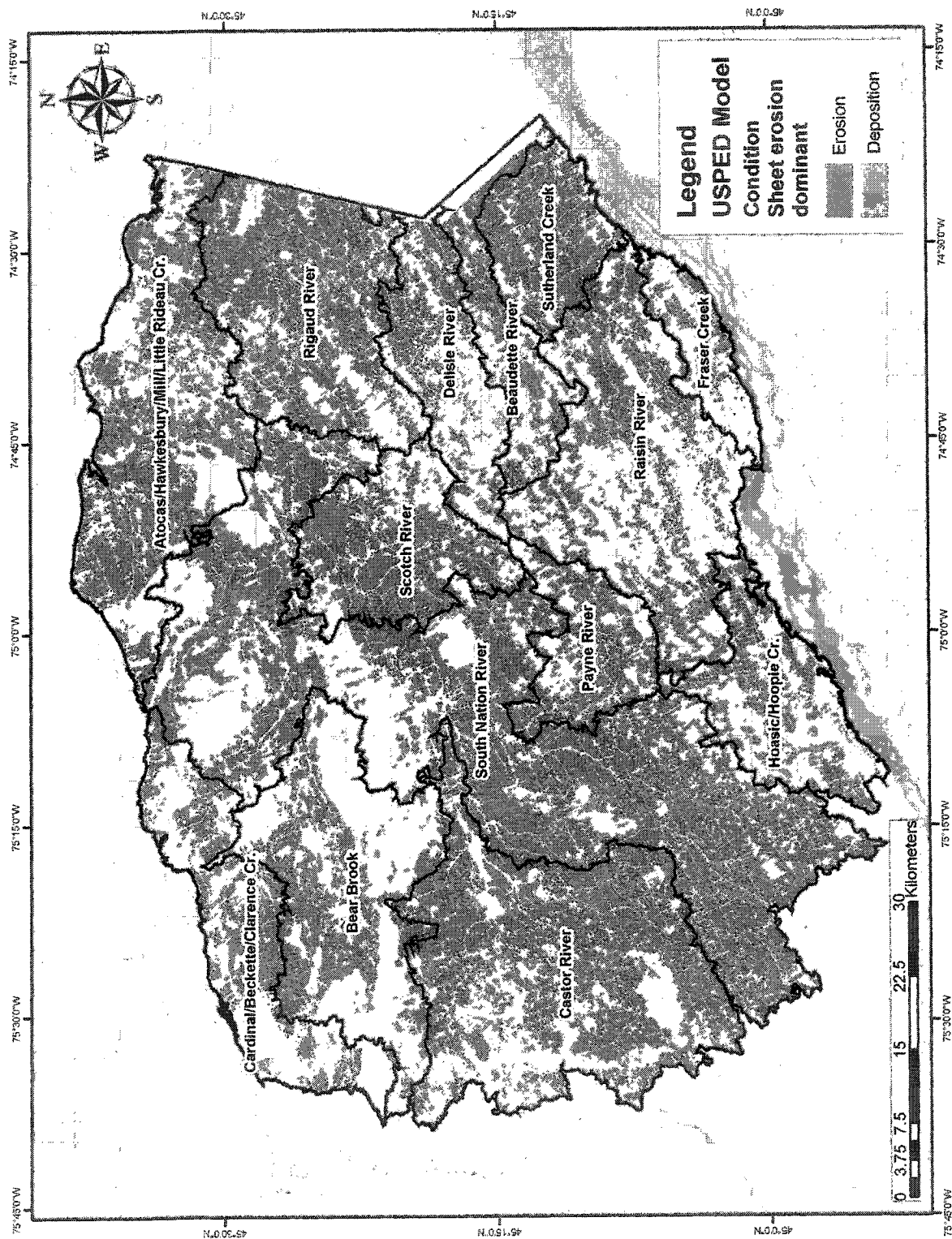


Fig. 48. Identification of deposition and erosion areas using the USPED model, eastern Ontario study region (sheet erosion dominant).

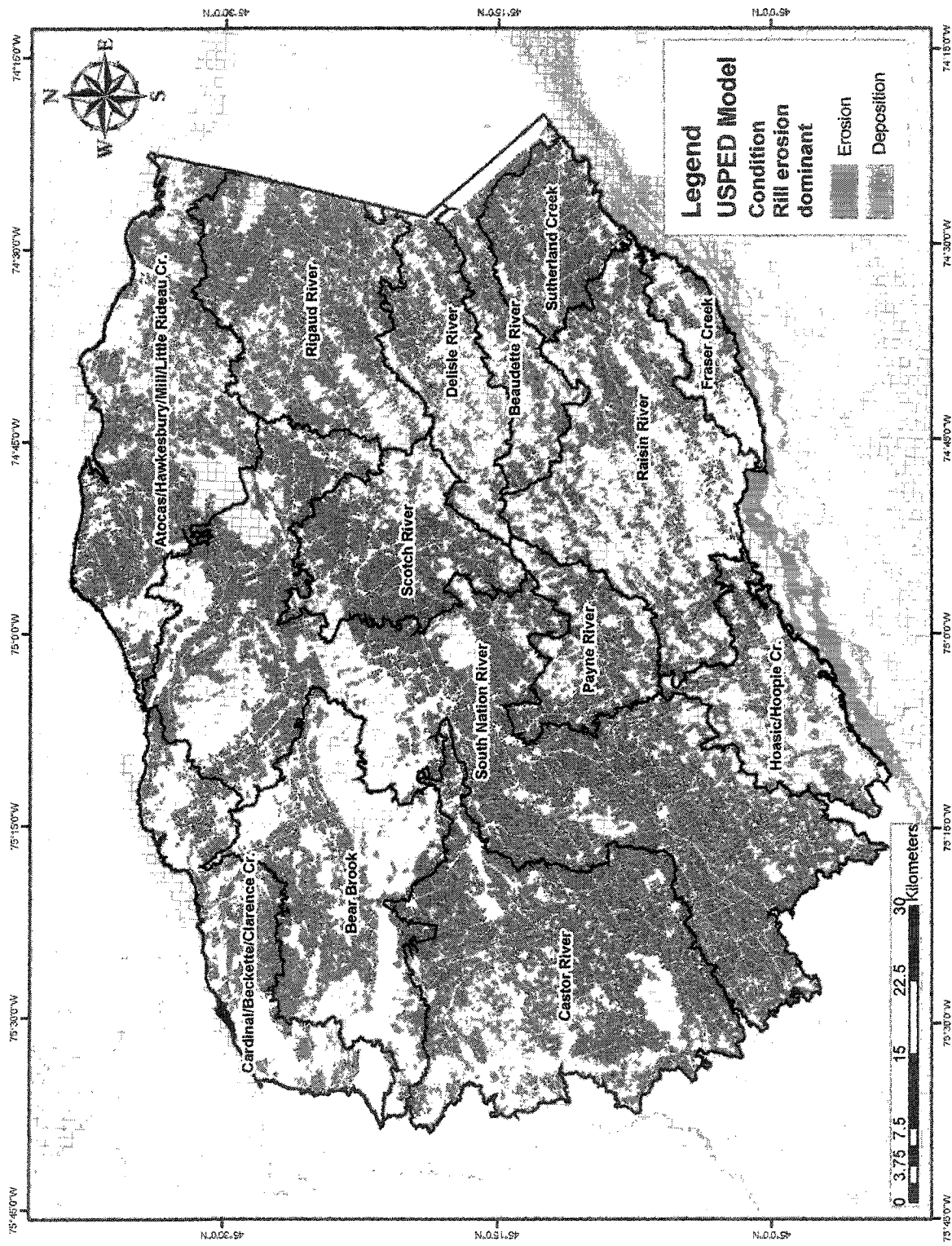


Fig. 49. Identification of deposition and erosion areas using the USPED model, eastern Ontario study region (rill erosion dominant).

3.16 Results

3.17 Summaries of Individual USLE Factors

Tabular data are provided for use in independent investigations of soil loss by farmers and conservationists and to more easily summarize the distribution of the universal soil loss equation factors over the landscape. Maps provide results of soil loss estimates at both micro and macro scales.

A breakdown of rainfall erosivity summarized by zone and the study region is provided (Table 12). The estimates are for the entire watershed region and were not summarized by agriculture field. Figure 50 demonstrates that the majority of mean annual erosivity histogram distributions summarized by watershed are skewed to the right. This shows that a better comparison statistic to use to compare overall erosivity between watersheds is the median in combination with the mean.

	<i>Minimum R.</i>	<i>Maximum R</i>	<i>Mean</i>		<i>Median</i>	<i>Standard Deviation</i>
			<i>Estimate</i>	<i>St. Error</i>		
<i>Study Area</i>	926.16	1158.30	1021.15	349.78	1015.00	49.98
<i>Atocas</i>	926.16	974.91	949.30	355.82	948.77	8.91
<i>Rigaud River</i>	937.5	1011.41	969.72	352.87	968.62	16.18
<i>Cardinal</i>	949.64	998.74	971.32	350.98	970.43	10.68
<i>South Nation River</i>	952.21	1151.34	1034.27	352.26	1033.95	50.31
<i>Bear Brook</i>	962.88	1028.12	966.53	350.66	996.28	11.13
<i>Sub Rigaud</i>	966.95	973.61	970.47	349.70	970.41	1.53
<i>Delisle River</i>	975.14	1037.72	1006.54	351.02	1005.71	15.01
<i>Beaudette River</i>	983.65	1047.80	1016.41	348.17	1018.94	18.26
<i>Scotch River</i>	984.70	1044.75	1009.38	354.47	1008.41	12.87
<i>Sutherland Creek</i>	992.34	1037.46	1013.17	346.86	1012.98	10.75
<i>Castor River</i>	996.73	1088.05	1043.67	345.40	1043.06	22.32
<i>Raisin River</i>	1028.26	1107.89	1066.73	342.65	1061.60	19.28
<i>Payne River</i>	1037.13	1083.79	1061.67	348.43	1066.23	10.17
<i>Fraser Creek</i>	1038.94	1110.85	1072.91	339.64	1073.64	16.26
<i>Hoasic/Hoopic Cr.</i>	1082.06	1158.30	1120.48	345.12	1119.11	15.85

Table 12. Mean annual erosivity summarized by study area and watershed with associated standard error ($\text{MJ mm ha}^{-1} \text{h}^{-1}$).

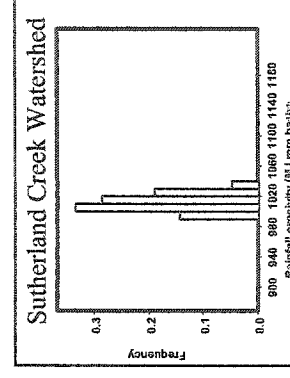
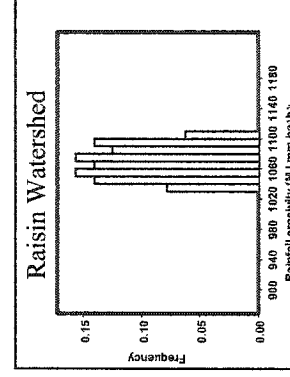
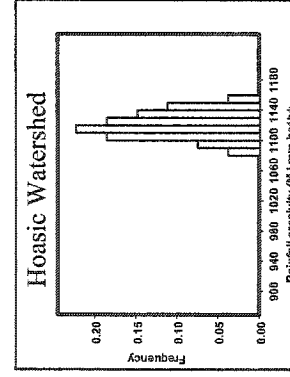
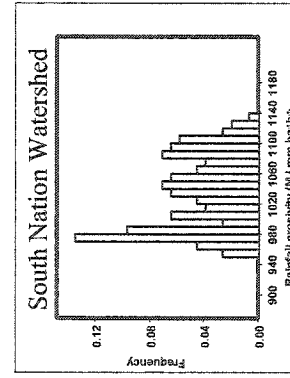
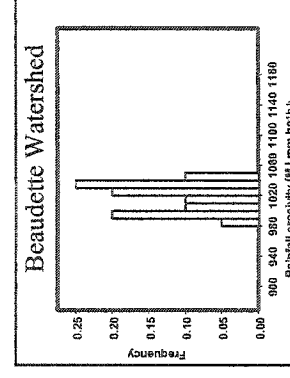
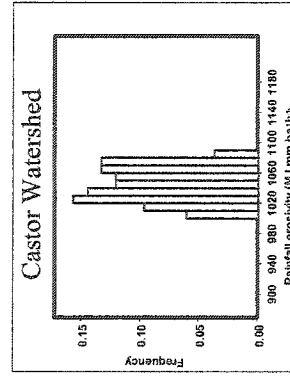
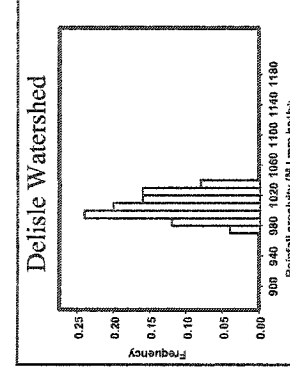
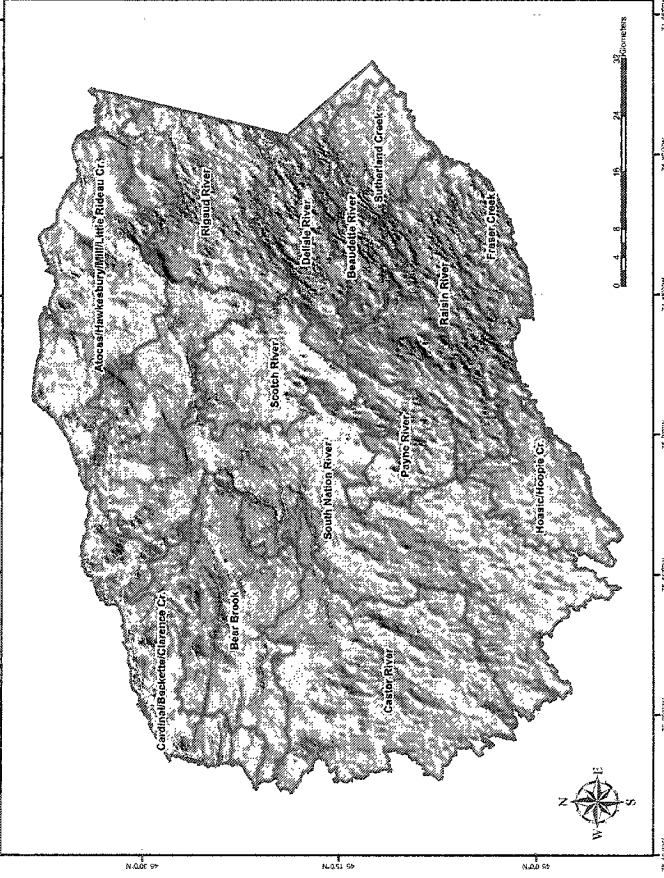
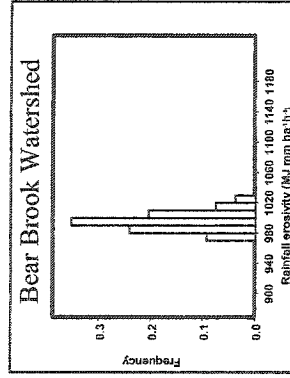
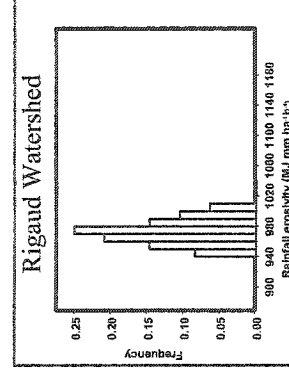
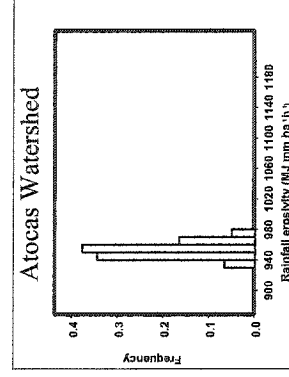
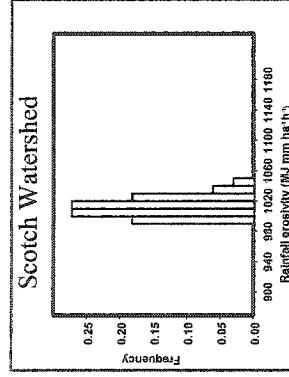
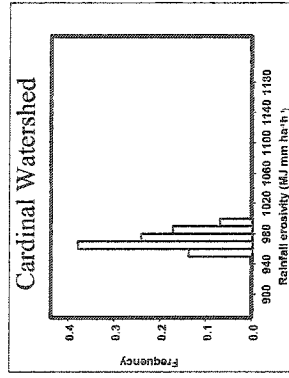


Fig. 50. Rainfall erosivity histograms for the study region, mean annual, units ($\text{MJ mm ha}^{-1} \text{h}^{-1}$).

Watersheds that experience less erosivity annually are the Atocas, Cardinal, Rigaud, and Bear Brook (Table 12, Fig. 50). The South Nation in the northern extent of the study region also experiences lower erosivity values. The Hoasic, Raisin, and Fraser Creek watersheds tend to have rainfall erosivity that is larger in comparison to neighbouring northern watersheds. The Atocas and Rigaud River watersheds have the lowest overall minimum erosivity while the Hoasic and Fraser Creek watersheds have the highest minimum erosivity value. These results indicate a decreasing erosivity trend occurring in a north-east direction. Table 12 also indicates that the watersheds to the north generally have less variation in their overall rainfall erosivity estimates in comparison to those further to the south.

Mean erosivity peaks in the months of August and September, while March and April tend to have the lowest overall rainfall erosivity (Table 13).

<i>Month</i>	<i>Min. R</i>	<i>Max. R</i>	<i>Mean R</i>	<i>Median R</i>	<i>St. Deviation</i>
<i>March</i>	66.41	100.08	79.34	78.30	7.89
<i>April</i>	93.00	128.73	107.59	106.75	8.28
<i>May</i>	121.71	144.80	132.13	131.81	5.30
<i>June</i>	141.65	152.64	145.52	144.96	2.40
<i>July</i>	141.17	161.67	149.66	149.21	4.34
<i>August</i>	153.31	178.63	163.54	163.00	6.20
<i>September</i>	141.46	173.07	154.38	153.54	7.54
<i>October</i>	124.91	154.57	138.54	138.08	6.39

Table 13. Rainfall erosivity index, March to October, eastern Ontario ($MJ\ mm\ ha^{-1}\ h^{-1}$).

Comparison of median and mean values in Table 13 indicates that the distribution of rainfall over the region is skewed right from March to June, while the distributions are more normal in late summer to early fall. Maximum values of erosivity are also found in August and September, while minimum values are found in the months of March and April. Variation in rainfall erosivity is at a minimum in June and July and at a maximum in March and April. These results suggest that rainfall erosivity is at a minimum in the spring period but also exhibits higher

variation in this period. Rainfall erosivity then increases into late spring-early summer and peaks in September. During the summer period rainfall erosivity is less variable. Variation in erosivity then increases into the fall months, where standard deviations are slightly less than that found in the spring.

Soil erodibility summarized by entire watershed and agricultural field area is provided in Table 14. Those watersheds that are modeled to have the highest soil erodibility on field are Fraser Creek, Raisin River, Sutherland Creek, Hoasic, and Beaudette River watersheds. Again, these are watersheds that are situated in the southeastern extent of the study region.

	<i>Min. K</i>		<i>Max. K</i>		<i>Mean K.</i>		<i>Median K</i>		<i>St. Dev. K</i>	
	Full extent	Field area	Full extent	Field area	Full extent	Field area	Full extent	Field area	Full extent	Field area
Study Area	0.0001	0.001	0.0641	0.0641	0.0317	0.0355	0.0305	0.0379	0.0171	0.0144
Atocas	0.0001	0.0001	0.0623	0.0623	0.0256	0.027	0.0269	0.0269	0.015	0.0123
Bear Brook	0.0001	0.0001	0.0623	0.0623	0.0236	0.0308	0.0221	0.0269	0.0151	0.0143
Delisle River	0.0001	0.0001	0.0623	0.0618	0.0294	0.0343	0.0269	0.0269	0.018	0.014
Rigaud River	0.0001	0.0001	0.0601	0.0601	0.0266	0.0276	0.0269	0.0269	0.0095	0.0073
Scotch River	0.0001	0.0001	0.0623	0.0623	0.0291	0.03	0.0269	0.0269	0.0123	0.0112
Sub Rigaud River	0.0001	0.0001	0.0454	0.0454	0.0261	0.0295	0.0269	0.0269	0.0114	0.0089
Cardinal	0.0001	0.0001	0.0641	0.0641	0.0291	0.0334	0.0315	0.0366	0.0152	0.0122
Castor River	0.0001	0.0001	0.0623	0.0623	0.0363	0.04	0.04	0.04	0.0161	0.0128
Payne River	0.0001	0.0001	0.0618	0.0618	0.0359	0.0391	0.04	0.04	0.018	0.0152
South Nation River	0.0001	0.0001	0.0623	0.0623	0.0318	0.0364	0.0315	0.04	0.017	0.0151
Sutherland Creek	0.0001	0.0001	0.0601	0.0601	0.0427	0.0428	0.04	0.04	0.0109	0.009
Beaudette River	0.0001	0.0001	0.0601	0.0601	0.0365	0.0417	0.04	0.0425	0.0206	0.017
Hoasic/Hoopie Cr.	0.0001	0.0001	0.0601	0.0601	0.0333	0.0396	0.0396	0.043	0.0179	0.0134
Raisin River	0.0001	0.0001	0.0623	0.0623	0.0371	0.0421	0.04	0.043	0.0209	0.0159
Fraser Creek	0.0001	0.0001	0.0618	0.0618	0.0413	0.0475	0.0454	0.0454	0.0203	0.0147

Table 14. The soil resistance to erosion (*K*) summarized by watershed and entire region as well as field region only. Units - $t h MJ^{-1} mm^{-1}$.

The Atocas, Rigaud River, Bear Brook, and Delisle watersheds tend to have the lowest soil erodibility across there region. These watersheds are situated in the northeast. There are deviations from these general trends, however, as the Hoasic, Raisin, Beaudette and Delisle Rivers tend to have lower soil erodibility values in the western sections at higher elevations. Overall, higher levels of soil erodibility tend to predominate in the southwest and southeast,

while lower soil erodibility is found more extensively in the north and in one general band running through the central southern section of the study area.

Additionally, erodibility values tend to be larger when summarized for field area only in comparison to erodibility for an entire watershed (Table 14). For the study area, mean K factor values are $0.0355 \text{ t h MJ}^{-1} \text{ mm}^{-1}$, whereas when summarized for the entire region mean values fall to $0.0317 \text{ t h MJ}^{-1} \text{ mm}^{-1}$. The median value for soil erodibility for the region is calculated at $0.0305 \text{ t h MJ}^{-1} \text{ mm}^{-1}$. This value rises to $0.0379 \text{ t h MJ}^{-1} \text{ mm}^{-1}$ when summarizing field area only.

Like the soil erodibility factor, there are some explicit trends that are displayed when examining the USLE2D slope length and steepness maps (Fig. 37 and 38). Areas to the east exhibit higher levels of erodibility. One exception to this generalization is the Sutherland Creek watershed, which has lower relief, and gentler, and lower LS factor values. To the North, past floodplain(s) that are assumed remnants of a previous course of the Ottawa River also have lower LS factor values. Finally, the mid to upper extent of the South Nation also has lower LS factor values than adjacent areas. At the field scale, higher values occur in the flatter areas of the South Nation, Castor, parts of the Bear Brook and Atocas watersheds as a result of longer slope lengths. Further, interspersed in these longer slope length areas are changes in relief which increase LS factor values due to elevated steepness (S factor). In the northeastern study region the higher LS factor values are due to greater changes in relief or the S factor, and are influenced to a lesser extent from slope length.

Table 15 lists the results of the slope length and steepness factor for two USLE2D scenarios (25% and 100% field boundary connectivity) with associated mean, median and standard deviation by watershed. General density distributions were examined for LS factors for

the entire region and for individual sheds only. One example of the density distribution of the LS factor for 25% field boundary connectivity, summarized on field areas in the study region is provided in Fig 51. Fig 52 provides the density distribution of the Beaudette watershed, which has higher relief. Fig 53 provides the histogram of the Hoasic watershed, which is relatively flat. Overall, the distributions were skewed to the right, indicating that the median in combination with the mean is a better comparative statistic for central tendency of LS factor values between watersheds than the median or mean alone. Further, the LS factor distributions look exponential in structure.

Examination of table 15 in combination with the LS factor histogram distributions indicates, under minimal transference of flow between field boundaries, that the slope length and steepness factor tends to be higher in the Beaudette, Delisle, Cardinal, Raisin River and Fraser Creek watersheds on field. The Beaudette, Raisin and Delisle watersheds are located in the southeastern portion of the study region, while the Cardinal and Fraser Creek watersheds are located along the boundaries with the Ottawa and St. Lawrence Rivers. Four of these five watersheds are located in the southeast of the study region. Overall, this area has higher relief in comparison to other areas in the region.

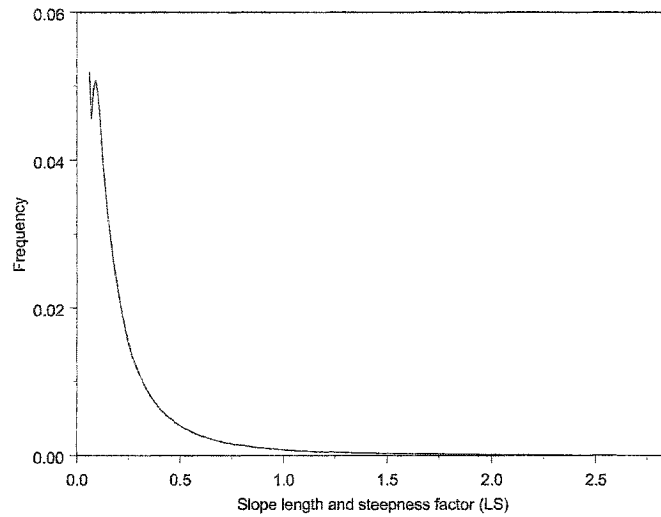


Fig. 51. Slope length and steepness density plot for the study region, 25% field boundary connectivity, summarized by field area only.

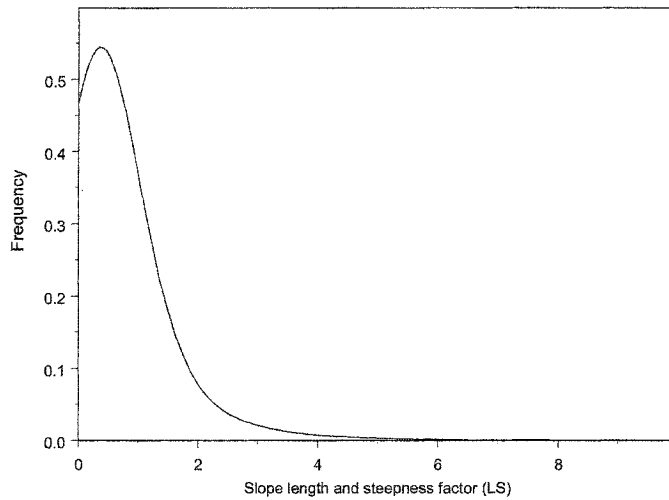


Fig. 52. Slope length and steepness density plot for the Beaudette watershed, 25% field boundary connectivity, summarized by field area only.

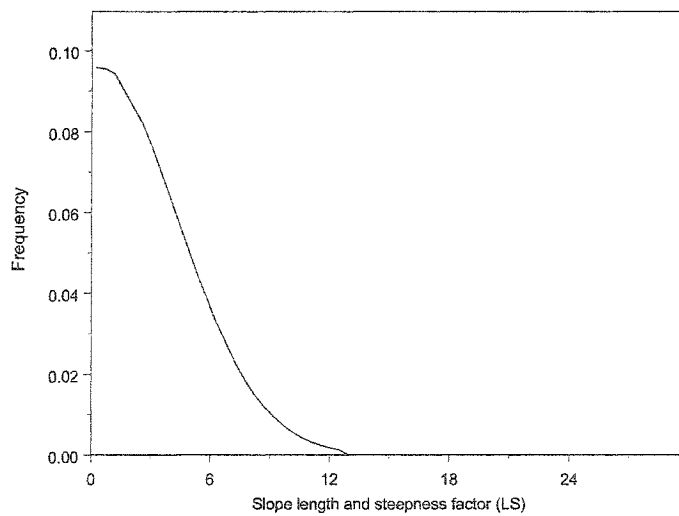


Fig. 53. Slope length and steepness density plot for the Hoasic watershed, 25% field boundary connectivity, summarized by field area only.

	<i>Entire watershed</i>						<i>Field regions</i>					
	<i>LS scenario 1</i>			<i>LS scenario 2</i>			<i>LS scenario 1</i>			<i>LS scenario 2</i>		
	<i>Mean</i>	<i>Median</i>	<i>St. D.</i>	<i>Mean</i>	<i>Median</i>	<i>St. D.</i>	<i>Mean</i>	<i>Median</i>	<i>St. D.</i>	<i>Mean</i>	<i>Median</i>	<i>St. D.</i>
Study Area	0.446	0.179	3.092	0.518	0.188	5.098	0.322	0.166	1.134	0.379	0.179	1.931
Hoasic/Hoopie Cr.	0.229	0.116	1.879	0.206	0.120	0.553	0.23	0.140	1.248	0.225	0.148	0.491
South Nation River	0.388	0.150	2.311	0.458	0.156	3.624	0.245	0.140	0.565	0.294	0.149	1.698
Castor River	0.307	0.150	2.371	0.337	0.158	2.521	0.258	0.143	1.32	0.269	0.151	0.809
Sutherland Creek	0.296	0.142	0.533	0.337	0.151	0.88	0.259	0.142	0.415	0.304	0.151	0.773
Atocas	0.486	0.182	2.146	0.552	0.194	2.945	0.315	0.149	0.985	0.379	0.159	1.723
Bear Brook	0.514	0.163	7.026	0.573	0.168	9.293	0.32	0.181	1.03	0.383	0.190	1.967
Payne River	0.336	0.198	1.814	0.357	0.213	1.335	0.337	0.210	1.699	0.361	0.223	1.234
Scotch River	0.492	0.171	4.073	0.523	0.183	6.777	0.366	0.156	2.735	0.341	0.166	1.468
Rigaud River	0.473	0.231	1.533	0.62	0.252	6.092	0.397	0.215	0.795	0.501	0.239	2.90
Raisin River	0.456	0.257	0.973	0.52	0.273	2.016	0.414	0.266	0.504	0.51	0.301	1.304
Sub Rigaud	0.669	0.300	0.892	0.691	0.300	0.898	0.42	0.206	0.399	0.507	0.238	0.484
Fraser Creek	0.462	0.200	0.791	0.494	0.213	0.887	0.463	0.199	0.62	0.535	0.225	0.779
Cardinal	0.965	0.253	5.702	1.222	0.269	12.608	0.471	0.208	1.626	0.615	0.235	4.298
Delisle River	0.515	0.282	0.725	0.61	0.306	1.525	0.508	0.311	0.573	0.645	0.366	1.064
Beaudette River	0.553	0.276	1.137	0.665	0.312	2.327	0.598	0.330	0.748	0.756	0.373	1.773

Table 15. Combined slope length and steepness factor of the USLE2D (LS) summarized by watershed for entire region and field area only. LS factor scenario 1 – 25% field connectivity. LS factor scenario 2 – 100% field connectivity.

When the LS factor is calculated with a greater influence from upslope contributing area or landscape effects, the Beaudette, Delisle, Cardinal, Raisin River and Fraser Creek watersheds continue to have the higher LS factor values on field. Further, the LS factor is higher on a watershed basis when one considers 100% transference of water flow between field locations when computing the LS factor using the USLE2D.

The refinement of analysis to field areas for the LS factor reveals that the LS factor is lower on these areas (Table 15). This comes as no surprise as farmers grow their crops on land segments that are less topographically complex, and prefer flatter land to sow and harvest their crops. If the traditional method of the USLE is applied with no refinement of the analysis to field areas it is expected that LS factors will tend to be inflated on a watershed by watershed basis. Additionally, these enlarged LS factor values will inflate estimates of soil loss.

From visual inspection of cropping and management factor maps (C factor), the C factor is higher in the central area of the study region running in a northeastern fashion, with a secondary high pocket of C factor values in the Sutherland Creek watershed. These high values tend to predominate with Gleysolic soils which are located here. As well, these areas show more Soybean crops that have higher C factor values than other crops. Hay and Alfalfa are sown in over larger areas on the Melanic Brunisolic soils of the northeast and the south-central study region. Under conventional tillage, these crops have lower C factor values.

3.18 Summaries of Soil Loss

Multiple scenarios were developed to model soil loss using the USLE, USLE2D, and USPED. The scenarios are listed in Table 16 with the parameters used to derive the soil loss estimates. Scenarios 1 through 6 were limited to erosion areas as defined by the USPED for sheet or rill dominant erosion. Standard errors are also provided for scenarios 1 through 6. Scenarios 1 through 6 model soil loss under conventional, conservation, and no till farming systems in combination with 25% and 100% parcel connectivity. Scenarios 7 through 14 model water erosion under traditional conventional tillage through the growing season under limited field connectivity. Outputs of scenario 7 through 14 are limited by erosion areas defined by the USPED model when sheet erosion dominants. Two limitations to the monthly estimates of scenarios 7 through 14 are that the C factor and the K factor have not been calibrated by month. However, the monthly estimates are generated to understand how rainfall variation through the growing season month's effects gross erosion over an agricultural field with soil erodibility and

<i>Scenario</i>	<i>R factor</i>	<i>K factor</i>	<i>LS factor Connectivity</i>	<i>C factor</i>
1	M.A.	M.A.	25%	Conv.
2	M.A.	M.A.	25%	Cons.
3	M.A.	M.A.	25%	No till
4	M.A.	M.A.	100%	Conv.
5	M.A.	M.A.	100%	Cons.
6	M.A.	M.A.	100%	No till
7	March	M.A.	25%	Conv.
8	April	M.A.	25%	Conv.
9	May	M.A.	25%	Conv.
10	June	M.A.	25%	Conv.
11	July	M.A.	25%	Conv.
12	August	M.A.	25%	Conv.
13	September	M.A.	25%	Conv.
14	October	M.A.	25%	Conv.

crop management parameters held constant.

The severity of erosion summarized by area is provided in Table 18 for scenarios 1 through 6 in Table 16. Note that 12 outputs are provided in Table 17, which correspond to the first six scenarios given in Table 16, with each

Table 16. Scenarios developed for the provision of soil loss estimates. M.A. – Mean Annual, Conv. – Conventional, Cons. – Conservation.

scenario of these six scenarios masked for either the domination of sheet or rill erosion.

Intolerable erosion is erosion that which occurs at a rate beyond $6 \text{ t ha}^{-1} \text{ yr}^{-1}$ (Wall et al., 2002). This corresponds to the class ‘low’ and all classes greater than this class given in Table 17 (Low to Severe). Each of these tolerance classes is generalized, but do provide a starting point for the examination of erosion within the study region.

<i>LS factor</i>	<i>C factor</i>	<i>USPED masking</i>	<i>Very low</i>	<i>Low</i>	<i>Moderate</i>	<i>High</i>	<i>Severe</i>	<i>>tolerable</i>
25%	Conventional	sheet erosion	1389	111	49	11	9	180
25%	Conservation	sheet erosion	1436	84	36	8	6	133
25%	No Till	sheet erosion	1471	62	26	5	4	98
25%	Conventional	rill erosion	1360	109	48	11	9	175
25%	Conservation	rill erosion	1405	82	35	7	6	130
25%	No Till	rill erosion	1439	61	26	5	4	96
100%	Conventional	sheet erosion	1354	127	61	15	13	215
100%	Conservation	sheet erosion	1405	98	45	11	9	163
100%	No Till	sheet erosion	1446	74	34	8	6	123
100%	Conventional	rill erosion	1325	124	59	14	13	209
100%	Conservation	rill erosion	1376	96	44	10	9	159
100%	No Till	rill erosion	1415	73	33	8	6	120

Table 17. Severity of area (km^2) field soil loss summarized by erosion class, Very low – less than $6 \text{ t ha}^{-1} \text{ yr}^{-1}$, Low $6\text{--}11 \text{ t ha}^{-1} \text{ yr}^{-1}$, Moderate – $11\text{--}22 \text{ t ha}^{-1} \text{ yr}^{-1}$, High – $22\text{--}33 \text{ t ha}^{-1} \text{ yr}^{-1}$, Extreme – greater than $33 \text{ t ha}^{-1} \text{ yr}^{-1}$.

One striking result of this summary is that erosion is occurring at intolerable levels under a variety of modeling parameters (Table 17). Under some liberal modeling conditions, with 100% field boundary connectivity, conventional farming, and the domination of sheet erosion, it is modeled that 215 km^2 of field area is experiencing intolerable rates of erosion. Under more conservative modeling conditions, with 25% field boundary connectivity, no till farming, and the domination of rill erosion, 96 km^2 of field area is experiencing intolerable erosion. This value is considerably lower than the previous modeling condition but there is still a significant amount of area experiencing intolerable erosion, especially when examining field area only.

When limiting our analysis to USPED erosion dominated by sheet processes with 25% connectivity of flow between field boundaries, or holding these factors constant, we can expect 82 km² less area providing intolerable levels of erosion when switching from conventional to no-till farming systems. When limiting our analysis to USPED erosion dominated by sheet processes with 25% connectivity of flow between field boundaries, the movement to no till from conventional tillage should result in 79 km² less area experiencing intolerable levels of erosion. Such minimal differences indicate that the masking by sheet or rill dominated erosion using the USPED makes little difference in the areal extent of erosion that is occurring in tolerance classes in the region.

When limiting our analysis to USPED areas of erosion under the dominance of sheet processes with 100% connectivity of flow between field boundaries, or holding these factors constant, we can expect 92 km² less area providing intolerable levels of erosion when switching from conventional to no till farming systems. Further, when limiting our analysis to USPED areas of erosion under the dominance of rill processes with 100% connectivity of flow between field boundaries, or holding these factors constant, we can expect 89 km² less area providing intolerable levels of erosion, when switching from conventional to no till farming systems. Overall, we could expect between 79 to 92 km² less area experiencing intolerable erosion under a total switch to no tillage farming.

In all scenarios, 7.8 to 11.5% of total field area is modeled to provide intolerable levels of erosion. This contradicts the work of Shelton *et al.* (2000) which mapped no intolerable levels of erosion within this study region in eastern Ontario under 1996 management practices (see Figure 54). Further, the results of this finer scale study contradict the results of Wall *et al.* (1995) which modeled soil loss in the Ontario region at a coarser resolution under 1991 management

conditions and found no intolerable levels of erosion in the eastern Ontario region (Figure 55). Additionally, the results of this analysis contradict that found by the Federal-Provincial Crop Insurance Program which indicates no high or severe levels of erosion in the eastern Ontario region (Federal-Provincial Crop Insurance Program, 1998). The results found in this work are viewed as more correct.



Fig. 54. USLE risk of water erosion on cropland in Central Canada (here zoomed to eastern Ontario) under 1996 management practices (Shelton et al., 2000).

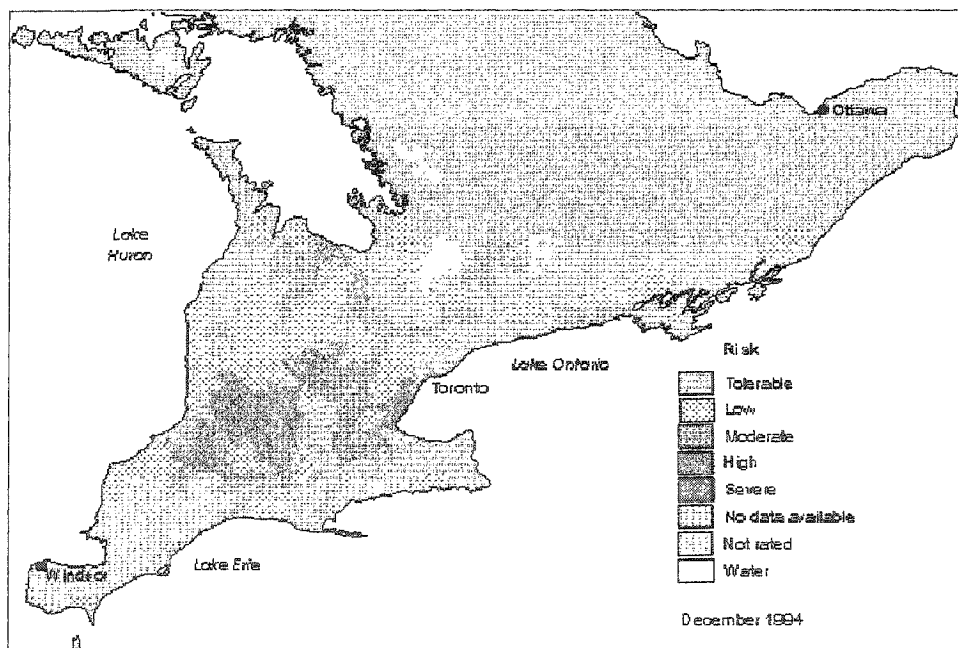


Fig. 55. USLE risk of water erosion in southern Ontario under 1991 management practices (Wall et al., 1995).

Results of erosion risk assessment in Fig. 20, Fig. 54 and Fig. 55 represent the current state of erosion modeling in Canada to date. Provided next are the extent and resolution of soil loss estimates made in this study. Given the minimal differences in extent and location of erosion when masking for sheet or rill dominated processes, maps of erosion under the masking for sheet erosion processes only are presented next for the region. Figures 56 to 65 provide estimates of soil loss under USPED sheet erosion dominated processes, with 25% and 100% field boundary connectivity, and conventional, conservation, and no tillage systems.

Comparing traditional estimates of soil loss (Fig. 20, Fig. 54 and Fig. 55) with the model results in this study indicate that this study provides a major improvement in the precision and accuracy of soil erosion modeling. This study presents model outputs at significantly higher resolutions, ensuring significantly higher amounts of information about the distribution of erosion over large regions such as eastern Ontario. Figures 56 to 61 point out that the spatial patterns of erosion varies little under the various scenarios undertaken that alter inputs of boundary connectivity or types of tillage practices for the assessment of erosion risk. Due to the problem of scale it is difficult to identify those areas that experience higher levels of erosion over the entire region with these diagrams. Thus, figures 62 to 65 are provided to demonstrate the spatial distribution of erosion that is occurring at intolerable levels in some of the most problematic watersheds, like the Beaudette (Fig. 62), Fraser Creek (Fig. 63), Delisle (Fig. 64) and Raisin River (Fig. 65). Under all scenarios, the central portion of the Beaudette and Delisle, the eastern portion of the Raisin, the central portion of the Payne River watershed and the western portion of the Sutherland Creek watershed are modeled to be experiencing intolerable levels of erosion to a greater extent than elsewhere.

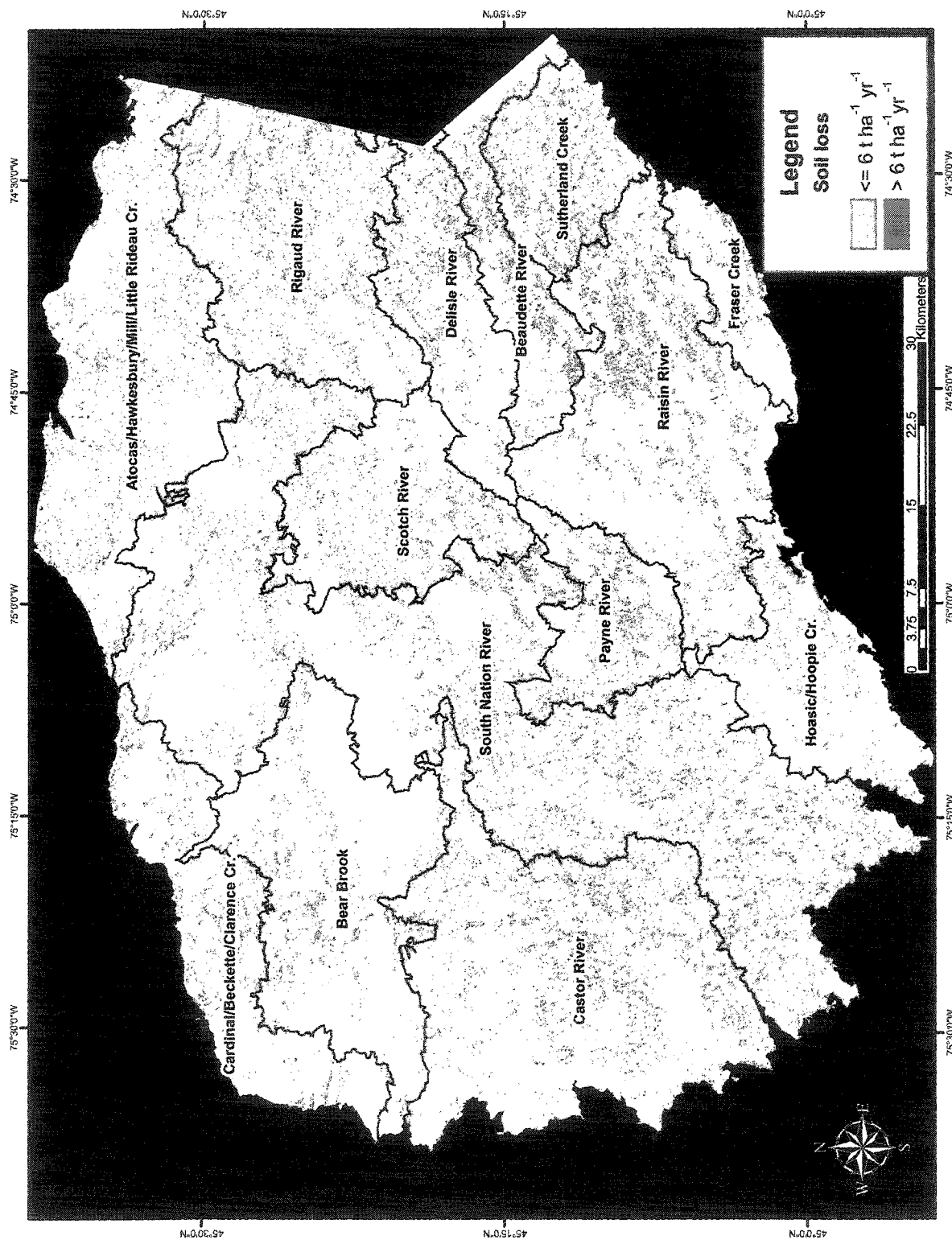


Fig. 56. Risk of water erosion in eastern Ontario calculated using the USLE, USLE2D, and USPED. Model inputs are LS factor connectivity 25%, conventional tillage farming systems with USPED analysis on areas dominated by sheet erosion.

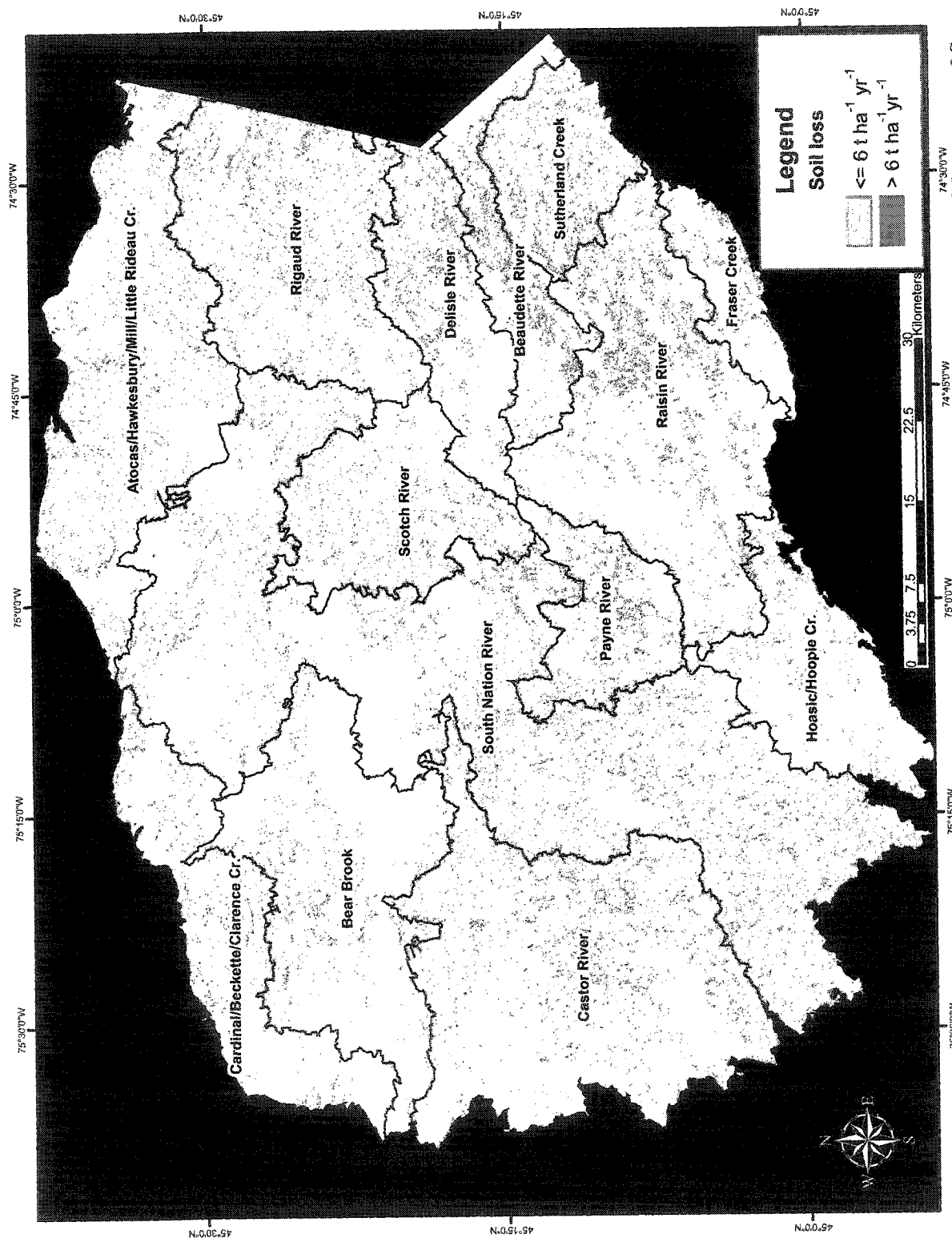


Fig. 57. Risk of water erosion in eastern Ontario calculated using the USLE, USLE2D, and USPED. Model inputs are LS factor connectivity 25%, conservation tillage farming systems USPED analysis on areas dominated by sheet erosion.

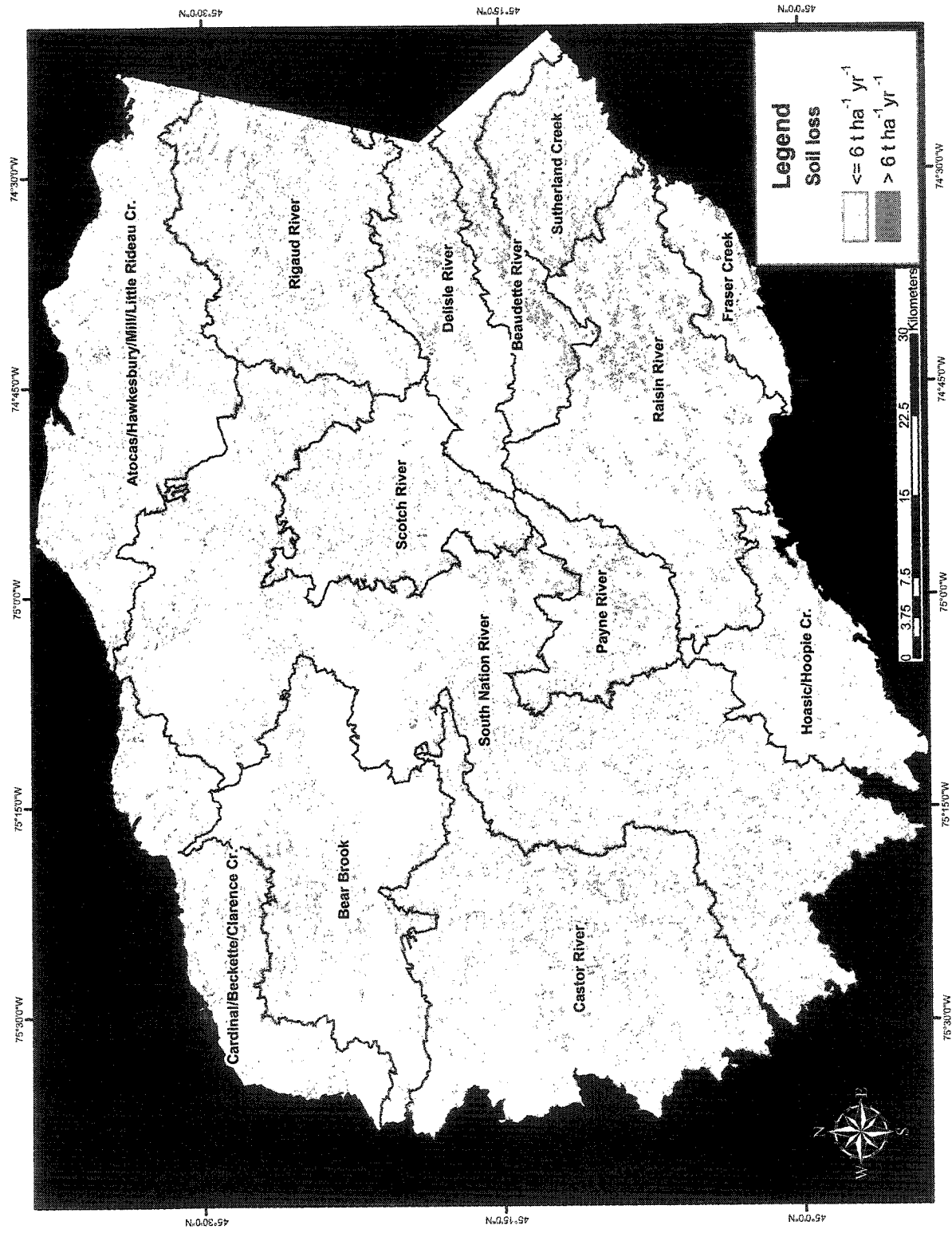


Fig. 58. Risk of water erosion in eastern Ontario calculated using the USLE, USLE2D, and USPED. Model inputs are LS factor connectivity 25%, no tillage farming systems USPED analysis on areas dominated by sheet erosion.

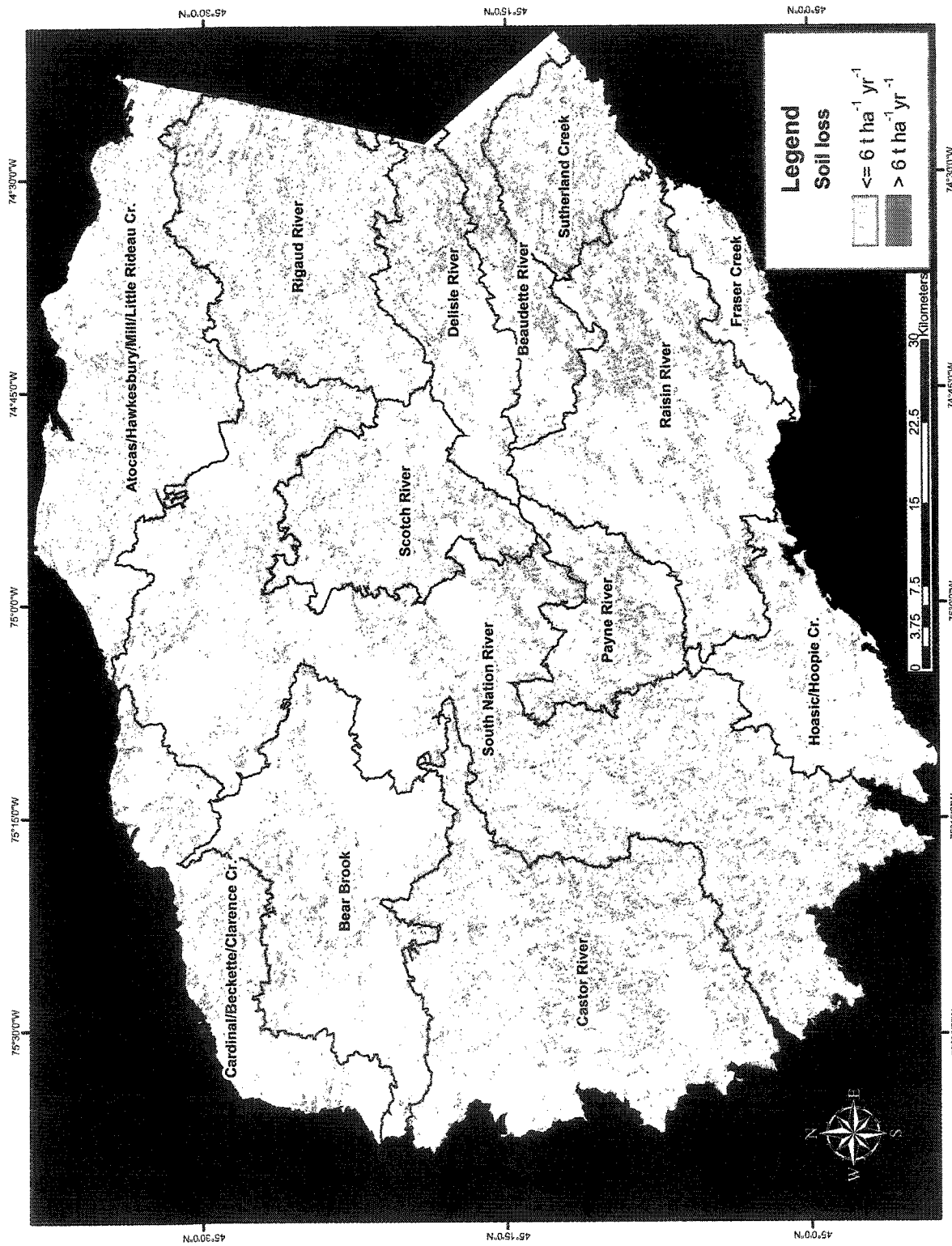


Fig. 59. Risk of water erosion in eastern Ontario calculated using the USLE, USLE2D, and USPED. Model inputs are LS factor connectivity 100%, conventional tillage farming systems USPED analysis on areas dominated by sheet erosion.

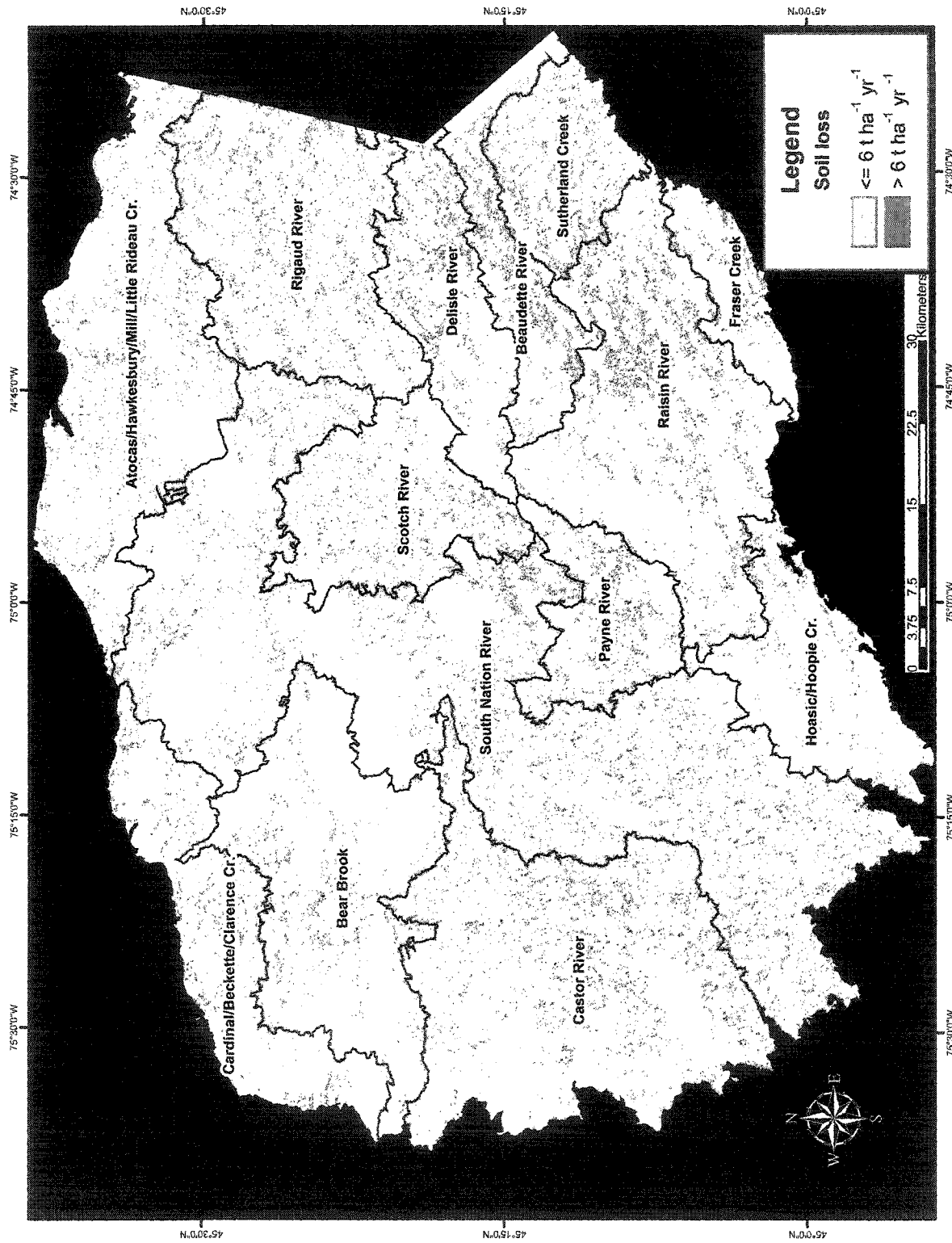


Fig. 60. Risk of water erosion in eastern Ontario calculated using the USLE, USLE2D, and USPED. Model inputs are LS factor connectivity 100%, conservation tillage farming systems USPED analysis on areas dominated by sheet erosion.

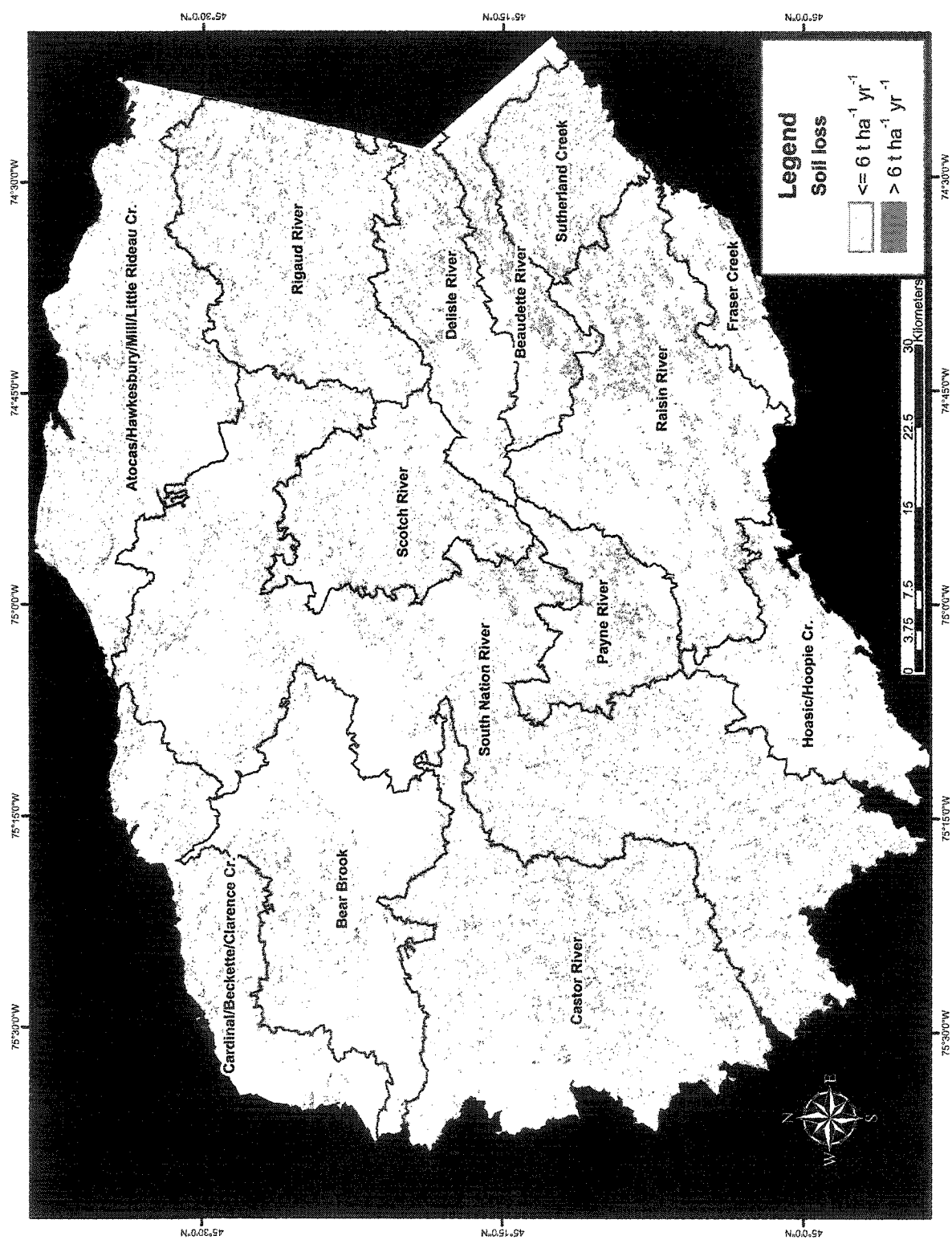


Fig. 61. Risk of water erosion in eastern Ontario calculated using the USLE, USLE2D, and USPED. Model inputs are LS factor connectivity 100%, no tillage farming systems USPED analysis on areas dominated by sheet erosion.

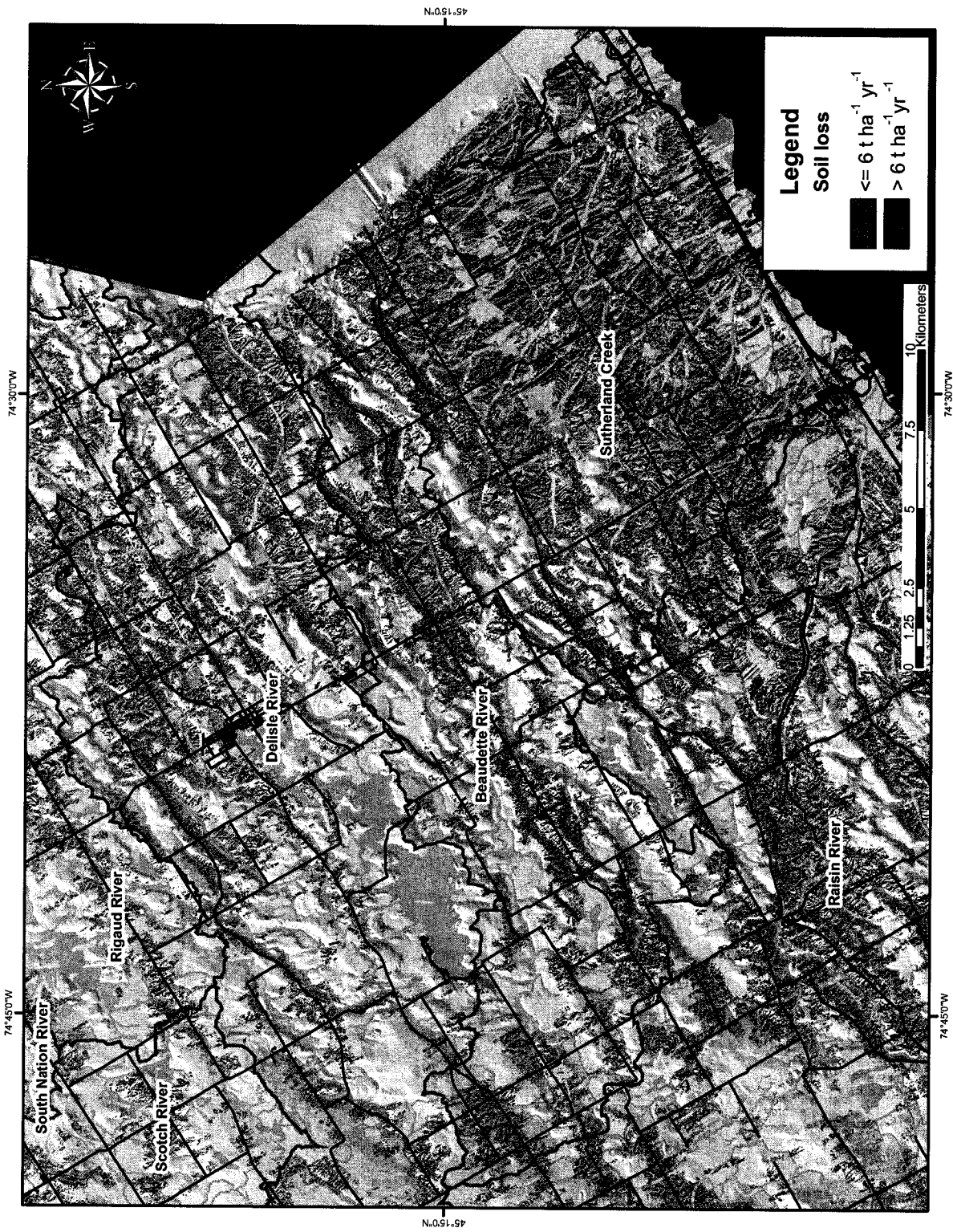


Fig. 62. Risk of water erosion in Beaudette River watershed calculated using the USLE, USLE2D, and USPED. Model inputs are LS factor connectivity 25%, under conventional tillage farming systems USPED analysis on areas dominated by sheet erosion.

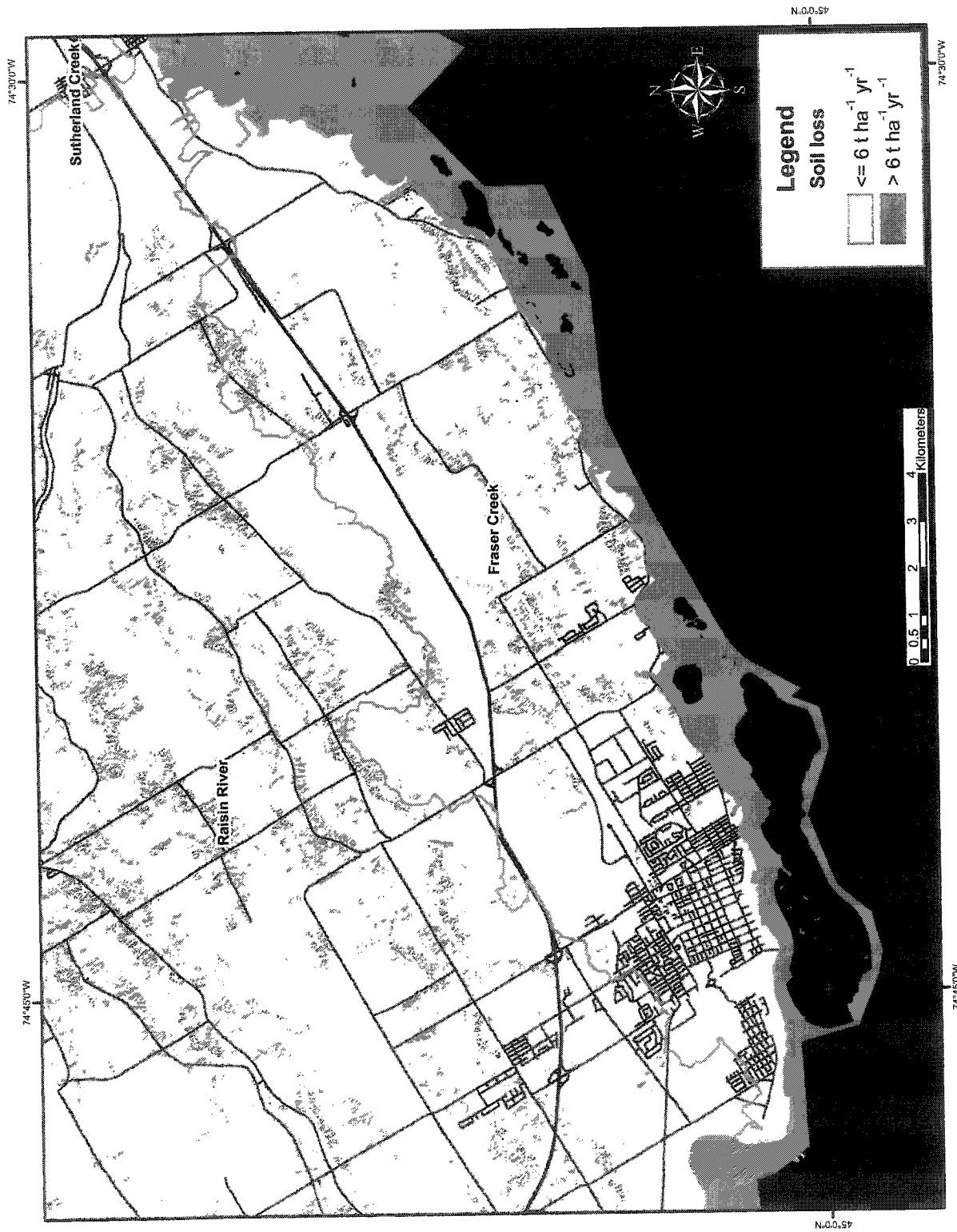


Fig. 63. Risk of water erosion in Fraser Creek watershed calculated using the USLE, USLE2D, and USPED. Model inputs are LS factor connectivity 25%, under conventional tillage farming systems USPED analysis on areas dominated by sheet erosion.

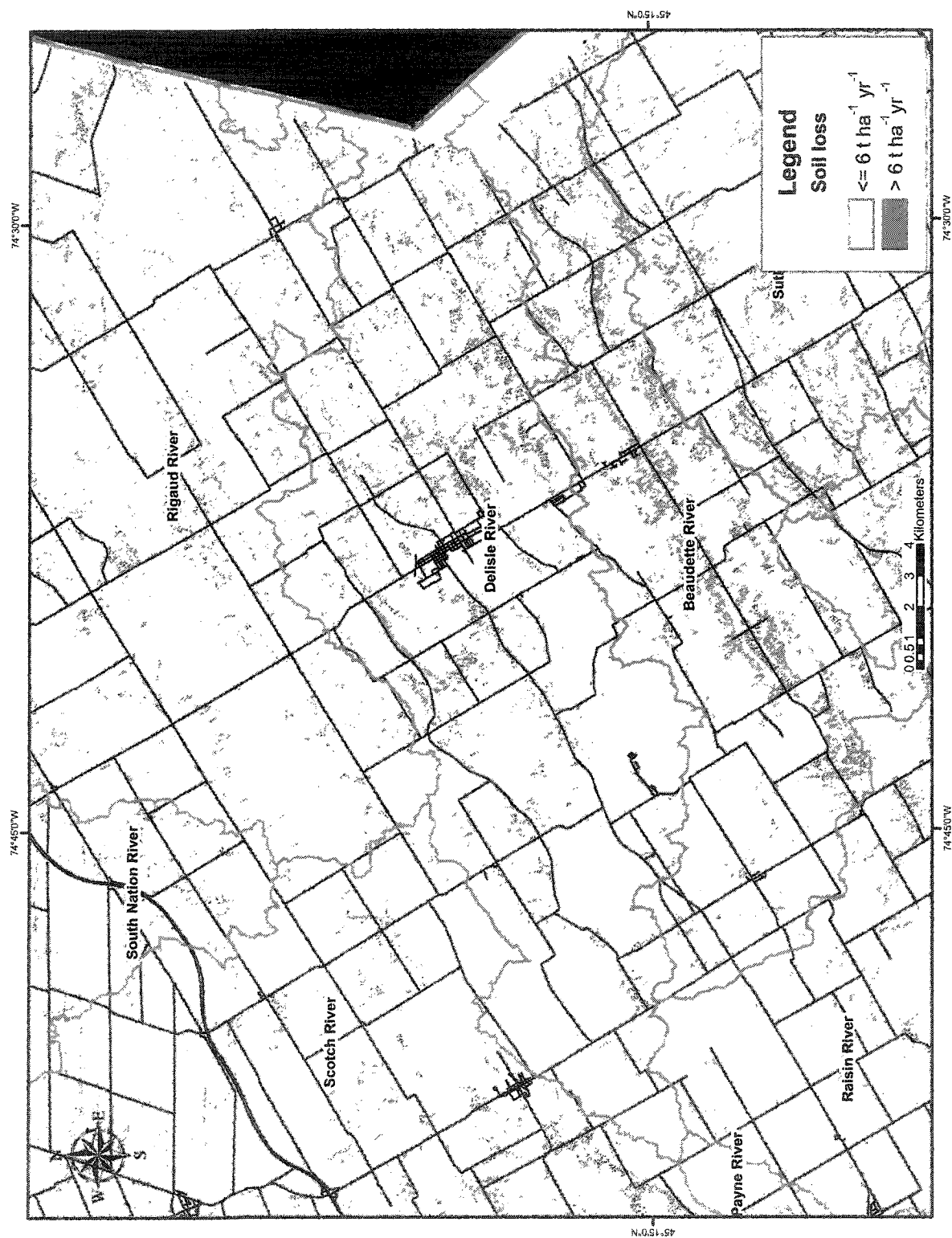


Fig. 64. Risk of water erosion in Delisle River watershed calculated using the USLE, USLE2D, and USPED. Model inputs are LS factor connectivity 25%, under conventional tillage farming systems USPED analysis on areas dominated by sheet erosion.

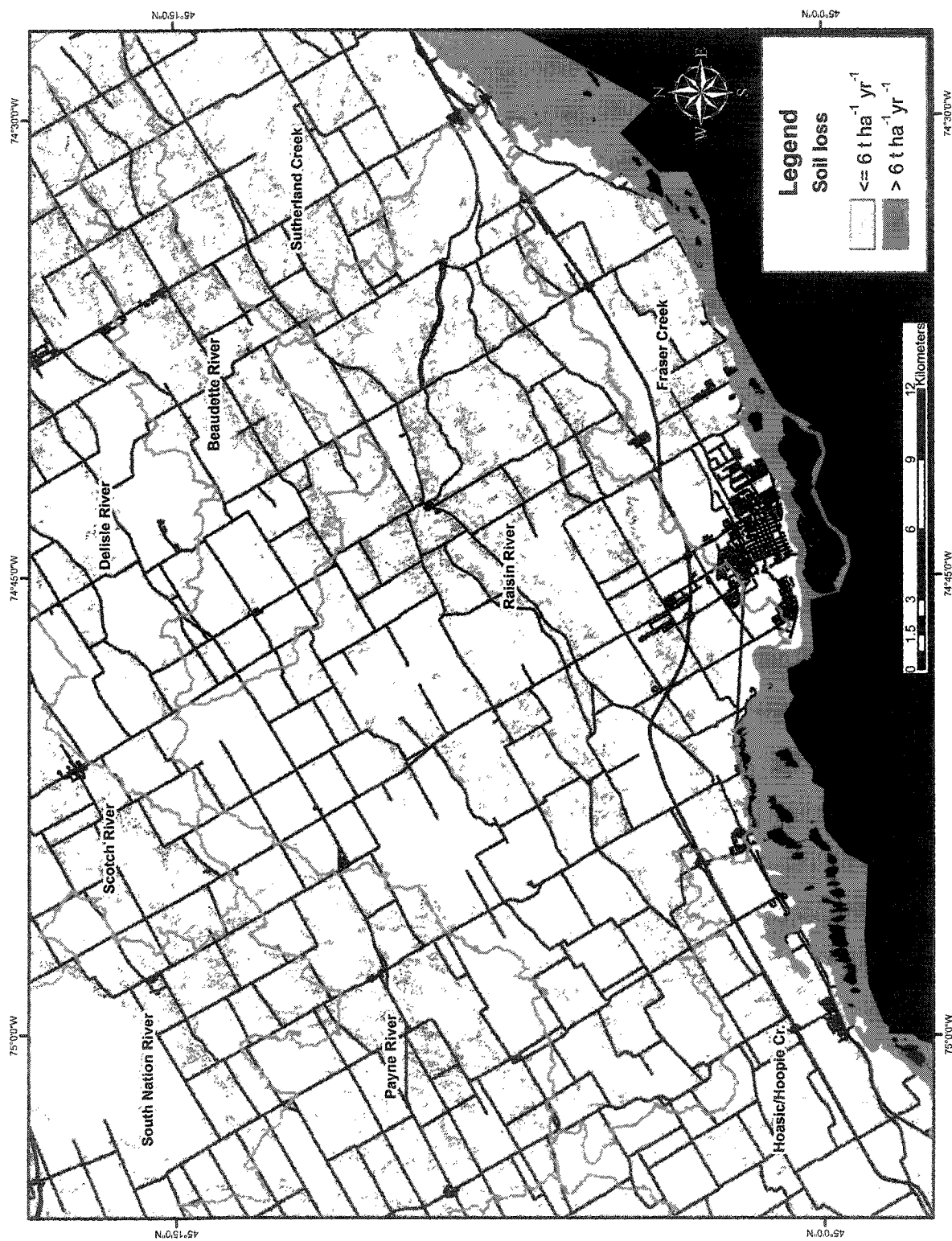


Fig. 65. Risk of water erosion in Raisin River watershed calculated using the USLE, USLE2D, and USPED. Model inputs are LS factor connectivity 25%, under conventional tillage farming systems USPED analysis on areas dominated by sheet erosion.

The regional maps of soil loss suggest that soil loss is at a maximum along the Beaudette, Sutherland and Raisin River watershed junctions where soil loss is modeled at intolerable levels. Such results indicate that the southeastern portion of the study region is a sector that must be examined to judge whether estimates are in line with actual levels of erosion in the region.

To better illustrate the distribution of soil erosion over those watersheds that are most at risk to erosion, Fig. 66 through 68 are given in perspective. These figures provide spatial estimates zoomed to the extent of the Beaudette, the Fraser Creek, and the Raisin River watersheds. Fig. 66 indicates that Beaudette River intolerable levels of erosion ($>6.0 \text{ t ha}^{-1} \text{ yr}^{-1}$) have a banding configuration that is consistent with areas of high slope along ridges. This indicates that the S factor may be a defining factor that separates low and high classes of soil loss from the extreme classification range. This trend is also observable in the Fraser Creek watershed (Fig. 67). Soil losses are expanded along the hillslopes that run in a northeast direction in this region. Concentrations of intolerable levels of erosion off of field do not occur on flat topography.

Examination and classification of soil loss is acceptable for the assessment of soil loss risk at the field scale, however, it is also beneficial to know the overall quantities of soil loss being removed from field over the study region annually. For example, this information can be used for sediment yield modeling and nutrient modeling. We can further assess the contributing soil loss by tolerance class to better understand the impact that the quantity of soil loss may have on the surrounding environment. Table 18 presents the total soil loss off of field in the region and associated standardized error for the estimate given by erosion tolerance levels. Notice that total soil loss error for each scenario is generally 42% of the total sum of expected soil loss. These

errors are high. Estimates and associated errors for the estimates are given by the characteristics of the model applied.

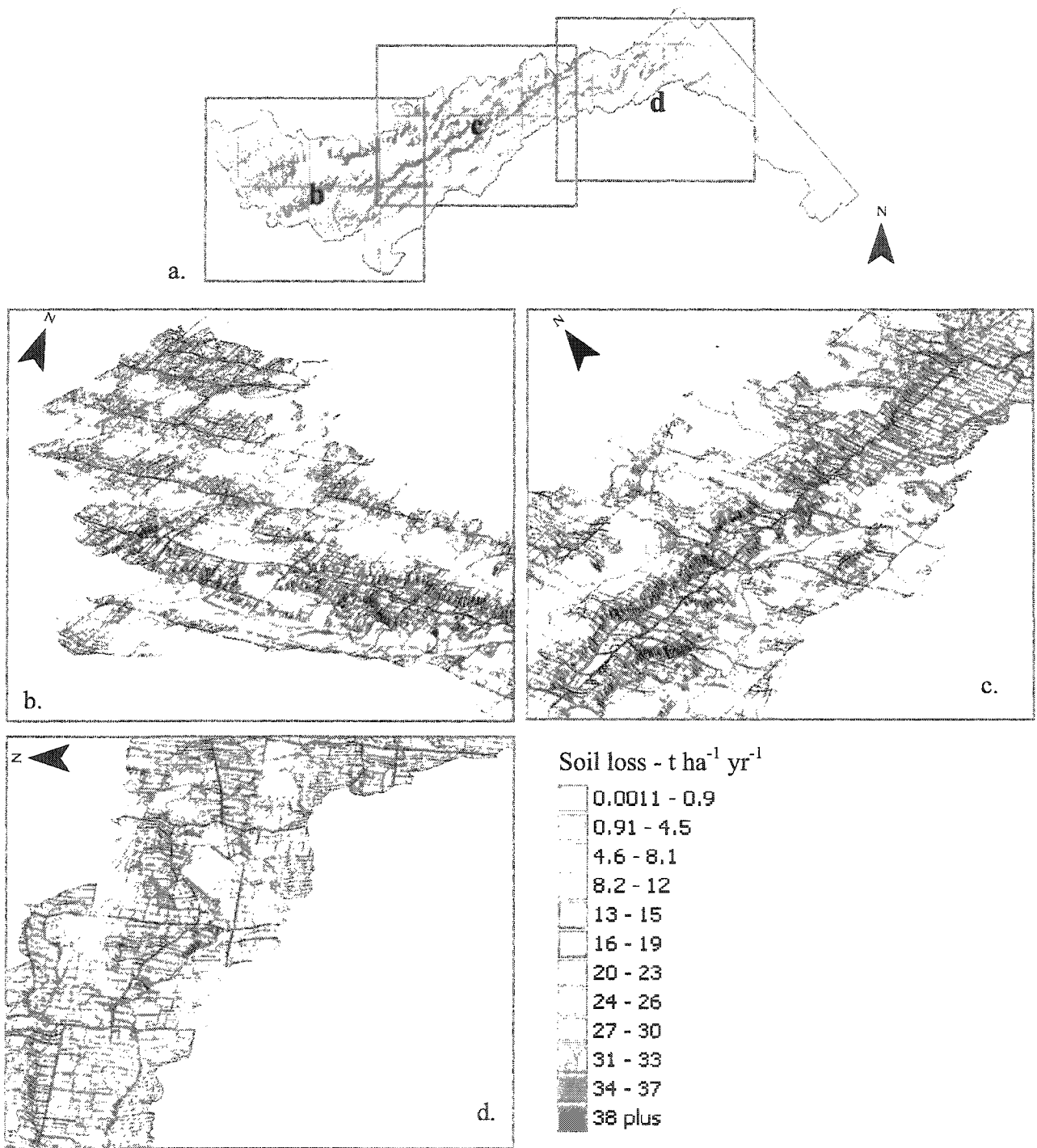


Fig. 66. Soil loss estimates derived using the USLE for Canadian conditions, the USLE2D, and the USPED model for the Beaudette River, watershed. Soil loss estimates made for conventional tillage practices, 25% field boundary connectivity, and USPED masking of analysis for sheet erosion. Estimates are given in $t\ ha^{-1}\ yr^{-1}$; a) Beaudette river watershed; b) estimated soil loss map in western section study region; c) estimated soil loss map in central region; d) estimated soil loss map in eastern region. Field boundaries are linear and depicted in black. Watercourses are depicted as blue lines.

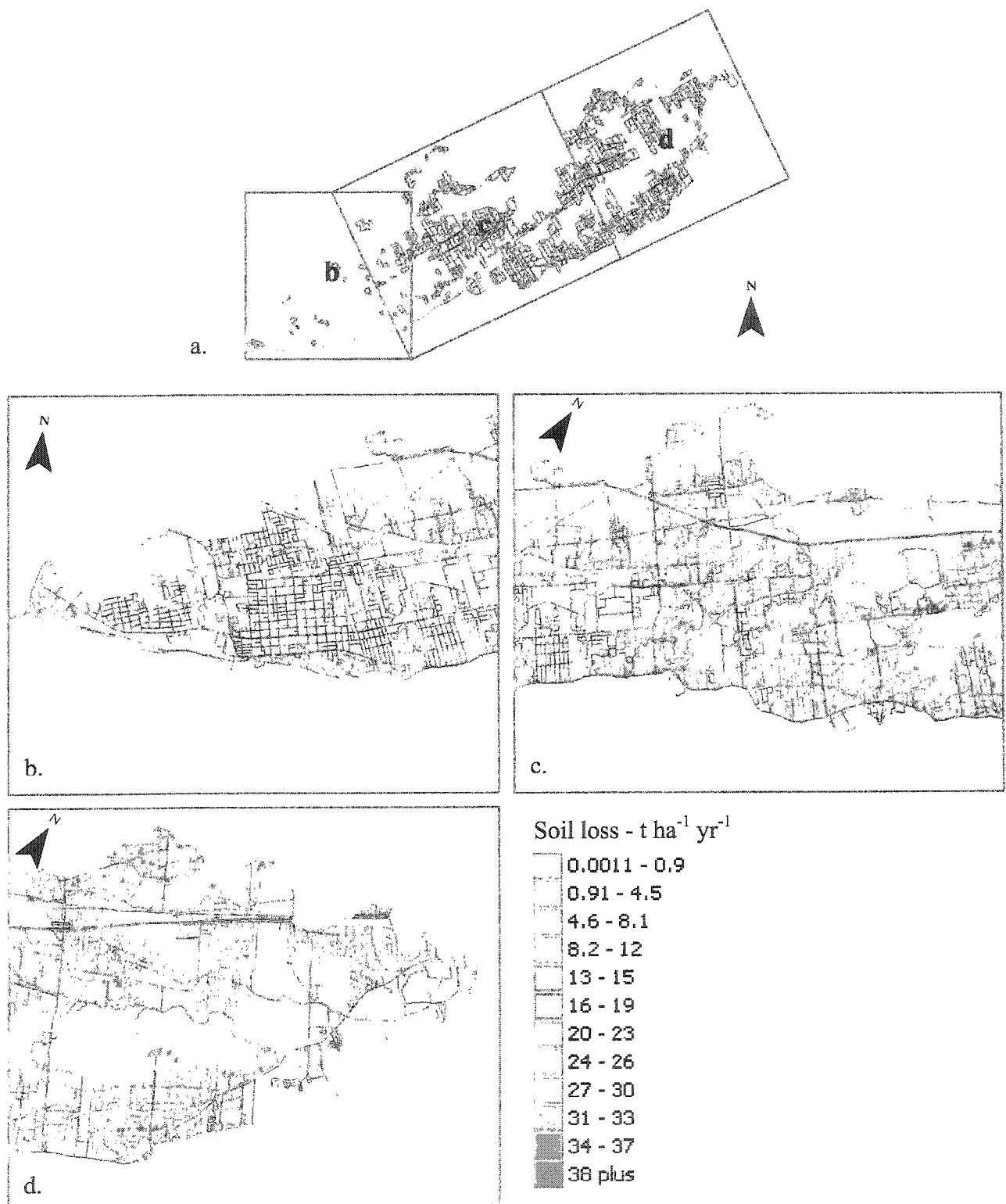


Fig. 67. Soil loss estimates derived using the USLE for Canadian conditions, the USLE2D, and the USPED model for the Fraser watershed. Soil loss estimates made for conventional tillage practices, 25% field boundary connectivity, and USPED masking of analysis for sheet erosion. Estimates are given in $t\ ha^{-1}\ yr^{-1}$; a) Fraser watershed; b) estimated soil loss map in western section study region; c) estimated soil loss map in central region; d) estimated soil loss map in eastern region. Field boundaries are linear and depicted in purple. Watercourses are depicted as blue lines. Roads are depicted in black.

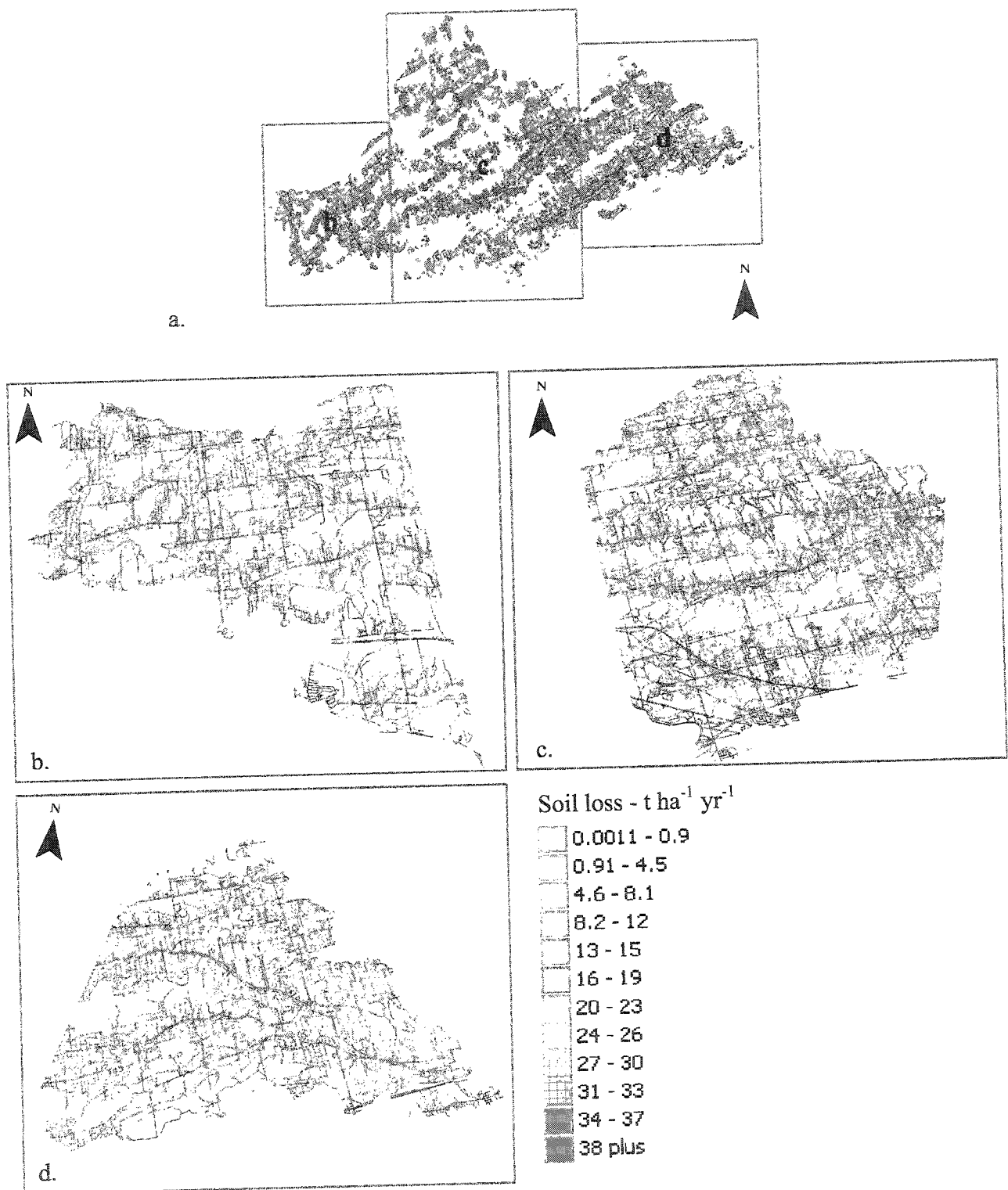


Fig. 68. Soil loss estimates derived using the USLE for Canadian conditions, the USLE2D, and the USPED model for the Raisin River watershed. Soil loss estimates made for conventional tillage practices, 25% field boundary connectivity, and USPED masking of analysis for sheet erosion. Estimates are given in $t\ ha^{-1}\ yr^{-1}$; a) Raisin watershed; b) estimated soil loss map in western section study region; c) estimated soil loss map in central region; d) estimated soil loss map in eastern region. Field boundaries are linear and depicted in purple. Watercourses are depicted as blue lines. Roads are depicted in black.

As indicated, the soil loss error estimates are high, and our initial assessment of error for each of the factors was set rather conservatively. Even with this drawback, one can notice that it is still possible to compare erosion risk between modeling scenarios with some degree of reliability, reliability that would not be present if errors were not assessed as is the case with many current USLE studies. For example, under conventional tillage, 100% field boundary connectivity, with sheet erosion dominated processes we can expect 95,919 tonnes of soil lost $\pm$ 41,237 tonnes for cells that fall into the severe class. Contrast the previous with a modeling scenario for which there is complete no till farming systems in place, and we presume there is 25% field boundary connectivity, with rill dominated erosion processes. We should expect 31,370 tonnes of soil lost $\pm$ 12,802 tonnes for cells within the severe class for the entire study region. The previous scenarios consider two extremely different situations, but both predict that a large quantity of soil is being lost in grid cells classified within the range of severe in eastern Ontario. Whether a more conservative or liberal modeling scenario is applied, a significant amount of soil is modeled as lost in cells categorized in the severe risk class.

Other scenarios are presented to understand the quantity of erosion occurring in the region. Under conventional tillage, 100% field boundary connectivity, with sheet erosion dominated processes, we can expect 325,772 tonnes of soil lost $\pm$ 139,146 tonnes for cells that fall into the intolerable category of erosion over the entire study region. Compare this same scenario with tolerable losses which are in the range of 260,859 tonnes of soil lost $\pm$ 111,391 tonnes. In this modeling situation, huge quantities of intolerable erosion are occurring over the landscape based on management policies in place for the year 2001.

				(tonnes • year)									
Attributes				Very low		Low		Moderate		High		Severe	
Sc.	LS (%)	C factor	Mask	Sum	± Error	Sum	± Error	Sum	± Error	Sum	± Error	Sum	± Error
1a	25	Conv.	sheet	259869	110938	88082	37488	72599	30920	28548	12169	68092	29164
1b	25	Conv.	rill	254379	108587	86013	36606	70903	30196	27810	11853	66279	28397
2a	25	Cons.	sheet	241148	102914	66173	28180	52713	22460	19860	8468	45643	19561
2b	25	Cons.	rill	224606	95850	61294	26102	48692	20747	18337	7818	42257	18110
3a	25	No Till	sheet	212115	90587	49219	20992	38709	16520	14046	6000	32252	13833
3b	25	No Till	rill	207543	84331	48114	19443	37835	15271	13712	5542	31370	12802
4a	100	Conv.	sheet	260859	111391	100613	42832	90552	38582	38688	16495	95919	41237
4b	100	Conv.	rill	255357	109033	98250	41825	88397	37662	37730	16086	93573	40228
5a	100	Cons.	sheet	244710	104459	77962	33206	67927	28960	27861	11883	65460	28180
5b	100	Cons.	rill	239469	97301	76165	30775	66312	26760	27211	10976	63817	26298
6a	100	No Till	sheet	217816	93034	58975	25161	51029	21790	20503	8758	45456	19597
6b	100	No Till	rill	202818	86624	54633	23309	47193	20152	18921	8082	42476	18315

Table 18. Total soil loss off of agricultural field within study region summarized by erosion class and modeling scenario. Relations to scenarios are provided in Table 12. Sc. – Scenario, a – masked for sheet erosion, b – masked for rill erosion, Sum – total soil loss in tonnes, ± error – estimated error associated with prediction, Very low – less than 6 t ha⁻¹ yr⁻¹, Low 6-11 t ha⁻¹ yr⁻¹, Moderate – 11-22 t ha⁻¹ yr⁻¹, High – 22-33 t ha⁻¹ yr⁻¹, Extreme – greater than 33 t ha⁻¹ yr⁻¹.

In contrast, for a more conservative scenario, with no till farming systems in place, and assuming there is 25% field boundary connectivity, with rill dominated erosion processes, we can expect 131,031 tonnes of soil lost ± 53,058 tonnes for cells that fall into the intolerable classes over the entire region. In contrast, losses from cells which are in the tolerable class are in the range of 207,543 tonnes ± 84,331 tonnes under the same scenario. Under conservative modeling scenarios one can expect a considerable amount of soil lost at intolerable levels when modeling at the field scale and within agricultural field.

Intolerable levels of erosion by cell are modeled to contribute between 38 and 56% of the total gross loss of soil within the region when summarizing the results for all scenarios (Table 18). This is startling, and indicates that intolerable levels of erosion could cost upwards of \$8,144,300 ± \$3,478,650 to a minimum of \$3,275,775 ± \$1,326,450 annually for the region if the price of a tonne of fertile soil is estimated at \$25. These very coarse estimates do not account

for costs related to lost productivity, environmental degradation and related costs, fertilization or nutrient management, nor do they include the cost of clearing drainage ditches, drainage pipes and the like.

To provide a target for the implementation of precision soil loss reduction, one approach is to first identify watersheds that are modeled to have relatively larger soil losses per analysis cell for further investigation of field scale erosion. Soil loss density distributions were examined by watershed and for the entire study region and for individual watersheds to assess the appropriateness of summary statistics. Density distributions are provided for the most conservative and the most liberal of modeling scenarios, 25% field boundary connectivity, no tillage farming systems, and the predominance of USPED rill erosion processes (Fig 69) versus 100% field connectivity, conventional tillage farming systems, and the dominance of USPED rill erosion processes (Fig 70). The distribution results for both soil loss modeling scenarios reveal that soil loss is skewed heavily to the right. All scenarios provide density distributions which exhibit the same pattern as seen in Fig. 69 and 70. These non-normal distributions which are heavily skewed positively indicate that the majority of soil loss occurs at lower levels, with exponentially reducing rates of soil loss at higher levels. Reductions in frequency peaks at lower soil loss levels, and how more heavily the tail is weighted provides insight into the severity of soil loss in the region. The skewed nature of these soil loss distributions for the region indicate that the central tendency statistic of median is more representative for the comparison of soil loss between watersheds.

Mean erosion and median erosion summarized by watershed and scenario are given (Table 19 and 20). Table 19 lists those scenarios with 25% LS connectivity. Table 21 lists those scenarios with 100% LS factor connectivity between field boundaries.

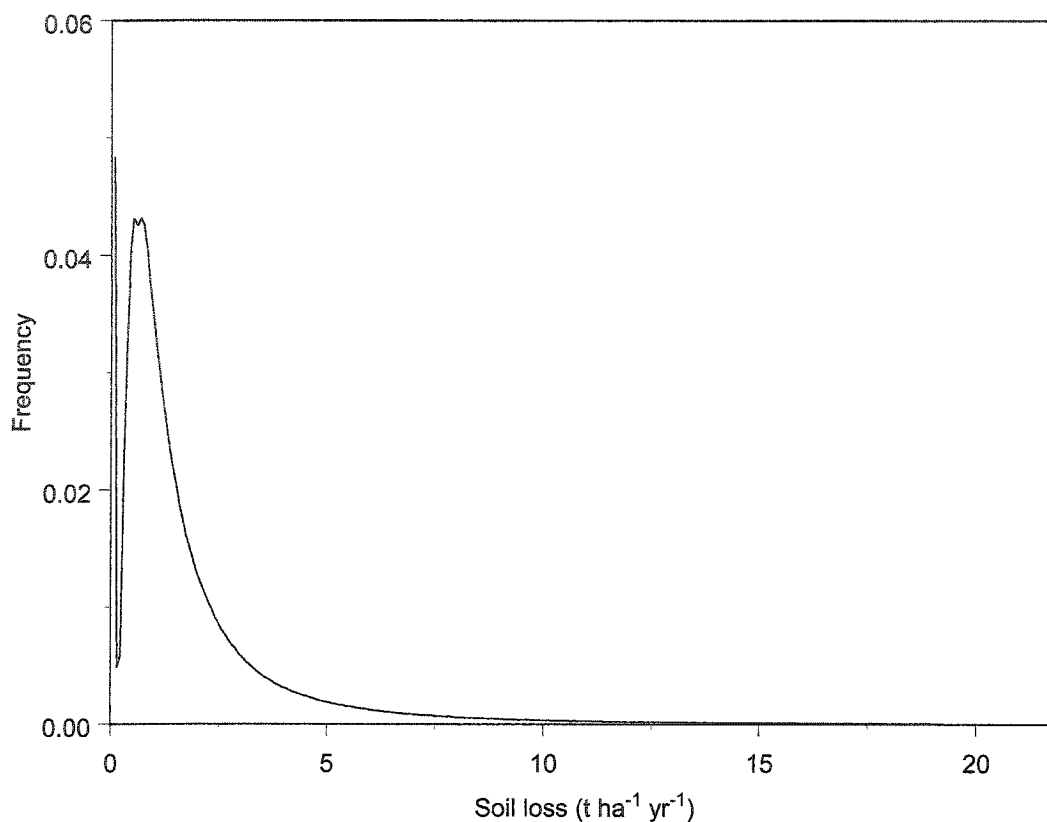


Fig. 69. Soil loss density plot for the study region, 100% field boundary connectivity, conventional tillage farming systems, USPED sheet erosion dominance, summarized by field area only.

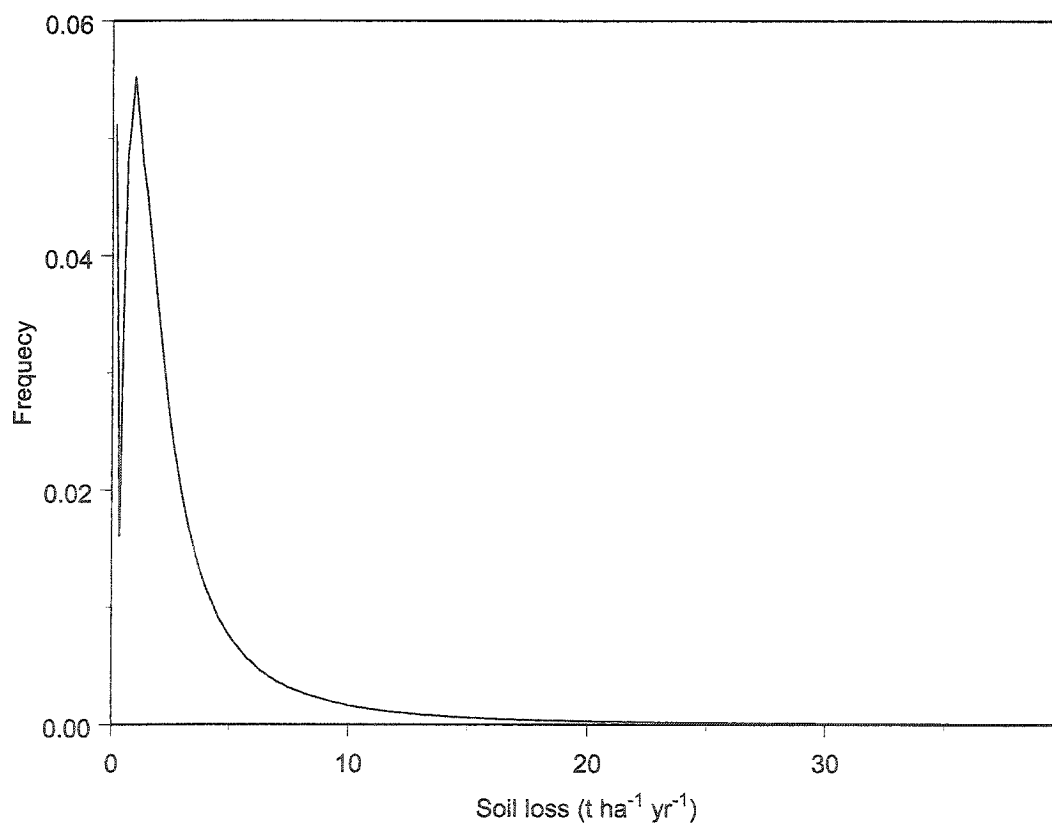


Fig. 70. Soil loss density plot for the study region, 25% field boundary connectivity, no tillage farming systems, USPED rill erosion dominance, summarized by field area only.

	Conventional Tillage						Conservation Tillage						No Till					
	No Mask		Sheet		Rill		No Mask		Sheet		Rill		No Mask		Sheet		Rill	
	Mean	Med.	Mean	Med.	Mean	Med.	Mean	Med.	Mean	Med.	Mean	Med.	Mean	Med.	Mean	Med.	Mean	Med.
A	1.18	1.07	4.06	0.62	4.06	0.62	1.18	1.07	3.35	0.62	3.35	0.62	1.18	1.07	1.93	0.62	1.93	0.62
B	1.84	0.91	2.23	1.04	2.29	1.03	1.58	0.79	1.94	0.92	1.99	0.89	1.40	0.69	1.75	0.82	1.78	0.80
C	2.73	1.43	3.03	1.36	2.95	1.33	2.26	1.15	2.47	1.13	2.40	1.12	1.87	1.00	1.95	0.96	1.87	0.95
D	3.04	1.57	2.55	1.49	2.54	1.49	2.54	1.35	2.15	1.32	2.16	1.32	2.14	1.08	1.81	1.09	1.81	1.09
E	2.96	1.46	5.25	1.50	5.32	1.50	2.35	1.14	3.82	1.18	3.88	1.21	1.94	0.86	3.00	0.93	3.05	0.95
F	2.62	1.73	2.70	1.68	2.68	1.69	2.10	1.38	2.18	1.36	2.17	1.38	1.64	1.05	1.72	1.06	1.70	1.07
G	3.66	1.61	5.60	1.68	5.67	1.77	3.10	1.43	4.61	1.45	4.66	1.47	2.21	1.07	2.95	1.04	2.97	1.05
H	3.99	1.71	3.08	1.80	2.82	1.82	3.33	1.44	2.65	1.52	2.44	1.56	2.79	1.17	2.13	1.21	2.04	1.29
I	3.85	2.03	3.39	1.83	3.49	1.88	3.08	1.55	2.74	1.40	2.82	1.47	2.49	1.15	2.16	1.06	2.21	1.08
J	3.37	1.84	3.02	1.88	3.00	1.85	2.73	1.52	2.44	1.48	2.42	1.45	2.07	1.17	1.91	1.15	1.89	1.11
K	5.21	2.04	4.10	2.06	4.22	2.09	4.82	1.81	3.98	1.61	4.10	1.63	4.40	1.76	3.87	1.61	4.00	1.63
L	7.43	2.51	4.82	2.44	4.60	2.41	5.68	2.09	4.03	2.09	3.86	2.07	4.63	1.62	3.34	1.60	3.26	1.60
M	4.39	2.80	4.03	2.79	4.13	2.80	3.71	2.49	3.41	2.51	3.46	2.51	3.12	1.92	2.89	1.97	2.96	1.97
N	6.91	3.20	5.68	2.88	6.06	3.02	5.99	2.69	5.04	2.63	5.30	2.66	5.19	2.20	4.52	2.18	4.64	2.39
O	5.17	3.05	5.29	2.96	5.29	2.96	4.36	2.66	4.42	2.54	4.43	2.54	3.65	2.16	3.58	2.12	3.59	2.09

Table 19. Mean and standard deviation of soil loss off of agricultural field within study region summarized by watershed and modeling scenario, LS – 25% connectivity between land units. A – Sub Rigaud, B – Atocas, C– Bear Brook, D – Rigaud, E – Scotch, F – South Nation, G – Hoasic, H – Cardinal, I– Sutherland, J– Castor, K – Fraser, L – Payne, M – Delisle, N – Beaudette, O – Raisin, a – USPED sheet, b – USPED rill, without a or b – no USPED mask. Units - $t\ ha^{-1}\ yr^{-1}$.

	Conventional Tillage						Conservation Tillage						No Till					
	No Mask		Sheet		Rill		No Mask		Sheet		Rill		No Mask		Sheet		Rill	
	Mean	Med.	Mean	Med.	Mean	Med.	Mean	Med.	Mean	Med.	Mean	Med.	Mean	Med.	Mean	Med.	Mean	Med.
A	1.35	1.24	5.80	0.66	5.80	0.66	1.35	1.24	4.77	0.66	4.77	0.66	1.35	1.24	2.70	0.66	2.70	0.66
B	2.21	0.97	2.48	1.14	2.54	1.13	1.92	0.85	2.15	0.98	2.19	0.96	1.70	0.74	1.91	0.87	1.94	0.86
C	3.17	1.48	3.75	1.46	3.61	1.42	2.63	1.24	3.08	1.20	2.94	1.19	2.22	1.06	2.43	0.99	2.28	0.99
D	3.66	1.73	3.03	1.61	3.01	1.61	3.08	1.48	2.57	1.46	2.56	1.43	2.63	1.19	2.14	1.22	2.14	1.24
E	3.20	1.54	2.66	1.62	2.68	1.64	2.51	1.19	2.11	1.27	2.13	1.30	2.04	0.90	1.75	0.98	1.78	0.98
G	2.75	1.68	3.06	1.78	3.11	1.83	2.37	1.48	2.56	1.50	2.59	1.57	1.88	1.15	1.90	1.07	1.91	1.10
F	3.04	1.83	2.94	1.79	2.93	1.79	2.44	1.47	2.38	1.45	2.37	1.47	1.87	1.11	1.89	1.10	1.87	1.11
H	4.90	1.82	3.45	1.96	3.08	1.97	4.14	1.59	2.98	1.64	2.68	1.69	3.46	1.29	2.39	1.33	2.24	1.37
J	3.30	1.96	3.28	1.97	3.26	1.96	2.70	1.63	2.65	1.56	2.63	1.53	2.08	1.24	2.08	1.19	2.06	1.16
I	4.40	2.16	3.82	1.97	3.93	1.98	3.55	1.63	3.11	1.45	3.19	1.53	2.90	1.21	2.46	1.08	2.51	1.10
K	5.58	2.16	4.94	2.19	5.06	2.22	5.18	2.07	4.81	1.63	4.93	1.63	4.74	1.90	4.70	1.63	4.82	1.63
L	4.40	2.69	4.55	2.63	4.28	2.63	3.61	2.29	3.68	2.25	3.48	2.25	2.72	1.69	2.94	1.66	2.82	1.66
M	5.42	3.16	5.33	3.17	5.54	3.22	4.57	2.79	4.49	2.90	4.60	2.94	3.84	2.19	3.78	2.32	3.88	2.33
O	6.32	3.50	6.29	3.24	6.32	3.32	5.32	3.01	5.27	2.80	5.31	2.80	4.43	2.41	4.30	2.39	4.34	2.38
N	8.23	3.55	7.11	3.53	7.62	3.56	7.16	3.12	6.39	3.19	6.76	3.19	6.19	2.64	5.80	2.54	5.98	2.57

Table 20. Mean and standard deviation of soil loss off of agricultural field within study region summarized by watershed and modeling scenario, LS – 100% connectivity between land units. A – Sub Rigaud, B – Atocas, C– Bear Brook, D – Rigaud, E – Scotch, F – South Nation, G – Hoasic, H – Cardinal, I– Sutherland, J– Castor, K – Fraser, L – Payne, M – Delisle, N – Beaudette, O – Raisin, a – USPED sheet, b – USPED rill, without a or b – no USPED mask. Units - $t\ ha^{-1}\ yr^{-1}$.

For any given scenario, the Raisin River, Beaudette, Delisle, and Payne watersheds have high median and mean erosion rates (Table 19 and 20). These three watersheds are adjacent and are situated in the southeast. Examination of the median value by watershed indicates that soil loss tends to be less on field area than non-field area. All median values are far less than mean values indicating that the density distributions are heavily skewed positively.

To more easily visualize the problematic watersheds over the region, median soil loss choropleth maps were produced for sheet erosion processes for all tillage farming systems with 25% boundary connectivity scenarios applied in this study. Figure 71 presents median soil loss for a scenario with 25% field boundary connectivity, under conventional tillage practices, masked for sheet erosion. Figure 72 presents median soil loss with 25% field boundary connectivity, under conservation tillage practices, masked for sheet erosion while Fig. 73 presents soil loss medians modeled under no tillage farming. All three maps suggest that the southeast is at higher risk of erosion. Figures 71 through 73 further suggest that the western extent is experiencing moderate losses under 2001 management practices. Finally, the northeast is modeled as experiencing the lowest levels of erosion.

These maps (Fig. 71 to 73) are highly generalized compared to those maps presented in figures 56 to 68. Figure 71 to 73 maps are offered for use in the selection of watersheds that are at most risk of soil loss for the application of mitigation strategies at the field scale. Such maps are presented for use at the policy making scale for the allocation of funding for the implementation and encouragement of soil loss reduction farming strategies in the region. Finally, maps are provide to demonstrate the potential of the thesis modeling results for use in precision agriculture (Fig. 62 to 65).

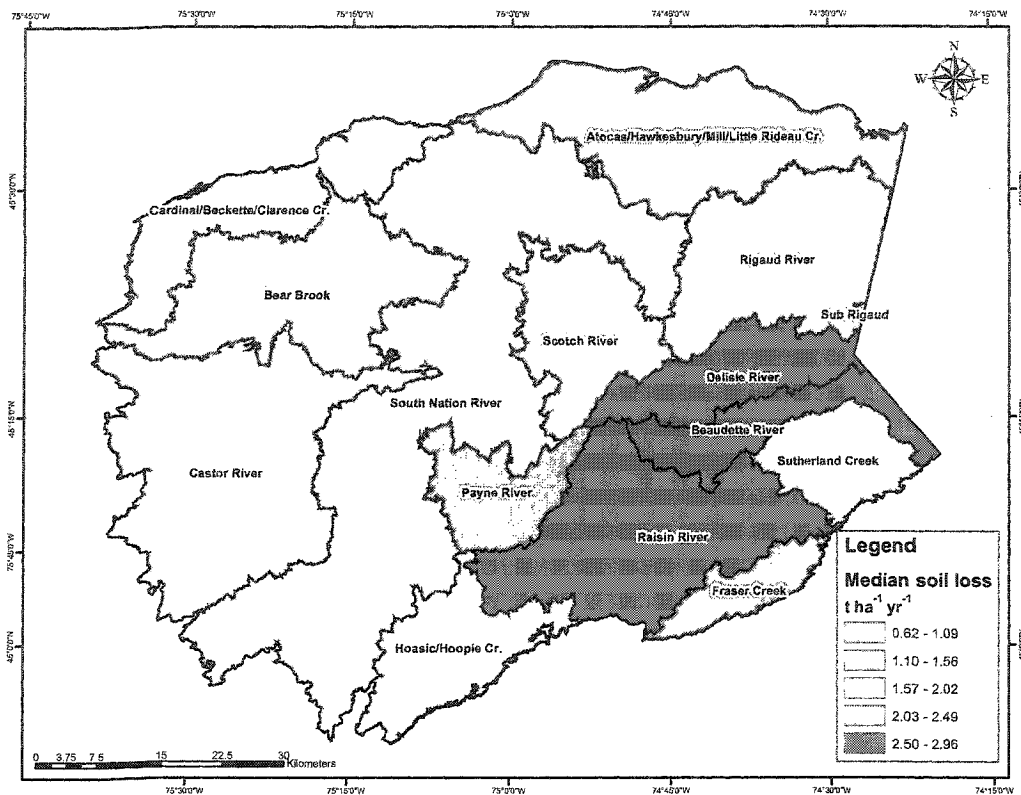


Fig. 71. Median soil loss for watershed calculated for 25% field boundary connectivity, conventional tillage farming, with analysis limited to erosion that is dominated by sheet losses under 2001 farm

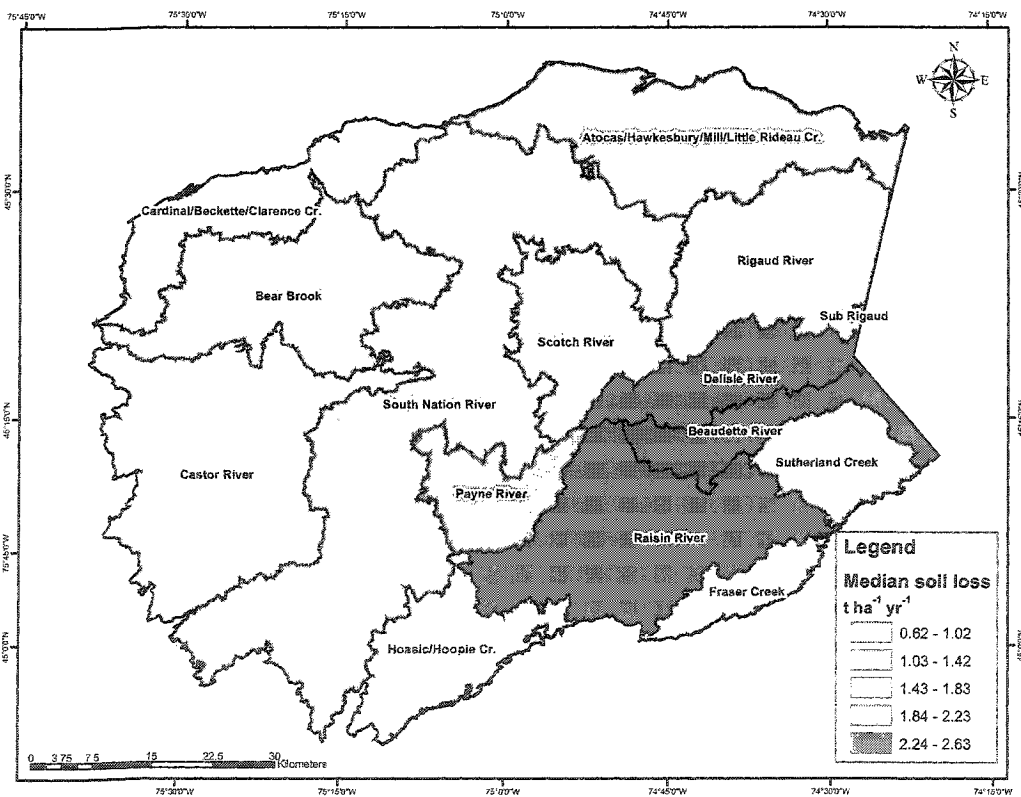


Fig. 72. Median soil loss for watershed calculated for 25% field boundary connectivity, conservation tillage farming, with analysis limited to erosion that is dominated by sheet losses under 2001 farm

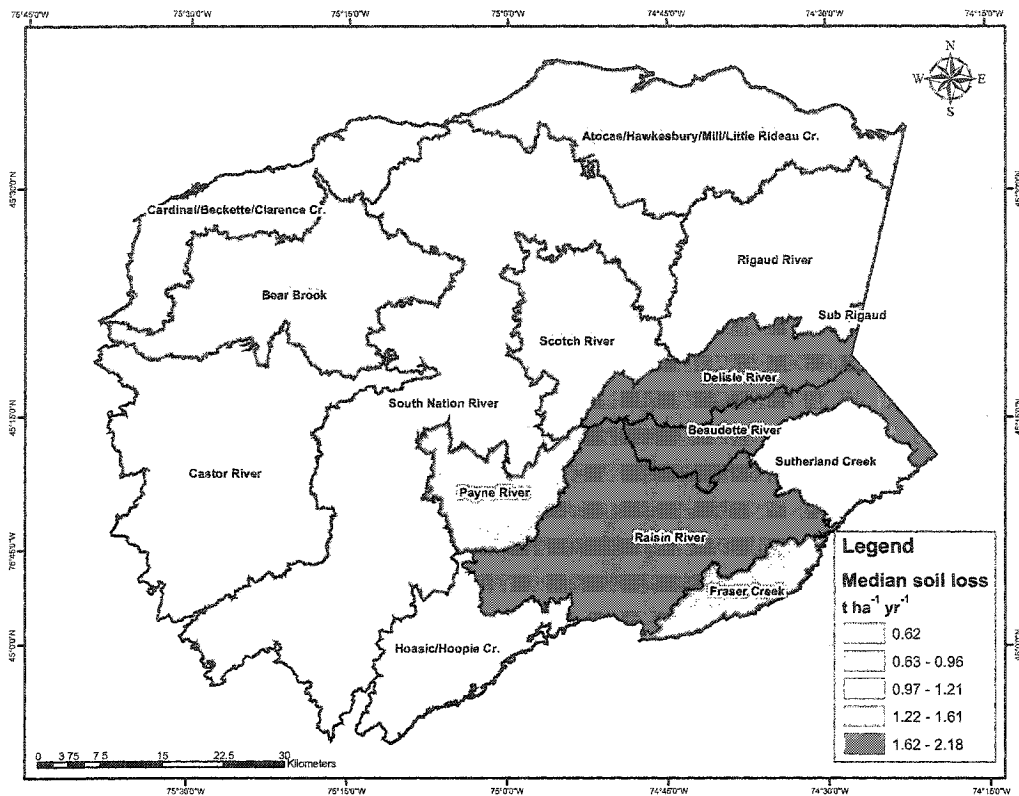


Fig. 73. Median soil loss for watershed calculated for 25% field boundary connectivity, no tillage farming, with analysis limited to erosion that is dominated by sheet losses under 2001 farm management.

At the beginning of this section we examined intolerable erosion summarized for the entire study region. Next, figures are presented which summarize tolerance categories for rates of erosion by watershed. These figures are in the form of bar graphs which provide relative rates of tolerable soil loss categories by modeling scenario and area. Figures 74 through 85 graph soil loss within toleration classes for the scenarios listed in Table 12. Figures 74 to 79 are for 25% LS factor field boundary connectivity while figures 80 through 85 provide area estimates for 100% LS factor field boundary connectivity. All results are summarized by field area only.

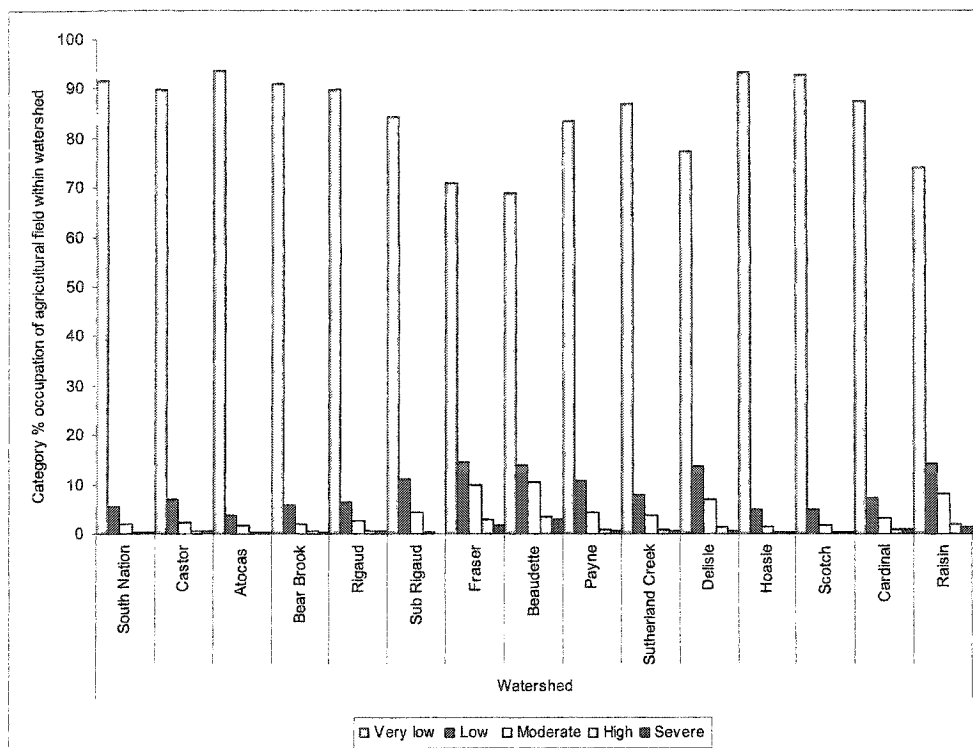


Fig. 74. Percent area under soil loss summarized by class and watershed for 25% field boundary connectivity, conventional tillage farming systems, USPED masking under the dominance of sheet erosion.

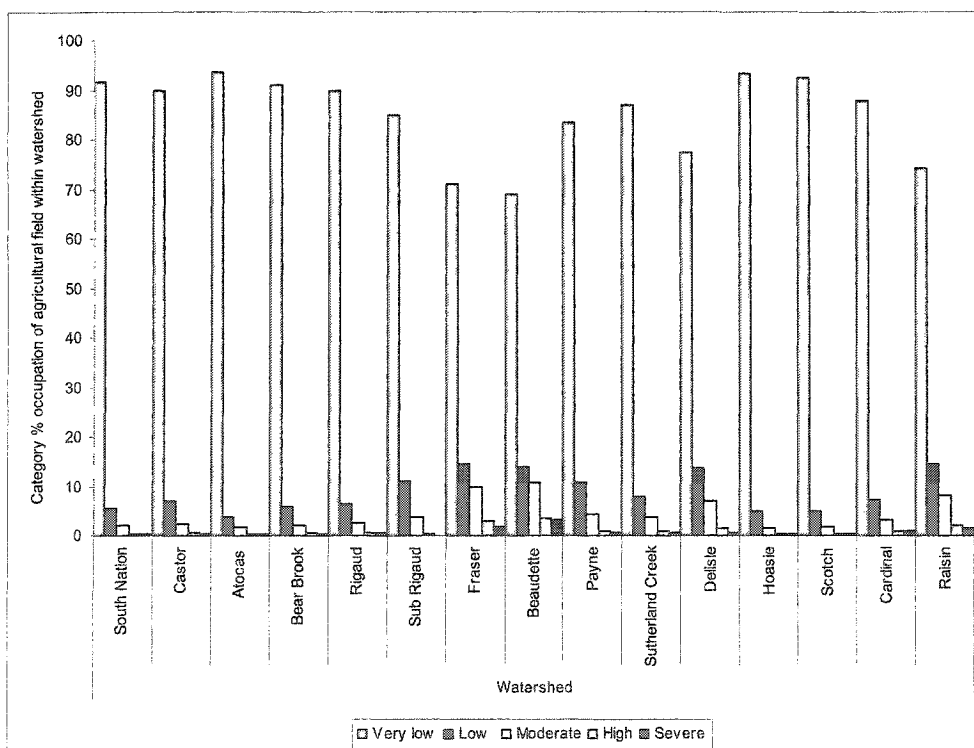


Fig. 75. Percent area under soil loss summarized by class and watershed for 25% field boundary connectivity, conventional tillage farming systems, USPED masking under the dominance of rill erosion.

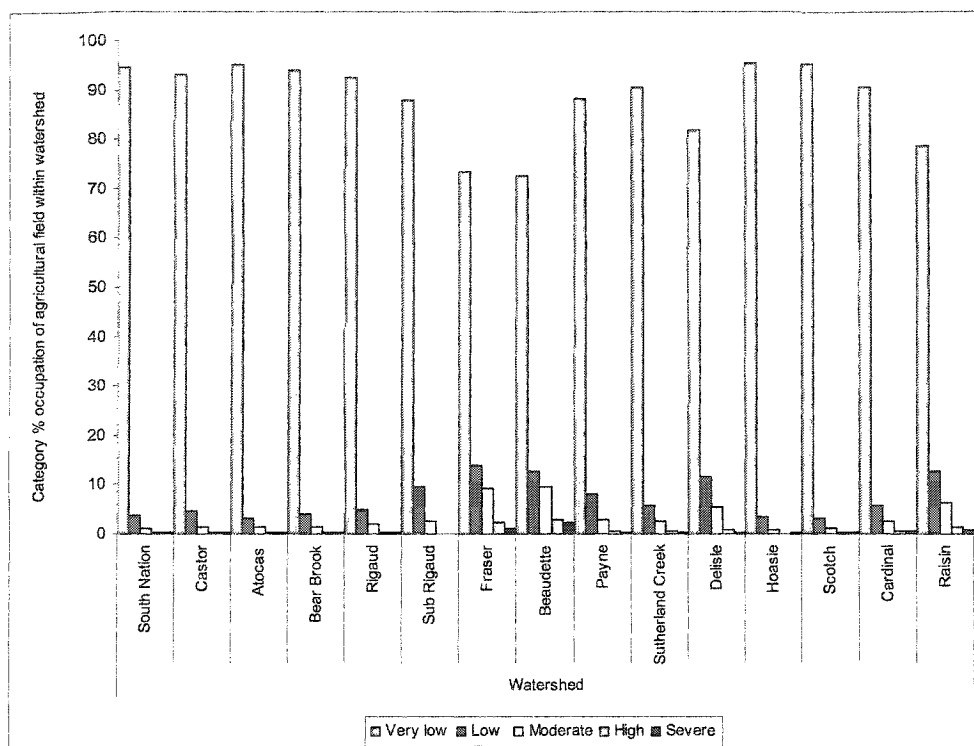


Fig. 76. Percent area under soil loss summarized by class and watershed for 25% field boundary connectivity, conservation tillage farming systems, USPED masking under the dominance of sheet erosion.

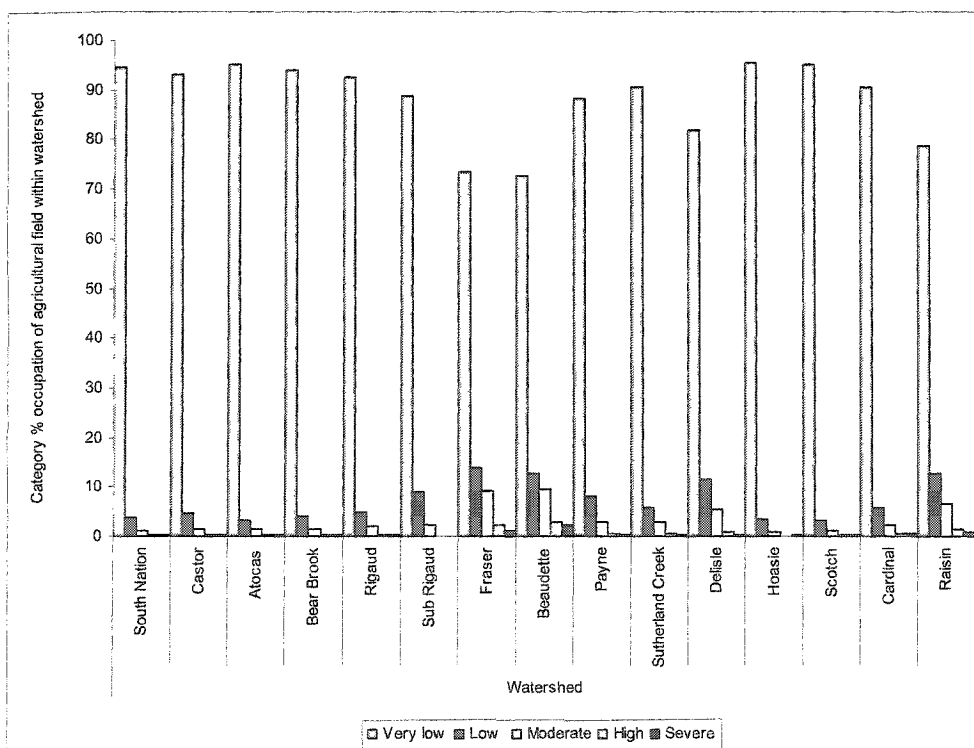


Fig. 77. Percent area under soil loss summarized by class and watershed for 25% field boundary connectivity, conservation tillage farming systems, USPED masking under the dominance of rill erosion.

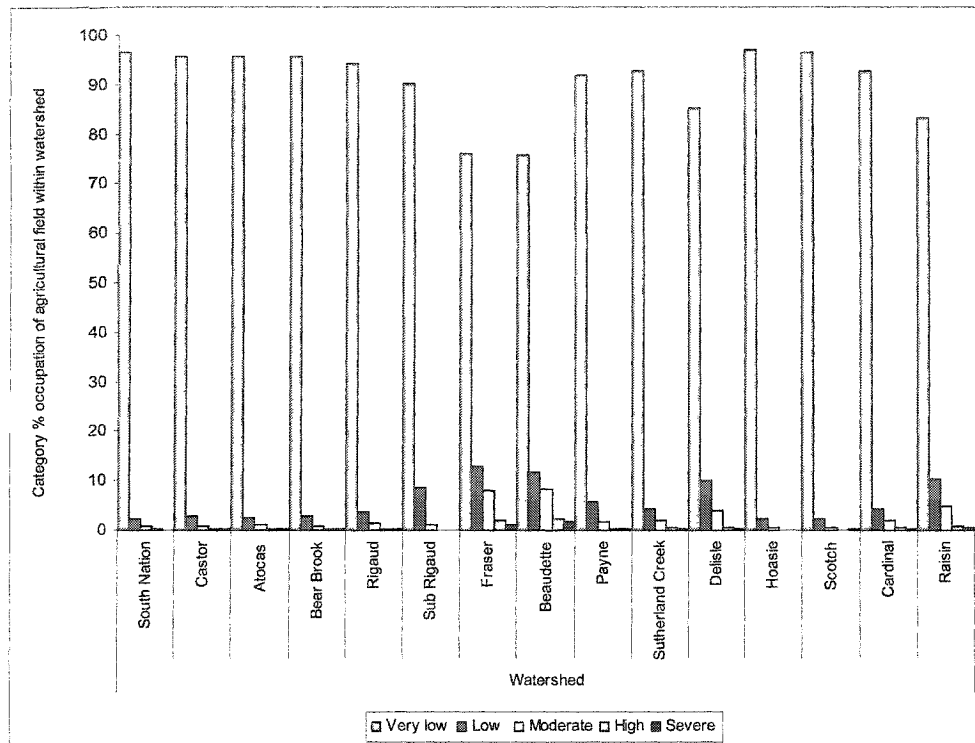


Fig. 78. Percent area under soil loss summarized by class and watershed for 25% field boundary connectivity, no tillage farming systems, USPED masking under the dominance of sheet erosion.

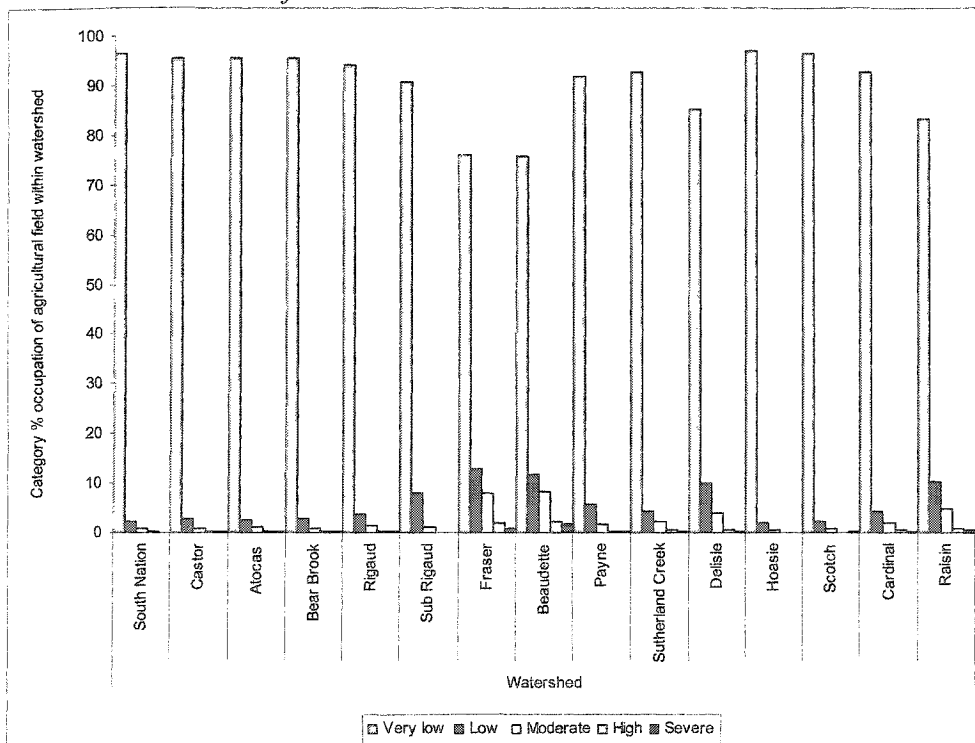


Fig. 79. Percent area under soil loss summarized by class and watershed for 25% field boundary connectivity, no tillage farming systems, USPED masking under the dominance of rill erosion.

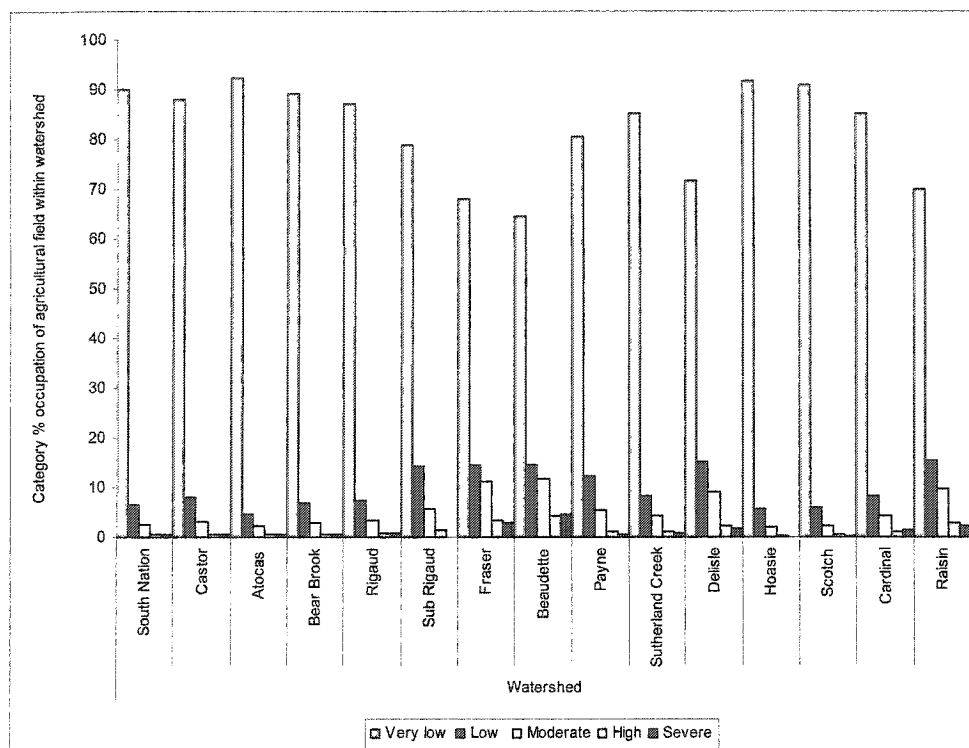


Fig. 80. Percent area under soil loss summarized by class and watershed for 100% field boundary connectivity, conventional tillage farming systems, USPED masking under the dominance of sheet erosion.

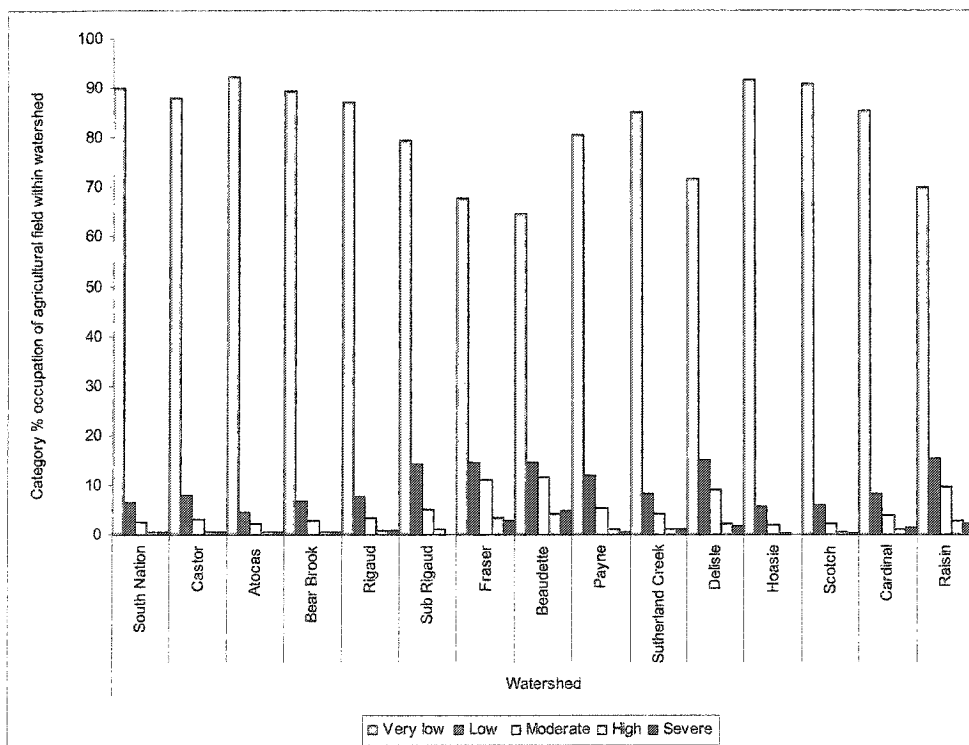


Fig. 81. Percent area under soil loss summarized by class and watershed for 100% field boundary connectivity, conventional tillage farming systems, USPED masking under the dominance of rill erosion.

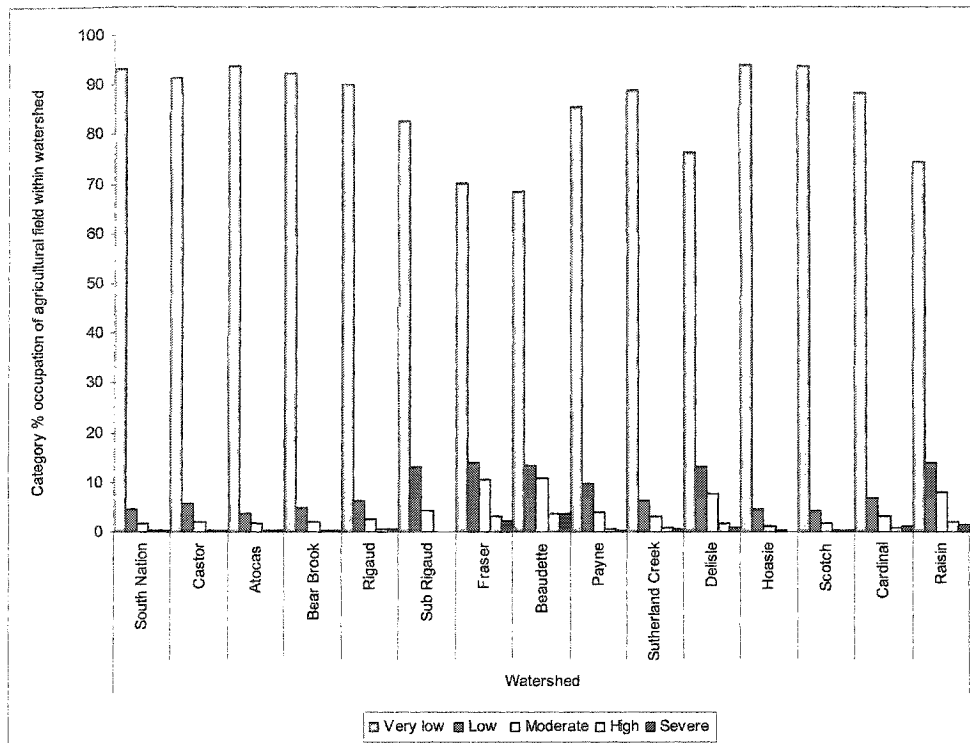


Fig. 82. Percent area under soil loss summarized by class and watershed for 100% field boundary connectivity, conservation tillage farming systems, USPED masking under the dominance of sheet erosion.

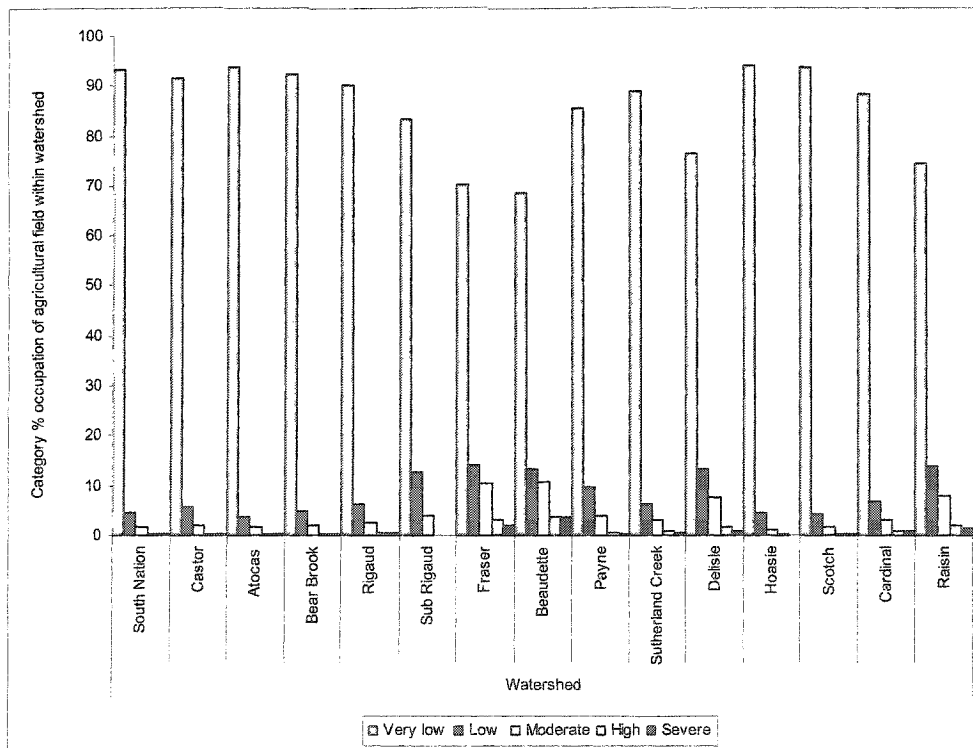


Fig. 83. Percent area under soil loss summarized by class and watershed for 100% field boundary connectivity, conservation tillage farming systems, USPED masking under the dominance of rill erosion.

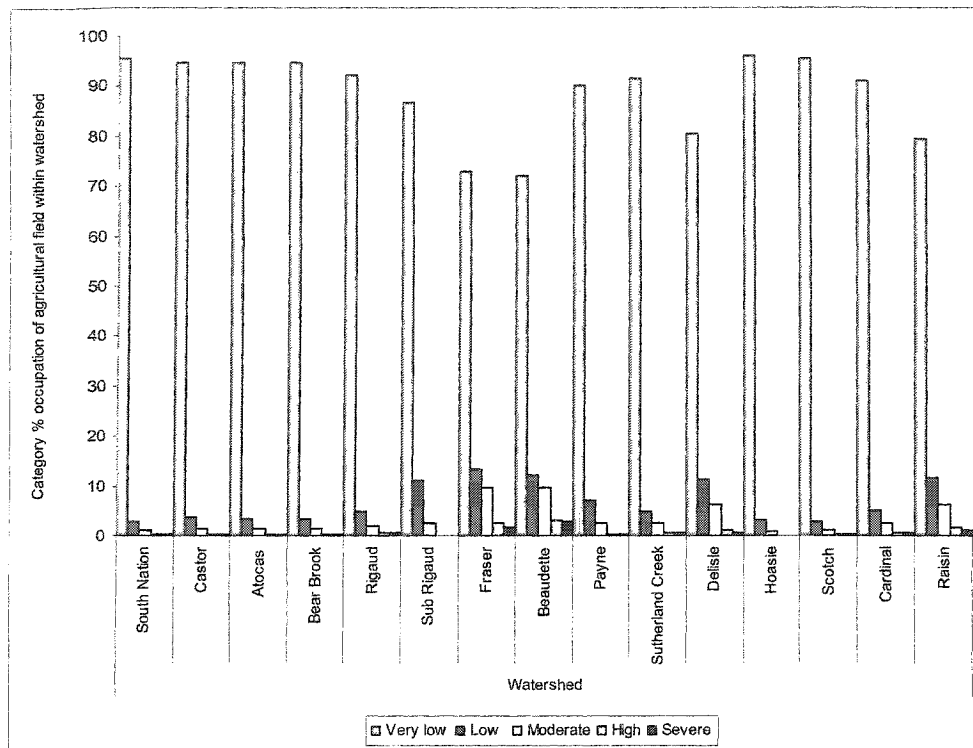


Fig. 84. Percent area under soil loss summarized by class and watershed for 100% field boundary connectivity, no tillage farming systems, USPED masking under the dominance of sheet erosion.

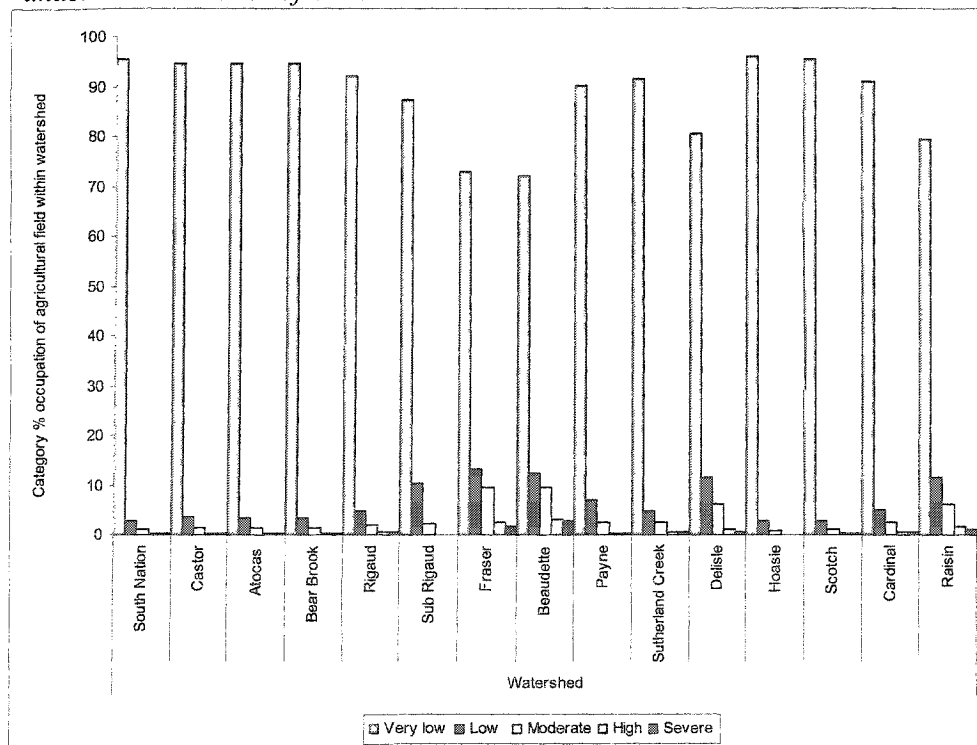


Fig. 85. Percent area under soil loss summarized by class and watershed for 100% field boundary connectivity, no tillage farming systems, USPED masking under the dominance of rill erosion.

Figures 74 through 85 can be summarized as follows. All categories beyond very low soil loss represent soil loss occurring at intolerable levels. Less than 92% of the field area of the South Nation River watershed is providing soil loss at levels beyond very low for conventional tillage farming systems, USPED masking for erosion dominated by sheet flow, and 25% field boundary connectivity (Fig. 74). Comparatively, the South Nation watershed, with the previous factors held constant, when switched entirely to no till farming is modeled to have less than 96% of its field area providing soil loss beyond very low levels (Fig. 78). Overall, the various scenarios and analysis limitations model outputs provided by watershed area vary relatively, meaning that the quantity of area changes but the ratios of very low or low between watersheds for instance generally remain the same. Under all twelve scenarios compared in figures 74 to 85, Fraser Creek, Beaudette River, Delisle River, and Raisin River watersheds are providing relatively higher overall area beyond very low tolerance classes. Further, Fraser River and Beaudette River watersheds provide the highest area in the severe, high, and moderate classes of soil loss tolerance.

With conservative estimates of the transference of water flow across field boundaries (25% field boundary connectivity), and under conventional tillage systems with the domination of sheet erosion, the Beaudette, Fraser, and Raisin have 31%, 29%, and 26% of field area experiencing intolerable levels of erosion (Fig. 74). With 25% field boundary connectivity, and under no tillage systems with the domination of sheet erosion, the Beaudette, Fraser, and Raisin have 24%, 24%, and 17% of field area experiencing intolerable levels of erosion (Fig. 78). With more liberal expectations of water flow transference (100% field boundary connectivity) under conventional tillage systems with

the domination of rill erosion, the Beaudette, Fraser, and Raisin have 35%, 32%, and 30% of their field area experiencing intolerable levels of erosion (Fig. 81). With the same modeling conditions under no till farming systems, the area providing intolerable levels of erosion reduces to 28%, 27%, and 20% (Fig. 85). In all modeling scenarios, these watersheds provide a significant amount of intolerable erosion, and should, therefore, be investigated further to see if actual losses are in line with those modeled. Finally, figures 74 through 85 indicate that Hoasic and Atocas watersheds are providing the least amount of intolerable erosion summarized by area, and should not be prioritized for soil erosion mitigation strategies.

A further investigation undertaken in this study was how changes in variation of rainfall erosivity over growing season months effects soil loss estimates when all other factors of the USLE and USLE2D are held constant. Further studies could extend these monthly soil loss results to account for variations in crop coverage, residue, and soil erodibility. Figure 86 and 87 graph the net monthly erosion occurring on each watershed for inputs of monthly erosivity, annual erodibility, conventional tillage, and 25% USLE parcel connectivity masked for USPED domination of sheet and rill erosion. Soil losses are modeled to increase until August, where soil losses drop until the last modeled month of October (Fig. 86 and 87). These estimates are based on changes solely in rainfall erosivity, and do not take account for crop cover or soil erodibility variation. The likely effect of this failure is that late season erosion is exaggerated. The peaking of monthly soil loss summarized by watershed in the month of August is in agreement with the results of monthly rainfall erosivity summarized for the entire region (Table 14). It is expected that a larger amount of soil loss occurs in the Spring period when soil is more

susceptible to erosion due to its partially frozen nature and lack of vegetable cover than is provided (Fig. 86 and 87).

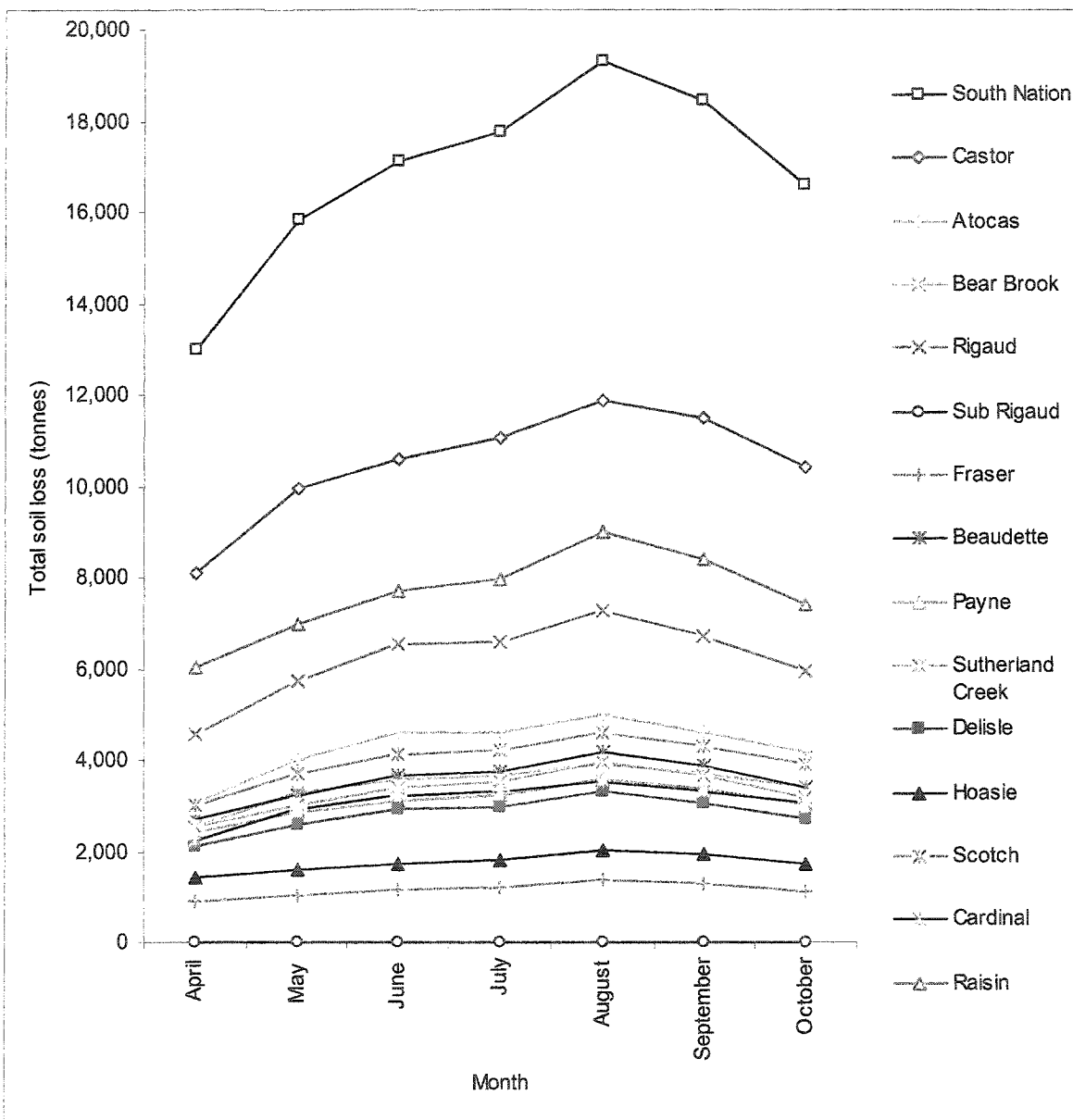


Fig. 86. Total soil loss estimated by month and summarized by watershed, agricultural fields only, USPED masking under the assumption that sheet erosion dominates.

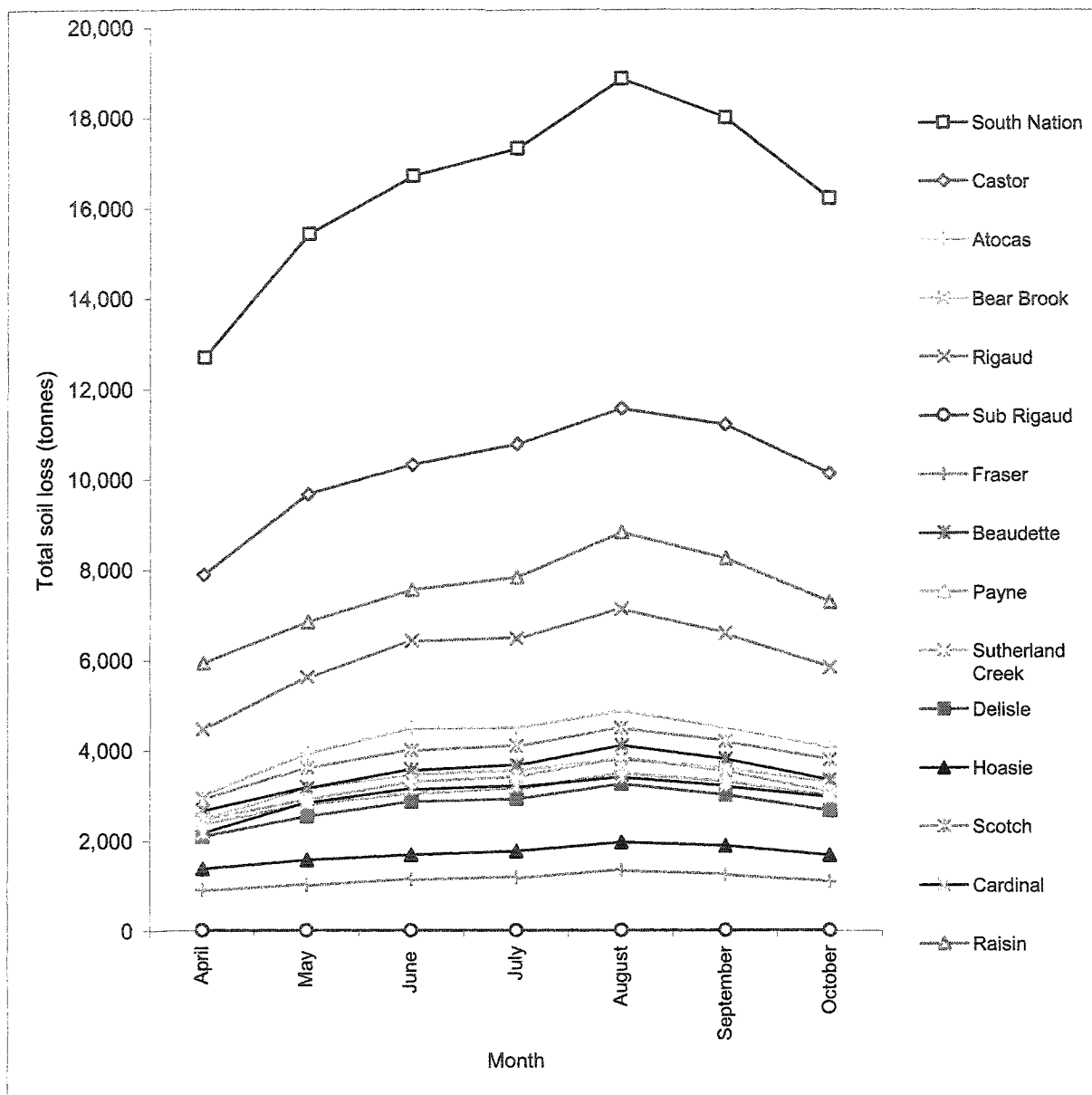


Fig. 87. Total soil loss estimated by month and summarized by watershed, agricultural fields only, USPED masking under the assumption that rill erosion dominates.

Overall, the greatest range of soil loss through the growing season months occurs on the South Nation watershed. This is due to this watershed being the largest and summary values are given as total soil loss within watershed field. Within the South Nation watershed, April total soil loss is roughly 32% less than that found in August and October soil loss is 14% of that found in August. For the Fraser Creek watershed, one of the smaller watersheds in the region, April total soil loss is 33% of that found in August and October soil loss is 19% that found in August. Ratios in other watersheds at roughly the same percentages. Rainfall energy and its effect on soil loss tends to peak in late summer and is sustained in the fall, and is much higher then early spring conditions. Luckily, vegetation cover follows this general increase. However, after early harvesting of certain crop types and the possibility of bare soil being exposed in the early fall there is the possibility of high late season water related soil loss.

An advance in soil loss modeling provided as a result in this thesis is the prioritization of the dominant factors effecting soil loss in the study region. This provides information about how strategies could be built to mitigate erosion at the field scale. If the cropping and management factor is found as the most dominant factor in a particular field that is experiencing extreme levels of erosion, it would be effective to change the type of crop growing on that particular field to one that provides overall coverage. If the slope length and steepness factor proves the most dominant factor in an adjacent field, it may be prudent to switch to crop slope cultivation or stripcropping to reduce erosion to tolerable levels.

Figure 88 provides the dominant factor when all factors of the USLE modified for Canadian conditions are compared on a cell by cell basis. Fig. 89 presents the dominant factor when the LS and C factor are compared independently on a cell by cell basis. The results of these two maps are summarized by watershed and are provided in tabular format as Table 21 and 22.

	South Nation	Castor	Atocas	Bear Brook	Rigaud	Sub Rigaud	Fraser	Beaudette	Payne	Sutherland	Delisle	Hoasic	Scotch	Cardinal	Raisin
R factor	92.5	92.0	86.8	87.7	80.9	73.9	72.5	64.0	86.1	89.2	68.4	94.9	89.8	82.2	76.0
LS factor	7.5	8.0	13.2	12.3	19.1	26.1	27.5	36.0	13.9	10.8	31.6	5.1	10.2	17.8	24.0

Table 21. Percentage of field area with soil loss dominated by either slope length and steepness factor or rainfall erosivity factor value. The results are from a comparison of all factor values on a cell by cell basis.

	South Nation	Castor	Atocas	Bear Brook	Rigaud	Sub Rigaud	Fraser	Beaudette	Payne	Sutherland	Delisle	Hoasic	Scotch	Cardinal	Raisin
LS factor	19.4	20.9	30.9	30.3	42.4	51.4	51.6	59.9	33.6	20.4	56.1	21.5	23.6	38.4	48.8
C factor	80.6	79.1	69.1	69.7	57.6	48.6	48.4	40.1	66.4	79.6	43.9	78.5	76.4	61.6	51.2

Table 22. Percentage of field area with soil loss dominated by either slope length and steepness factor or cropping and management factor value. The results are from a comparison of only the LS and C factor on a cell by cell basis.

The examination of dominant ULSE factors for the region revealed that when considering all ULSE factors together, the rainfall erosivity factor was the most dominant, where fifteen of fifteen watersheds are dominated by the rainfall erosivity factor (Table 22). In some areas, however, the LS factor proved the most influential at the cellular level. Those watersheds that tend to be the most highly influenced from LS factor are the Beaudette, Delisle, Fraser, and Raisin River watersheds.

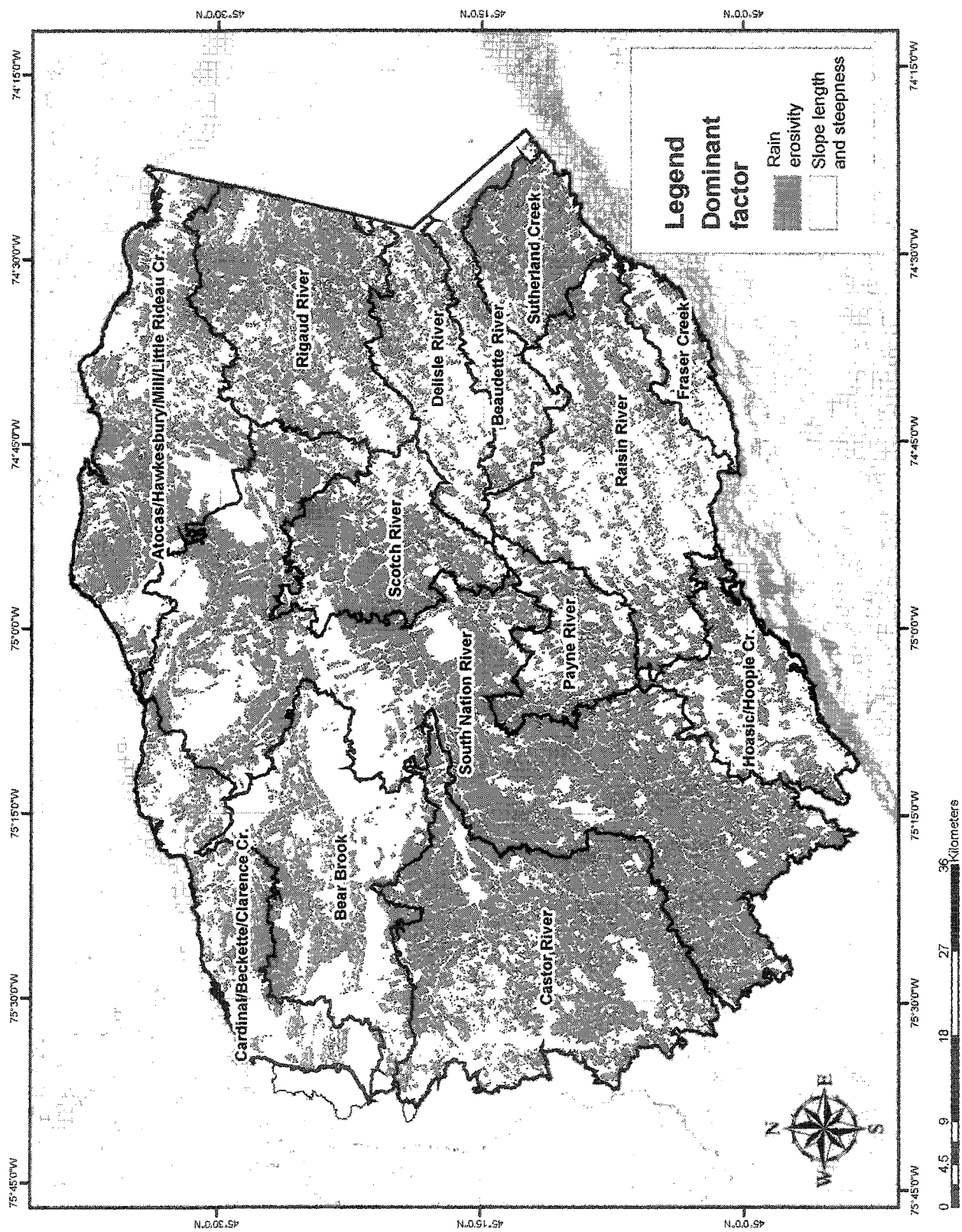


Fig. 88. Dominant factor of the USLE for Canadian conditions, comparison of all factor values (excluding the P factor).

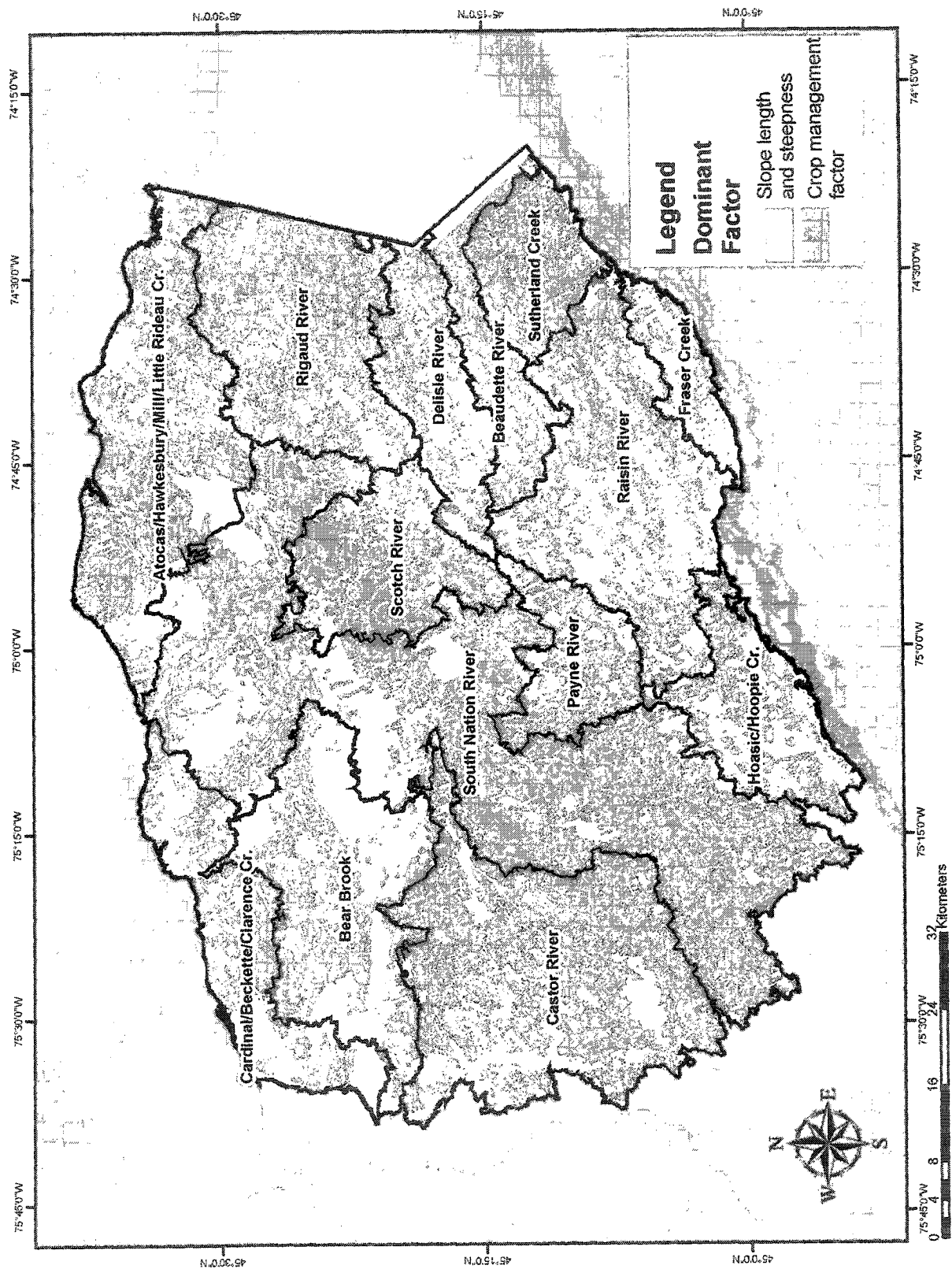


Fig. 89. Dominant factor of the USLE for Canadian conditions, comparison of LS and C factors of the USLE.

This comes as no surprise as these watersheds demonstrated the greatest levels of area contributing intolerable levels of erosion. In fact, those areas that tend to have the highest erosivity values are in most cases located where the slope length and steepness factor dominates. Such results suggest that erosion is dominantly a function of the variation in relief across the study region, and more specifically related to the steepness factor of the merged LS factor.

The slope length and steepness factor and the cropping coefficient factor were compared on a cell by cell basis as these factors of the USLE are unitless unlike the R and K factors. When comparing the LS factor and the C factor for influence on soil loss estimates at the cellular level the C factor dominated on eleven of the fifteen watersheds compared. These watersheds were to the north and west. As expected, the C factor dominated in areas of low relief and in watersheds with low relief. When comparing the C and LS factors the LS factor dominated in the Sub Rigaud, Fraser, Beaudette, and Delisle River watersheds again in areas with higher relief. Generally, other than the R factor the LS factor dominates in areas with high relief for which the LS factor is more effective in causing soil loss. In areas where relief is low the C factor becomes more influential in effecting soil loss. The LS factor dominates along the edge of watercourses and tributaries whereas the R and C factors tend to dominate on field planes and within uniform areas.

The USPED provides insight into the areal extent of erosion. For USPED dominated by sheet erosion, it was estimated that 1,569 km² of field was experiencing net erosion, while 1,309 km² was experiencing net deposition, for a total of 2,879 km² of field area. For USPED dominated by rill erosion, it was estimated that 1,536 km² of field was experiencing net erosion, while 1,342 km² was experiencing net deposition. When examining USPED model maps at the field scale, there is a tendency for depositional areas to run perpendicular to stream courses or

also run parallel to stream course, depending on the location examined. This suggests that the DEM provides finer scale channel areas that are likely not visible or not present in the NRVIS stream course data. This indicates that the USPED model is likely adhering to drainage patterns at finer scales that are provided in the DEM that are not evident in the stream network for which the comparison was made. The stream network dataset does not contain lower order streams or channels that are producible in the DEM. Those depositional areas that are perpendicular to the stream courses are likely modeled properly, indicating that the model could be used in the future to potentially improve or derive lower order stream networks or channels.

Field scale depictions of selective model results obtained in this study are provided to corroborate the use of the USLE, USPED, and the USLE2D models for determining soil loss risk within field areas in the South Nation watershed (Figures 90 to 94). Figure 90 presents soil loss estimates within field and is accompanied by standard errors of the assessment given in Fig. 91. The dominant factor effecting erosion when all model parameters are compared is provided for the same area in Fig. 92, and the dominant factor when only the LS and C factors are compared is given in Fig. 93. Figure 94 presents expected erosion and deposition areas from USPED model outputs.

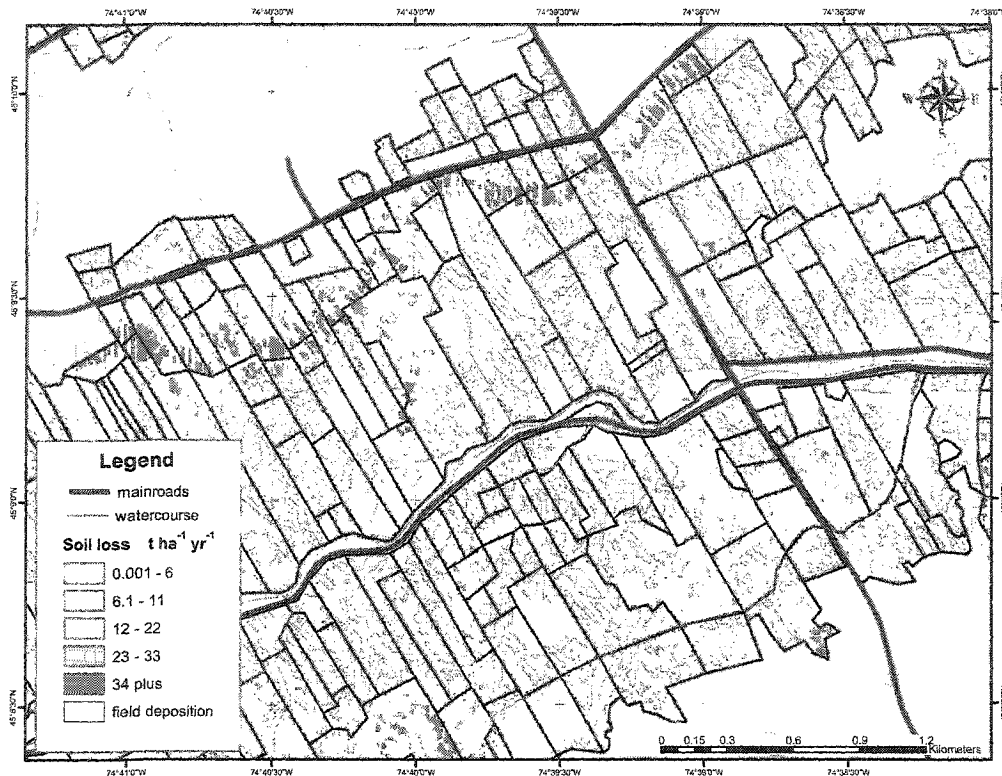


Fig. 90. USLE, USLE2D, USPED soil loss estimate for a portion of South Nation watershed, 25% LS field boundary connectivity, under 2001 conservation tillage practices, erosion dominated by USPED sheet processes.

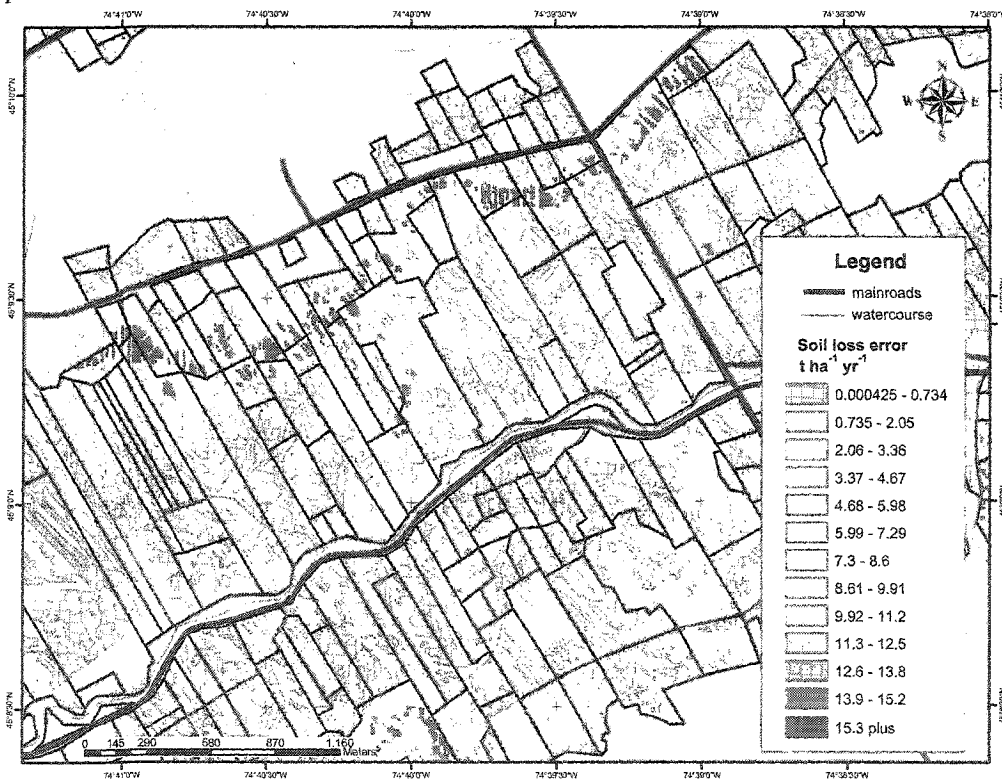


Fig. 91. USLE, USLE2D, USPED soil loss estimate standard errors for a portion of South Nation watershed, 25% LS field boundary connectivity, under 2001 conservation tillage practices, erosion dominated by USPED sheet processes.

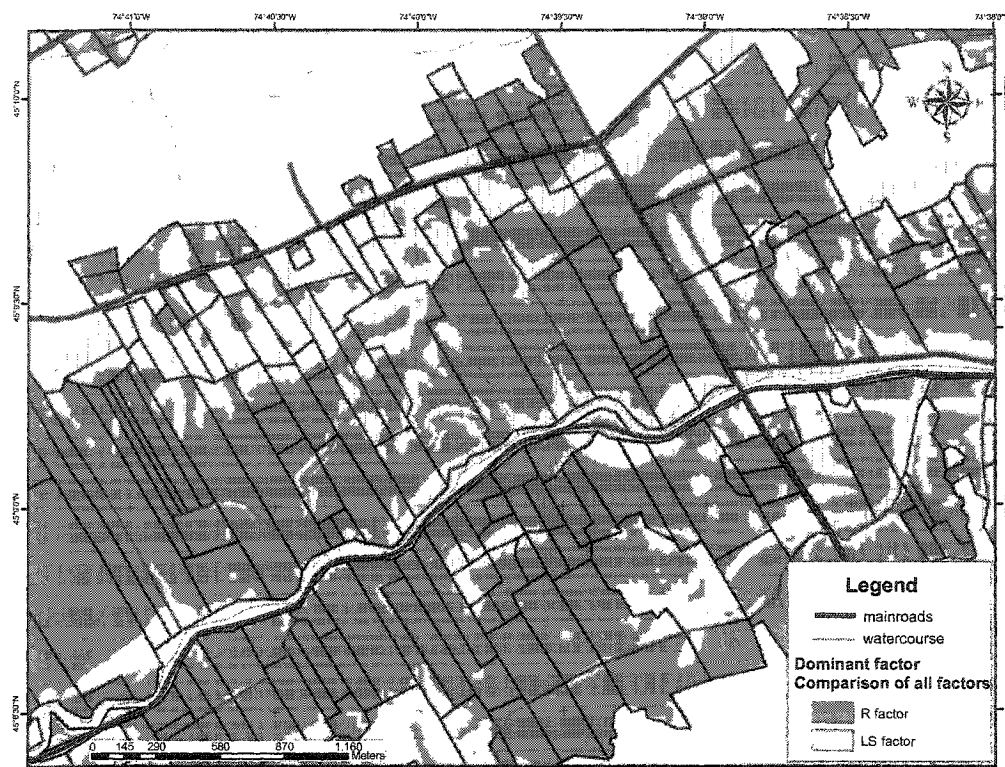


Fig. 92. Most dominant factor effecting erosion when comparing the R, K, LS, and C factors for a portion of South Nation watershed, under 25% LS field boundary connectivity, with 2001 conservation tillage practices.



Fig. 93. Most dominant factor effecting erosion when comparing the LS and C factors for a portion of South Nation watershed, under 25% LS field boundary connectivity, with 2001 conservation tillage practices.

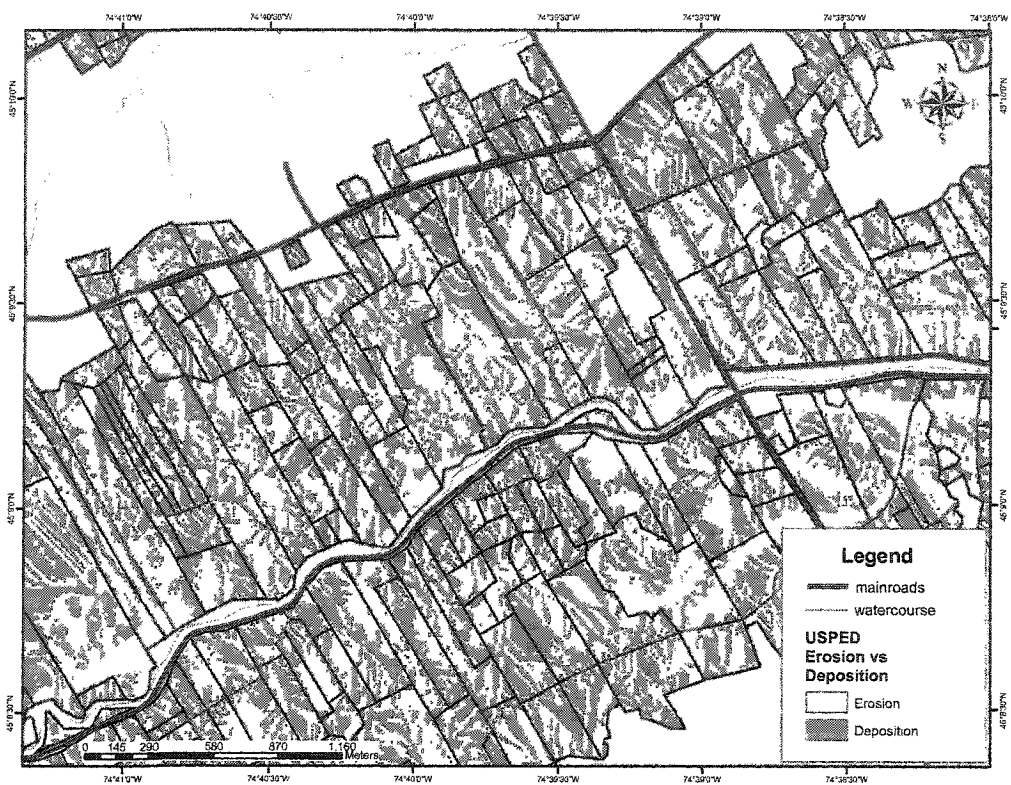


Fig. 94. Erosion and depositional areas calculated using the USPED model for a portion of the South Nation watershed.

3.19 Discussion

The methodology and results presented herein are a step toward quantifying soil loss over the landscape at the field scale. These model outputs require validation at the field scale to assess their accuracy and integrity before the next step is taken in any mitigation of soil loss within the region or within any particular field. This assessment should be understood as one single assessment based on soil erodibility as defined by the K factor from soil survey and cover as assessed during the summer of 2001 using Landsat 7 (ETM+) imagery.

A future direction of research that must be pursued is the assessment of the reliability of the combination of the USLE, USPED, and USLE2D modeled predictions with actual observations of soil loss within the region. This requires the use of experimental plots and/or the potential use of Caesium-137 techniques to assess medium term soil loss and potential soil loss rates. This requires significant field work and allocation of resources if the GIS results are to be verified for reliability. To our knowledge, no monitoring sites of soil loss have been constructed in Eastern Ontario to assess long term erosion losses at the plot scale.

The use of USLE C and K factor parameters which have been developed for the unit plot being applied on more spatially complex landscapes that have complex runoff run on relationships is problematic. The original USLE was designed specifically with no input exterior from the unit plot. This problem has been indicated by Mitsova and Mitsova (1999), who stress that more accurate predictions require that the cover and soil erodibility parameters be recalibrated for specific use with the USPED. This is one future direction of work that would improve soil loss assessment within GIS. However, this difficulty should not undermine the first approximation which indicates that 45.5 to 56.5% of field is potentially experiencing deposition. In regular applications of the USLE, and RUSLE in GIS all 2,878 km² of field would be

expected to contribute net soil loss. This problem is persistent and is addressed in Trimble and Crosson (2000).

An avenue of research that should be investigated is the sensitivity of model estimates of loss to the type of input data utilized in the analysis, with specific reference to the cropping management factor. For this study, field work was performed for in summer of 2003 to characterize the land use and cover in the region to validate the C factor values calculated for the summer of 2001. The satellite sensor that was planned for this purpose was the Landsat 7 Enhanced Thematic Mapper Plus (ETM+) sensor. Unfortunately, in late May early June, an instrument anomaly was discovered which corrupted sensor output, rendering it useless for this investigation. Landsat 5 Thematic Mapper Plus imagery was obtained for the summer of 2003, but images were interspersed with too much cloud cover to obtain acceptable crop classifications. The examination of other sensor outputs and their potential crop classifications would be an interesting and useful study to assess how model outputs are sensitive to the input sensor used, Quickbird imagery, for example, might be useful for the assessment of the C factor.

Limitations to the analysis include the currentness of soil properties used to calculate the erodibility factor, assumption of homogeneity of soil properties within soil polygons, homogeneity of cropping and management properties within particular crop types defined over the landscape, the resolution of the digital elevation model applied to assess the impact of topography on soil loss, and non – calibration of soil and cover properties used to compute erosion and deposition with the USPED model. Nevertheless, faced with these limitations it is still possible to make a relative assessment of soil loss risk within field while accounting for estimate error and estimate accuracy.

Overall, there tends to be more severe soil loss in those watersheds that are in the southeastern section of the study area. There are several USLE factors that interrelate which cause these high soil loss estimates. First, rainfall erosivity is higher in the south. This is likely a result of more long term thunderstorm activity in this area, peaking in late summer, causing an increase in rainfall erosivity in comparison to northern portions of eastern Ontario. This hypothesis is supported by the intensification of the R factor within the months of August and September when thunderstorm activity is at a peak. However, the southern extent of the South Nation watershed shares these high levels of rainfall erosivity during these months and does not experience such high levels of soil loss as that found in adjacent areas to the east.

The LS factor was found as the second dominate factor when all USLE factors were compared within the region. The southern extent of the South Nation watershed is a plateau in contrast to the variable relief that runs in a northeastern band through the Raisin, Payne, Beaudette, Delisle and Rigaud River watersheds. This variable relief is in areas corresponding to higher estimates of the LS factor and subsequent higher estimates in mean annual soil loss. Topography and more specifically slope steepness dominates in this relationship. Further, northern areas of the Castor and the Sutherland Creek watershed are also positioned in these areas of higher rainfall erosivity but do not exhibit pronounced levels of erosion as a result of low LS factor values estimates on plateaus.

Superimposed on these southeastern areas of high slope length and steepness and rainfall erosivity are high soil erodibility factor values. Lower soil losses are modeled in the western Raisin River watershed where soil erodibility is lower, in contrast to the higher erodibility found in the eastern section of the Raisin River watershed where a majority of the high soil loss estimates are found.

Cropping and management factor values provide more impact on soil loss in those areas that are flatter. Under such conditions, the LS factor is minimal and the C factors combines with the R and K factors to determine overall soil loss rates. Such interactions of the USLE factors contribute to higher and lower estimates of soil loss over the region.

These results suggest that selective strategies are necessary if a program is invoked to promote best management strategies to reduce soil loss. Certain areas would require the reduction in slope gradient and or length, such as the Bear Brook watershed, while other watersheds, like the Hosaic require more focus on the implementation of different crops and cropping strategies to make a significant change in soil loss estimates, and likely soil losses. Further, the determination of the most dominant factor in soil loss estimates indicates what factors are the most important to derive accurately or most influential in future modeling exercises, and, therefore, require the greatest degree of accuracy in future modeling.

Differences in the quantity of soil loss are large when one compares watershed total loss with no USPED analysis limitation and total loss summarized by watershed that has been masked by USPED sheet and rill dominated erosion. Total losses change by very little under USPED masking for rill erosion and USPED masking for sheet erosion. Even so, overall losses tend to be less when erosion is masked using USPED predominance of rill erosion. Further, there is generally a 50% difference in losses between those sheds that have been refined for assessment based on erosion areas only and those that have not been masked for erosion areas when summing annual soil losses.

An important point to make is that the quantity of net erosion that is occurring may not be as important as the quantity of the type of erosion that is occurring on agricultural fields. Wall *et al.* (2002) provide guidelines for assessing potential soil erosion that combines soil loss into

classes for Canadian conditions based on very, low, moderate, high and extreme categories. All classes excluding very low are considered intolerable and a threat to long term soil productivity. These categories may be over-generalized but they provide a starting point for an assessment of the potential erosion occurring on field over the region. Even with large error, it is evident that these intolerable soil losses are a cause for concern under conventional tillage practices. The results indicate that there is cause for concern over the sustainability of agriculture in the region under conventional and conservation tillage farming practices.

The spatial accuracy of our predictions of soil loss is another issue of discussion. All input factors were reduced ultimately to the scale of the smallest input resolution dataset. This smallest resolution input dataset is that of the input digital elevation model. This was undertaken so that information was not lost during the integration of factor values. However, no information is gained in reducing the resolution of the R, K, LS, and C factors. Given the potential for misleading results, it was deemed necessary that the spatial accuracy be described, using again, the basis of error propagation theory.

Let's assume that the R factor varies little spatially at an extremely large scale. We assume that there is little potential for spatial error in the estimate of R in the region. We know that the soil erodibility can range spatially to the same spatial accuracy as the accuracy provided in the original soil surveys, that being ± 12.5 to ± 32 meters horizontally. We also know that the DEM was provided with a horizontal accuracy of ± 10 meters. With confidence, we can also assume that our cropping and management factor spatial predictions are as accurate as our original Landsat (ETM+) resolution, which is ± 25 meters. Our mapping function can be viewed as:

$$p = f(x_i, x_{i+1}, \dots, x_n) \quad (3.37)$$

where:

p = mapping output from the factor integration,

f = our mapping function,

n = number of input maps,

x_i = our input maps and their associated error.

In the integration of USLE factor values, we can ignore the R factor and P factors, and equation (3.37) can be written as:

$$A = f(K, LS, C) \quad (3.38)$$

where:

A = potential long term annual soil loss,

K = soil erodibility factor (scale accuracy: - ± 12.5 to ± 32 meters),

LS = slope length and gradient coefficient (scale accuracy: - ± 10 meters),

C = cropping management coefficient (scale accuracy: - ± 25 meters).

When combining several variables together, or map variables together, the uncertainty of the accuracy of the mapped variables can be written in the following way:

$$p = \sqrt{\sum_{i=1}^n \delta x_i^2} \quad (3.39)$$

where:

p = mapping output from the factor integration,

x_i = our input maps and their associated error,

n = number of input maps.

When one substitutes the errors given in equation (3.38) into equation (3.39), we find that our output mean annual soil losses are accurate to ± 30 m if the minimal scale for K is used, and up to ± 41 m if the maximum scale for the soil erodibility factor is used. Therefore, the soil loss predictions are spatially accurate to a maximum of 4 cells at a 10 m output resolution.

Finally, at such resolutions and accuracies we were able to show that a significant portion of the area previously classified by the Federal Provincial Crop Insurance Program, the *Environmental Sustainability of Canadian Agriculture – Report of the Agri-Environmental Indicator Project*, and the *Health of Our Soils* study as experiencing tolerable levels of erosion in eastern Ontario were incorrectly classified. At finer modeling scales intolerable levels of erosion become evident whereas at coarser scales soil loss rates seem normal or less severe due to a larger scale of generalization. After consecutive spatial generalizations of the original 10 meter soil loss grid, at 20 m, 40 m resolutions and so on it was found that the spatial integrity of tolerable levels of erosion were not observable at resolutions of 200 m and beyond. Further, at a 1 km resolution identifiable levels of intolerable levels of erosion all but disappear and become too generalized to be of any use in policy formation or policy recommendation. These findings indicate that regional scale assessments of erosion should be performed at resolutions that are no coarser than 200 m for policy formulation and at resolutions of 10 meters and below for precision farming purposes. These recommendations are integral so that investment in such soil loss assessment research provide the most meaningful and effective results for both policy formulation as well as soil loss mitigation strategies. Failure to do so may result in misleading assessments about the severity of erosion occurring on Canadian agricultural land.

3.20 Conclusion

The universal soil loss equation (USLE), universal soil loss equation 2 dimensions (USLE2D), and the unit stream power erosion deposition (USPED) models were applied to replicate warm season soil erosion in eastern Ontario for a variety of cropping management systems and types of erosion for the summer of 2001. The USPED was utilized to map depositional areas so that USLE soil losses could be summarized on areas experiencing net erosion. Associated with these predictions were provided first approximation error estimates of soil loss and the spatial error of the estimates, found to be ± 30 m to ± 41 m. The dominant factors causing erosion were the slope length and steepness factor. It was possible to predict within plot soil losses that are applicable for precision farming using GIS and Geographic Information Science. A number of farming and erosion scenarios were applied to examine the range of potential losses under a variety of farming conditions.

Overall, net losses are shown to be significantly lower when depositional areas are removed when summarizing losses using the USLE. Further, the study also demonstrated the potential for erosion to occur at levels that are intolerable and that pose a risk to agricultural sustainability in eastern Ontario. However, modeled outputs must be further validated for robustness of the thesis results. An excellent medium for the provision of this soil loss information would be the Internet. To summarize, this study provides outputs that can be used to mitigate erosion at the field scale using a novel approach of model integration.

CHAPTER 4

THESIS CONCLUSIONS AND RECOMMENDATIONS

4.1 Thesis Summary and Contributions

A new approach to modeling soil erosion in Canada is presented that improves predictions in those areas that are erosional as defined by the USPED. The approach provides soil loss estimates with an approximate precision of 10 m, with a ± 30 m to ± 41 m accuracy, an accuracy that is acceptable as a first step towards assessment of soil risk to loss for precision farming. This modeled spatial accuracy is slightly less than the accuracy of commercially available Global Positioning Systems, which are normally utilized for precision farming. A second contribution of this research project is the addition of a first approximation modeling error to the quantity of soil that can potentially be lost at a modeling grid cell, which is an important step forward in the USLE methodology when applied in GIS. Few, if any studies that utilize the USLE in GIS provide any error estimates in their outputs. However, the error estimates indicate that it is possible to compare soil loss risk spatially using tolerance classes relatively. A third major contribution of this research is the assessment of erosion within eastern Ontario, for which there have been no large scale analyses in the region at fine spatial scales. Fourthly, an assessment method for prioritizing the most dominant factors effecting erosion in the region is presented for developing mitigation and soil erosion reduction strategies. Such a method for the assessment of the dominant factor effecting erosion can be applied in all areas where it is deemed acceptable to apply the USLE.

A further next step in erosion technology is reducing the time scale over which we apply estimates regionally. This was performed by varying the rainfall factor temporally and holding all other factors constant. This application has its limitations, however, as time varying data relating to soil and cropping management factors is not available in published format for the region. Finally, the last contribution of this study is the development of continuous updated isoerodent maps across the lower Great Lakes region, for improvement of soil loss predictions in the region.

4.2 Recommendations for Future Work

The listed recommendations are given in order of priority.

1. Assess the reliability of soil loss estimates made using the USLE, USLE2D, and USPED with field scale observations of soil loss.
2. Calibrate soil and cover factors of the USPED for eastern Ontario and assess erosion and depositional areas with ground-truthed data.
3. Derive a methodology to assess the support practice factor in the region spatially.
4. Apply sub-component to the USLE, USLE2D, and USPED model integration that accurately models soil loss for partially frozen soil and for Spring conditions.
5. Implement the use of fuzzy boundaries for more accurately modeling soil erodibility transition between soil polygons. Assess experimentally whether smoothing of erodibility over boundaries in GIS replicates transitions found in the field.
6. The creation of updated isoerodent maps for greater North America.
7. The infilling of soil attribute data for those soil types that are missing specific attribute information for eastern Ontario.
8. Apply finer scale imagery for the assessment and derivation of the cropping and management factor.
9. Collect monthly and bimonthly K and C factor values for more accurate representation of soil loss over growing season months.

There are two distinct lines of research that should be investigated and they are the validation of model results and the improvement of input data necessary for the assessment of soil loss risk. The first priority of future research in soil loss assessment using GIS is the collection of field level soil losses for the validation and corroboration of the results found in this study. This is to ensure that the USLE and USLE2D models applied in the region are appropriate even when input parameters such as the cropping and management factor and the soil erodibility factor are calibrated to the study region. If results are not supported by ground-truthing the alteration or selection of a different model may be necessary for application in the region.

This line of research could be associated with an investigation of the appropriate cover and soil erodibility parameter recalibration needed for use with the USPED. Such work would confirm whether or not areas defined as depositional using the USPED are actually depositional at the field scale. A methodology must be developed to assess one major parameter held constant in this study, the support practice factor (P). The support practice factor is influential in effecting erosion but is extremely difficult to apply at the field scale in GIS due to limitations on the collection and storage of this data. The support practice factor is a major variable and its quantification is necessary and should be set as a major priority. Support practice data is difficult to collect using survey methods and remote sensing technology over large regions. Such a methodology would enable a larger scale application of this methodology over Canada, if accompanied by the development of updated isoerodent maps. This model refinement should be accompanied by a sub model which accounts for increases in soil losses due to Spring snow melt conditions. Supplementary to this improvement should be an investigation of the use of fuzzy boundaries to provide more gradual transition in erodibility between soil map units and to assess whether such smooth transitions are found in reality. This may refine or improve soil loss

estimates found in this study. Results may be further improved with the use of centimeter to meter resolution imagery to derive the cropping and management factors and reducing the temporal scale over which the K and LS factors are applied.

Finally , the model results will have to be dissiminated in some way to farmers and land managers over an easily accessible medium. We believe that the development of an on-line mapping system would be most beneficial. This system would allow users to enter addresses or coordinates to create maps with field boundaries and erosion estimates for examination of soil loss potential where they live or farm. Further, the user could also specify current and future cropping and management parameters or support practices to refine estimates on-line to build more complex scenarios that more accurately reflect current land use practices. Such a system would provide necessary data for precision farming to those that need it most, the farmer/conservation, in an effort to make them better stewards of one of our most precious resources. This is feasible given the current state of GIS-based webserver technologies.

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APPENDIX A: DESCRIPTION OF SELECTED THESIS ABBREVIATIONS

ANSWERS (Bouraoui and Dillaha, 1996; Bouraoui and Dillaha, 2000) - Areal Nonpoint Source Watershed Environment Response Simulation. A process based event model that has limited applicability beyond single rainfall events and small watersheds. It was developed at Purdue University's Agricultural Engineering Department for control of erosion processes within watersheds. Components of ANSWERS include a modified version of the USLE, adjustments for sedimentation and transport, and budgeting of nitrogen and phosphorous within cellular regions. This model has been linked to GIS, such as GRASS (Mitasova and Neteler, 2004), IDRISI (Clarke University, 1999), and ArcInfo (ESRI, 1996), with emphasis on modeling topography using a gridded tessellation of elevation. Beasley and Higgins (1982) originally created ANSWERS to model sediment delivery, nitrogen leaching and runoff under various best management practices to streams and rivers. It was originally designed for land use planners where data for model calibration was not available (Dillaha et al., 2001). The model is most recently interfaced with ArcInfo and assumes homogeneity within cell boundaries with input data requirements of soil properties, climate, and surface cover. The model replicates water movement (interception, retention, infiltration, percolation) and soil movement processes in 30 second increments during erosion events and daily time steps between events (Dillaha et al., 2001).

CREAMS (Knisel, 1980) - Chemicals Runoff and Erosion from Agricultural Management Systems, a field scale continuous simulation model for the monitoring and assessment of chemicals, runoff, and erosion to assess best management practices. It is a detailed individual

storm model with complex algorithms utilizing factors of the USLE, with additional transportation component for sediment movement. It differs from most other models in that it can compute chemical movement. Detailed soil and crop data are needed as inputs. Original development requirements of the model include a physical basis, non-calibration, simplicity, the estimation of runoff, and percolation. The model assumes crop uniformity within a field, and assesses movements of water with two hydrologic methods – the Soil Conservation Service curve number model and an infiltration based model. The hydrologic method utilized is chosen based on whether hourly or daily inputs are used for the computation of runoff. The curve number method uses a relationship between precipitation and water retention to calculate runoff volume based on an estimated curve number deduced from soil type and antecedent moisture conditions (Singh, 1992; pg. 474). CREAMS also provides a plant sub model which considers mineralization, nitrification, denitrification, plant uptake, and nitrate leaching to model nitrogen movement, and a pesticide component to model movements of pesticides in the soil (Skaggs, 1997). The model runs stand alone from any GIS platform and is written in FORTRAN and runs on DOS or UNIX operating systems (Skaggs, 1997). Further, CREAMS models edge of field loadings of sediment and chemicals (Leonard *et al.*, 1987).

EPIC (Sharpley, 1990) - Erosion Productivity Impact Calculator or also designated the Environmental Policy Integrated Climate. EPIC is a model originally designed by the United States Department of Agriculture (USDA) Agricultural Research Service (ARS), under the Soil Conservation Service (SCS) in collaboration with the Economic Research Service (ERS) for computation of the costs and benefits of soil erosion control. This model was developed to estimate the impact soil erosion has on soil productivity. It is limited to application at the small watershed scale. Since its inception, the model has been expanded to simulate many agricultural

processes. Erosion Productivity Impact Calculator simulates soil erosion, economic conditions, hydrologic conditions, weather, nutrients, plant growth and crop management (Williams *et al.*, 1997). The model is designed to accept input from GRASS and was built in FORTRAN (Williams *et al.*, 1997). Simulation of rainfall runoff is based on several modifications of the USLE, with no budgeting of sediment movement.

GIS – Geographic Information System. A computer system designed to visualize, analyze, query, store, and update spatial data. Computer tools for collecting, storing, retrieving, transforming, and displaying spatial data from the real world for some user defined purpose (Burrough and McDonnell, 1998; page 301).

RUSLE (Renard *et al.*, 1991) – Revised Universal Soil Loss Equation. The revised universal soil loss equation is a modified form of the universal soil loss equation (USLE) which includes more detailed techniques for calculating parameter values due to increased scientific knowledge of the process of erosion since the original development of the USLE. Technical modifications for calculating USLE parameters were performed to improve the predictability of soil loss. Improvements include functions for the seasonal variability of the soil erodibility factor; addition of new scenarios for the support practice factor; slope steepness and length factors reliant on rill to interrill erosion ratios; and adjustments to the support practice factor based on storm severity (Sonneveld and Nearing, 2003). The revised universal soil loss equation is an empirical model designed for predicting average annual soil loss caused by rainfall in the United States and surrounding regions.

RUSLEFAC (Wall *et al.*, 2002) – Revised Universal Soil Loss Equation For Application in Canada. The revised universal soil loss equation is a modified form of the USLE, of which RUSLEFAC has specific factor input values provided for Canadian conditions. The purpose for

the development of RUSLEFAC was to present a reference document which illustrates the methods for estimating water related soil loss for conservation planning and to make available a collection of material required to predict erosion rates in Canada (Wall *et al.*, 2002). The rainfall erosivity factor of RUSLEFAC utilizes Ateshian's (1974) approximation for eastern Canada and British Columbia, while the rainfall erosivity factor for the Prairie regions is computed using Stolte and Wigham's (1988) rainfall erosivity technique enhanced with more up to date data. The soil erodibility factor is calculated using Wischmeier and Smith's (1978) numerical approximation based on soil texture, organic matter, structure, and permeability, or approximations based on textural classes alone calculated for Canadian soils. Within RUSLEFAC it is suggested that the slope length and steepness factor be calculated using the RUSLE guidelines. Finally, the cropping and management and support practice factor have been specifically given in the handbook for locals throughout the Canada.

USLE (Wischmeier and Smith, 1965) – Universal Soil Loss Equation. An empirical model of soil loss susceptibility or potential for movement that is multiplicative in nature with six parameters, rainfall erosivity (climate) - designated R, soil erodibility (soil properties) - designated K, slope length and steepness (topography) - designated LS, cropping conditions (land use) - designated C, and support practice factor (anthropogenic) – designated P, providing an estimate of soil susceptibility to erosion at the field scale.

Empirical models are based on statistically significant relationships between variables collected that were assumed important in causing soil loss, and are only applicable when a reasonable database exists for input into the model (Gregory and Walling, 1973; Morgan, 1995). The model estimates long term soil loss based on sheet and rill erosion, does not model individual rainfall events, and does not include any components for gully, wind, or tillage

erosion. The USLE was designed for conservation planning in the United States and combines 11 000 plot years worth of data from 24 states collected from 1930 to 1950. The term universal in its name is a result of its use and success in estimating water induced soil loss external to the United States where it was originally designed.

The USLE models detachment limited erosion and does not account for deposition interior or exterior to the plot. The soil loss average over the slope is first a function of storm intensity and energy averaged over a minimum of 22 years, which is calculated to a unit quantity. The rainfall erosivity factor (R factor) parameterizes the force of raindrop impact on the detachment of soil. The USLE should not be applied in mountainous regions where runoff provides more energy than rainfall. Further, it should not be used in mountainous regions due to possible differences between rainfall intensity and kinetic energy from that found in the plains of North America. The soil erodibility factor parameterizes how soil will resist dislodgement and detachment from the impact and movement of water. The soil erodibility or K factor is not unitless. The slope length and steepness factors are coefficients that adjust losses related to the length and steepness of a field slope. Based on numerical relationships in the original LS factor equation, longer and steeper field slopes produce more soil loss than do shorter and flatter field slopes. The C factor accounts for the variable of crop canopy, surface cover over the year, soil biomass, and tillage (Wall *et al.*, 2002). The C factor is unitless. Lastly, the support practice factor or P factor coefficient, which is also unitless, represents how anthropogenic factors like cross slope cultivation, contour farming, stripcropping, and terracing reduce overall mean annual soil losses.

USLE2D (Desmet and Govers, 1996a; 1997) - Universal Soil Loss Equation in 2 Dimensions.

USLE2D is a computer program designed to calculate the slope length and steepness (LS)

parameter of the universal soil loss equation from a grid-based elevation model. However, the LS factor is not calculated using the contemporary upslope divide but is adjusted to the area per unit of contour length contributing runoff to a particular point in space under examination. This model combines the benefits of the USLE with hydrologic and mechanical processes of flow convergence and divergence to create a hybrid empirical/physical model to more accurately calculate soil loss in convergent and divergent areas. The USLE2D was introduced in the Journal of Soil and Water Conservation in 1996 to implement the method suggested by Kirkby and Chorley (1967) for slope length and steepness factor calculations applied to a two dimensional landscape by using upslope drainage area per unit contour length as an input into the LS factor calculation. Support for the use of upslope contributing areas is given by Desmet and Govers (1996a), who cite the works of Ahnert (1976), Bork and Hensel (1988), Carson and Kirby (1972), and Moore and Nieber (1989) for additional support for the use of upslope contributing area in the LS factor.

WEPP (Laflen *et al.*, 1997) – Water Erosion Prediction Project. WEPP was developed by the United States Department of Agriculture (USDA) Agricultural Research Service (ARS), NRCS (Natural Resources Conservation Service), the U.S. Forest Service (FS), and the Interior Bureau of Land Management (Flanagan *et al.*, 2001). It is a process based continuous simulation model with a time step component developed to provide estimates as good as those provided by the USLE. WEPP consists of nine major components, 1) climate generation, 2) winter process, 3) irrigation, 4) hydrology, 5) soils, 6) plant growth, 7) residue decomposition, 8) hydraulics of overland flow, 9) and erosion deposition (Bhuyen *et al.*, 2002). WEPP is a set of computer programs designed for modeling soil loss by conservationists. The model is applicable only at the small USLE plot to large field scale. It is not applicable at the large watershed scale.

Characteristics of plant and soil conditions are used to establish whether surface runoff will occur during a storm, after which the amount of detachment, transportation and deposition to channels is calculated to estimate soil loss.

APPENDIX B: VISUAL BASIC CODE FOR PARSING NATIONAL CLIMATIC DATA CENTER (NCDC) HOURLY PRECIPITATION DATA

This program converts a variable width TD 3240 (DSI - 3240) hourly precipitation file (U.S.) to a fixed width comma delimited text file. First open the file in Word Pad or the text processor (program designed to emulate Word Pad) and then save it. Use this saved file as input into the processor. The TD 3240 data is provided with End Of Line (EOL) characters not recognized by VB. Opening and saving the file in Word Pad or the text processor replaces the EOL characters with standard Windows EOL characters. The TD 3240 file extension must be *.txt. Fig. 95. illustrates the processor's graphical user interface (GUI). Following the GUI is the Text Processor interface (Fig. 96).

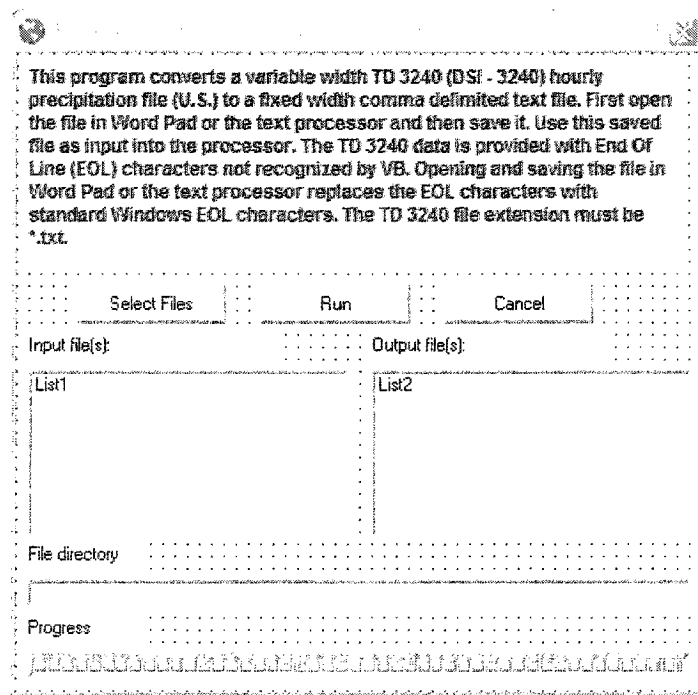


Fig. 95. The graphical user interface used to convert TD 3240 hourly precipitation files from variable width to fixed width format.

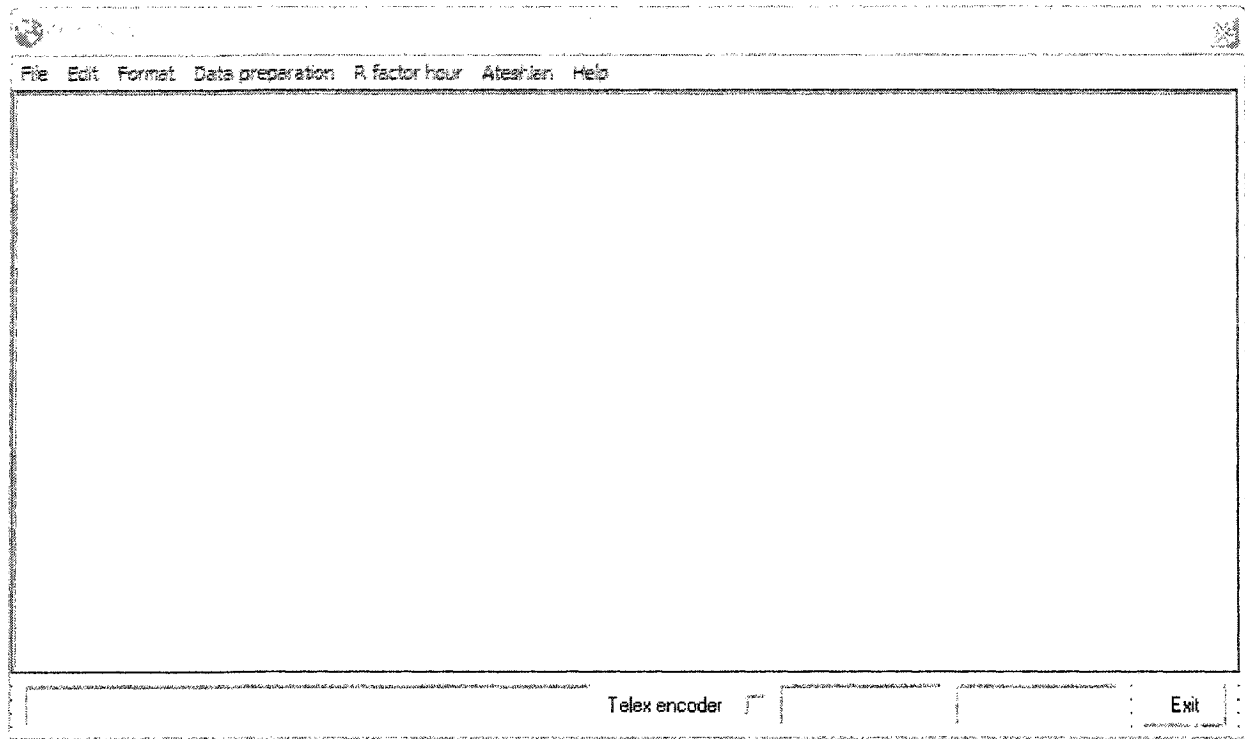


Fig. 96. Depicted above is a text processor created to remove end of line characters not recognized by Visual Basic.

'Globals

Dim DynArray(1, 1000) As String

Dim Counter As Integer

Dim pathName As String

Private Sub Command1_Click()

CommonDialog1.Flags = CommonDialog1.Flags Or cdlOFNAllowMultiselect Or _
cdlOFNHideReadOnly 'Specifies File Namelist, allows multiple selections, hides read only box
CommonDialog1.Filter = "All Files|*.*" 'Set the CommonDialog filter to

Label1.Caption = "" 'Set label1 caption to nothing

List1.Clear 'Clears the contents of a ListBox1

List2.Clear 'Clears the contents of a ListBox2

Command3.Enabled = False

CommonDialog1.ShowOpen 'Open and show the commondialog

filenames = CommonDialog1.filename 'Multiple file names placed in the variable file names

If Len(filenames) = 0 Then 'If the length of filenames is zero then no files were selected

 MsgBox "No files selected", vbOKOnly, "Error" display the previous error

 Exit Sub

End If

Counter = 0 'Counter is used to keep track of the files to process

' Extract path name:

' IF FILETITLE IS NOT EMPTY, THEN A SINGLE FILE

```

' HAS BEEN SELECTED.
If CommonDialog1.FileTitle <> "" Then
    List1.AddItem CommonDialog1.FileTitle 'Add the file title to the list
    DynArray(0, Counter) = CommonDialog1.FileTitle 'Add the title to the array
    DynArray(1, Counter) = InputBox("Enter a name for output. Include the .txt extension: ", _
    "File name", ".txt")
    If DynArray(1, Counter) = "" Then 'If the user input is nothing then
        MsgBox "You have not entered a file name", vbOKOnly, "Error"
        List1.Clear 'Clear list 1
        List2.Clear 'Clear list 2
        Label1.Caption = "" 'Set path to nothing
        Exit Sub
    ElseIf DynArray(1, Counter) = ".txt" Then 'If the user input is .txt only
        MsgBox "You have not entered a file name with you extension", vbOKCancel, "Error"
        List1.Clear 'Clear list 1
        List2.Clear 'Clear list 2
        Label1.Caption = "" 'Set path to nothing
        Exit Sub
    ElseIf Right(DynArray(1, Counter), 4) <> ".txt" Then 'If the user input not .txt only
        MsgBox "You have not entered a proper file extension with your file name", _
        vbOKCancel, "Error"
        List1.Clear 'Clear list 1
        List2.Clear 'Clear list 2
        Label1.Caption = "" 'Set path to nothing
        Exit Sub
    End If
    List2.AddItem DynArray(1, Counter) 'Add to list2 output filename and extension
    MsgBox "The number of files you have selected to process is: " & Counter + 1, vbOKOnly, _
    "File"
    Command3.Enabled = True 'Enable the run command
    Value = Len(DynArray(0, Counter)) 'Determine the length of the filename and extension
    Label1.Caption = Mid(filenamees, 1, Len(filenamees) - Value) 'Set label1 caption to directory
    pathName = Mid(filenamees, 1, Len(filenamees) - Value) 'Set pathname
    MsgBox "Ensure that your directory path is correct. Your directory path is: " & pathName, _
    vbOKOnly, "File" 'Display message
    Counter = 0 'Set counter to zero, needed in the processing loop
    Exit Sub
End If
' filetype is not empty. There were many files selected. We must extract them
spPosition = InStr(filenamees, " ") 'set spPosition to the occurrence of the first space
pathName = Left(filenamees, spPosition - 1)
Label1.Caption = pathName 'Set the caption to pathName
filenamees = Mid(filenamees, spPosition + 1) 'Selects all characters past first space
' then extract each space delimited file name
If Len(filenamees) = 0 Then 'If the length of the file names is 0, then no files selected
    List1.AddItem "No files selected" 'The list has string no files selected added

```

```

Exit Sub
Else
    spPosition = InStr(filenamees, " ") 'set spPosition to the occurrence of the first space
    While spPosition > 0 'While spPosition is greater than zero
        List1.AddItem Left(filenamees, spPosition - 1)
        DynArray(0, Counter) = Left(filenamees, spPosition - 1)
        filenamees = Mid(filenamees, spPosition + 1)
        spPosition = InStr(filenamees, " ")
        Counter = Counter + 1 'Bumps the counter up 1
        MsgBox "This is the input file selected: " & DynArray(0, Counter - 1), vbOKOnly, _
            "File input" 'Display message box this is your input file
        DynArray(1, Counter - 1) = InputBox("Enter a name for the converted file. Include the _
            .txt extension: ", "File output name", ".txt")
        If DynArray(1, Counter - 1) = "" Then 'If the user input was ""
            MsgBox "You have not entered a file name", vbOKOnly, "Error"
            List1.Clear 'Clear list 1
            List2.Clear 'Clear list 2
            Label1.Caption = "" 'Set path to nothing
            Exit Sub
        ElseIf DynArray(1, Counter - 1) = ".txt" Then 'If the user did not input a name
            MsgBox "You have not entered a file name with you extension", vbOKCancel, "Error"
            List1.Clear 'Clear list 1
            List2.Clear 'Clear list 2
            Label1.Caption = "" 'Set path to nothing
            Exit Sub
        ElseIf Right(DynArray(1, Counter - 1), 4) <> ".txt" Then 'If the last 4 characters not .txt
            MsgBox "You have not entered an extension with your file name", vbOKCancel, "Error"
            List1.Clear 'Clear list 1
            List2.Clear 'Clear list 2
            Label1.Caption = "" 'Set path to nothing
            Exit Sub
        End If
        List2.AddItem DynArray(1, Counter - 1) 'Add to list the extracted new name for the file
    Wend
    ' Add the last files name to the list
    ' (the last file name isn't followed by a space)
    List1.AddItem filenamees 'adds the last item to list1
    DynArray(0, Counter) = filenamees 'Sets the last name to the position (0, counter)
    MsgBox "This is the input file selected: " & DynArray(0, Counter), vbOKOnly, "File input"
    DynArray(1, Counter) = InputBox("Enter a name for the converted file. Include the .txt _
        extension: ", "File name", ".txt")
    List2.AddItem DynArray(1, Counter)
    If DynArray(1, Counter) = "" Then 'If the output name given by the user was nothing then
        MsgBox "You have not entered a file name", vbOKOnly, "Error" 'Display message
        List1.Clear 'Clear list 1
        List2.Clear 'Clear list 2
    End If
End Sub

```

```

Label1.Caption = "" 'Set path to nothing
Exit Sub
ElseIf DynArray(1, Counter) = ".txt" Then 'If the output name was not given but ext. was
MsgBox "You have not entered a file name with you extension", vbOKCancel, "Error"
List1.Clear 'Clear list 1
List2.Clear 'Clear list 2
Label1.Caption = "" 'Set path to nothing
Exit Sub
ElseIf Right(DynArray(1, Counter), 4) <> ".txt" Then 'If the extension given by is not .txt
MsgBox "You have not entered an extension with your file name", vbOKCancel, "Error"
List1.Clear 'Clear list 1
List2.Clear 'Clear list 2
Label1.Caption = "" 'Set path to nothing
Exit Sub
End If
End If
MsgBox "The num. of files you have selected to process is: " & Counter + 1, vbOKOnly, "File"
MsgBox "Ensure directory path is correct. Your dir. path is: " & pathName, vbOKOnly, "File"
Command3.Enabled = True 'Enable the run command
End Sub

Private Sub Command2_Click()
Unload Me
End Sub

Private Sub Command3_Click()
Dim theFile As String 'Sets a variable thefile as string
Dim outFile As String 'Sets a variable outfile as string
Dim currentLine1 As String 'Sets a variable currentLine as string
Dim currentLine2 As String 'Sets a variable currentLine as string
Dim currentlinecount1 As Variant 'Set the currentlinecount1 as variant
Dim currentlinecount2 As Variant 'Set the currentlinecount2 as variant
Dim lineHeader As String 'Sets a variable lineHeader as string
Dim lineData As String 'Sets a variable lineData as string
Dim lenData As Long 'Sets a variable lenData as string
Dim OUTARRAY() As Variant 'Set the manipulating array as variant
ReDim OUTARRAY(83, 1) 'Creates 83 rows

For i = 0 To Counter 'Begin a for next loop to process the number of files
theFile = pathName & DynArray(0, i) 'Set theFile as con. of pathName and input filename
MsgBox "The file being processed is (theFile): " & theFile, vbOKOnly, "File being processed"
outFile = pathName & DynArray(1, i) 'Set outFile as con. of pathName and output filename
MsgBox "The output file is (outFile): " & outFile, vbOKOnly, "Output File" 'display message
currentlinecount2 = 0 'Set the currentlinecount2 as zero
'Begins a safety save of the theFile to remove non-Windows EOL characters
Form1.Editor.LoadFile theFile, rtfText 'loads the theFile into the editor.text Window

```

```

Form1.Editor.SaveFile theFile, rtfText 'saves theFile with Windows carriage returns
Form1.Editor.Text = "" 'remove the text from the Editor Window
'This loop determines the number of lines to process
Open theFile For Input As #1 'open the file to process for input as 1
    Do While Not EOF(1) 'Do while not at the end of the file
        Line Input #1, currentLine2 'Reads a single line file and assigns to currentLine2
        currentlinecount2 = currentlinecount2 + 1 'Add one to currentlinecount2
    Loop
    'Display a message box indicating the number of lines processed
    MsgBox "The number of lines in the file to process is: " & currentlinecount2, vbOKOnly, _
        "Lines processed"
Close 1
currentlinecount1 = 0 'Reset the currentlinecount1 variable to 0
Open theFile For Input As #1 'Opens file theFile for input and names theFile as 1
Open outFile For Output As #2 'Opens file outFile for output and names theFile as 2
'Print to outFile 2 the following line
Print #2, _
"Rectype,StID,ELEMTYP,ELEMUNIT,YEAR,MONTH,DAYOFMON,NUMVALS,100F1
F2,200F1F2,300F1F2,400F1F2,500F1F2,600F1F2,700F1F2,800F1F2,900F1F2,1000F1F2,1
100F1F2,1200F1F2,1300F1F2,1400F1F2,1500F1F2,1600F1F2,1700F1F2,1800F1F2,1900F1
F2,2000F1F2,2100F1F2,2200F1F2,2300F1F2,2400v,2500F1F2"
Parses with tags in data achieved when writing to file
Do While Not EOF(1) 'Do loop while not at the end of the file
    Line Input #1, currentLine 'Reads a single line assigns to currentLine2
    linestartinfo = Left(currentLine, 30) 'gets header, retrieves the 1st 30 chr.,sets to linestart
    'Add line header to array, retrieves 1st 30 char. in each line and output parses into array
    'The column represents station recording for the day
    OUTARRAY(1, 1) = Mid(linestartinfo, 1, 3) 'Outarray record 1, column - currentline, _
    is equal variant retrieval (String - linestartinfo) at pos. 1 for 3 chr.
    OUTARRAY(2, 1) = Mid(linestartinfo, 4, 8) 'Outarray record 2, column - currentline, _
    is equal variant retrieval (String - linestartinfo) at pos. 4 for 8 chr.
    OUTARRAY(3, 1) = Mid(linestartinfo, 12, 4) 'Outarray record 3, column - currentline, _
    is equal variant retrieval (String - linestartinfo) at pos. 12 for 4 chr.
    OUTARRAY(4, 1) = Mid(linestartinfo, 16, 2) 'Outarray record 4, column - currentline, _
    is equal variant retrieval (String - linestartinfo) at pos. 16 for 2 chr.
    OUTARRAY(5, 1) = Mid(linestartinfo, 18, 4) 'Outarray record 5, column - currentline, _
    is equal variant retrieval (String - linestartinfo) at pos. 18 for 4 chr.
    OUTARRAY(6, 1) = Mid(linestartinfo, 22, 2) 'Outarray record 6, column - currentline, _
    is equal variant retrieval (String - linestartinfo) at pos. 22 for 2 chr.
    OUTARRAY(7, 1) = Mid(linestartinfo, 24, 4) 'Outarray record 7, column - currentline, _
    is equal variant retrieval (String - linestartinfo) at pos. 24 for 4 chr.
    OUTARRAY(8, 1) = Mid(linestartinfo, 28, 3) 'Outarray record 8, column - currentline, _
    is equal variant retrieval (String - linestartinfo) at pos. 28 for 3 chr.
    'c(3,8,4,2,4,2,4,3)
    'takes from the right of currentLine string the length minus 30 - determines the length, _
    then takes characters from right less those retrieved above

```

```

lineData = Right(currentLine, Len(currentLine) - 30) 'gets the data section of each line
lenData = Len(lineData) / 12 'determines the number of chr. retrieved, divides by _
[6(prec.value)+4(hour)+1(flag)+1(flag)] = 12 to determine number of records
For k = 1 To lenData 'Loop from 1 to number of records
    thisrecord = Left(lineData, 12) 'retrieves the first twelve characters of linedata – the _
    first record in linedata
    thetime = Mid(thisrecord, 1, 4) 'takes the first four chr. as variable the time
    thevalue = Mid(thisrecord, 5, 6) 'at pos. 5 take the next six chr. and save as the value
    flag1 = Mid(thisrecord, 11, 1) 'at pos. 11 take the 1st chr. as variable flag1
    flag2 = Mid(thisrecord, 12, 1) 'at pos. 12 take the 1st chr. as variable flag2
    'put the variables in the array
    arraysub = CInt(thetime) / 100 'coerces thetime to an integer then divides by 100 - _
    gives us an hour value (0100/100 = hr 1)
    OUTARRAY(arraysub + 8, 1) = thevalue 'the 1st 8 records are above, the next _
    value is placed in 8 + array sub (if arraysub = 1, then record 9 depicts hr 1 recording)
    'parsed into as 1-8 heading, 9-33 values, 33-58 flag1, 58-83 flag2
    OUTARRAY(arraysub + 33, 1) = flag1 'sets the first flag to record 34 and above
    OUTARRAY(arraysub + 58, 1) = flag2 'sets the second flag to record 58 and above
    'first 8 records set heading values, 9 to 33, recordings, 33 to 58, flag1, 58 to 83 flag2
    lineData = Right(lineData, Len(lineData) - 12) 'retrieves the length of linedata _
    minus the recently selected 12 from the left and assigns to line data
Next
'uses previous count of lines to determine progress through loop
currentlinecount1 = currentlinecount1 + 1 'Bump line count up by one
Form5.ProgressBar1.Value = (currentlinecount1) * 100 / (currentlinecount2 + 1)
For j = 1 To 8 'Comma delimits the headers to currentlineout
    currentlineout = currentlineout + "," + OUTARRAY(j, 1)
Next j
For k = 9 To 33 'Comma del. the con of value, flag1, flag2 and sets to currentlineout
    currentlineout = currentlineout + "," + OUTARRAY(k, 1) + OUTARRAY(k + 25, _
    1) + OUTARRAY(k + 50, 1)
Next k
Print #2, Right(currentlineout, Len(currentlineout) - 1) 'Writes display-formatted data
currentlineout = "" 'Set the currentlineout variable to nothing
Erase OUTARRAY 'Reinitializes the elements of fixed-sizearrays
ReDim OUTARRAY(83, 1)
Loop 'End Do While Loop
Close 1
Close 2
Form5.ProgressBar1.Value = 0 'Set the progress bar value to 0
Form1.Editor.LoadFile outFile, rtfText 'loads the outFile into the editor.text Window
Form1.Editor.SaveFile outFile, rtfText 'saves the outFile with the same name to create proper
Windows carriage returns
Form1.Editor.Text = "" 'remove the text from the Editor Window
Form5.ProgressBar1.Value = 0 'Set the progress bar value to 0
currentlinecount2 = 0 'Reset the currentlinecount2 variable to 0

```



```
    currentlinecount1 = 0 'Reset the currentlinecount1 variable to 0
Next i
List1.Clear 'Clear list 1
List2.Clear 'Clear list 2
Label1.Caption = "" 'Set path to nothing
MsgBox "Finished processing!", vbOKOnly, "End"
End Sub

Private Sub Form_Load()
Command3.Enabled = False 'disable the run command on load
End Sub
```

APPENDIX C: SQL STATEMENT FOR THE AGGREGATION OF DATE AND TIME INFORMATION IN RAINFALL DATABASE

The following provides an example argument passed to a SQL statement in Microsoft Access to unify separate year, month, and day columns into one date/time column that Access can work more effectively. This example works on table 610, which contains separate columns for Year – YR, Month – MO, and Day – DY. This query is designed to unify the separate date values in each table so that the date is listed in one unique column for sorting and selection. The new column Field1 must already be present within the table to accept the concatenated dates. The argument passed to Structure Query Language is as follows:

```
Update 610  
Set Field1 = CDate(MO & "/" & DY & "/" & YR)  
Where MO > 0
```

There are no months that are attributed month “0” in this dataset so all records are updated. A special piece of advice is provided here, if using extremely large flat files like the rainfall records imported into Microsoft Access, you are likely to receive the following error when undertaking an update query on the table- “Microsoft Access can’t change the data type. There isn’t enough space or memory.” Use the regedit.exe utility of Microsoft XP from the Start/Programs/Run to edit the Windows registry to increase max file locks per file to a value beyond which it was previously set (in my case I set maxfilelocks 200 000). This is under the following tree:

```
HKEY_Local_Machine\Software\Microsoft\Jet\4.0\Engines\Jet 4.0
```

APPENDIX D: VISUAL BASIC FOR
APPLICATIONS CODE FOR STANDARDIZATION
OF MISSING U.S. RAINFALL DATA

Within the ASCII text files for rainfall data for the states of Michigan, Ohio, Pennsylvania, and New York there were essentially two sets of unknown depicted with 99999, 99999M represents missing data while 99999D represents a deleted period. These records were replaced by -99999M which corresponds to the Canadian automated population of an empty cell or recording, essentially a population of a null value. This was performed in Microsoft Access with the following code in a multiple update passed to Access via Microsoft Visual Basic for Applications for both scenarios.

Scenario 1: Conversion of 99999M to -99999M.

```
Sub MultipleUpdate()  
Dim db As DAO.Database  
Dim strSQL  
Dim fieldnames(23)  
Dim sheet1(3)  
Dim sheet2  
Set db = CurrentDb()  
For i = 0 To 23  
    j = i + 1  
    fieldnames(i) = "HR" & j  
Next i  
'tblHpd30, tblHpd33, tblHpd36, tblHpd20  
sheet1(0) = "tblHpd30"  
sheet1(1) = "tblHpd33"  
sheet1(2) = "tblHpd36"  
sheet1(3) = "tblHpd20"  
For l = 0 To 3  
    sheet2 = sheet1(l)  
    For k = 0 To 23  
        field1 = "[" & fieldnames(k) & "]"  
        strSQL = "Update " & sheet2 & _  
            " Set " & field1 & " = " & "Replace(" & field1 & ", '99999M', '-99999M')" _  
            db.Execute (strSQL)
```

```

    Next k
Next l
'update tablename
'Set FieldName = Replace(FieldName, "Avenue", "Ave")
MsgBox "Finished processing."
End Sub

```

Scenario 2: Conversion of 99999D to -99999M.

```

Sub MultipleUpdate()
Dim db As DAO.Database
Dim strSQL
Dim fieldnames(23)
Dim sheet1(3)
Dim sheet2
Set db = CurrentDb()
For i = 0 To 23
    j = i + 1
    fieldnames(i) = "HR" & j
Next i
'tblHpd30, tblHpd33, tblHpd36, tblHpd20
sheet1(0) = "tblHpd30"
sheet1(1) = "tblHpd33"
sheet1(2) = "tblHpd36"
sheet1(3) = "tblHpd20"
For l = 0 To 3
    sheet2 = sheet1(l)
    For k = 0 To 23
        field1 = "[" & fieldnames(k) & "]"
        strSQL = "Update " & sheet2 & _
            " Set " & field1 & " = " & "Replace(" & field1 & ", '99999D',' -99999M') " _
            db.Execute (strSQL)
    Next k
Next l
'update tablename
'Set FieldName = Replace(FieldName, "Avenue", "Ave")
MsgBox "Finished processing."
End Sub

```

APPENDIX E: VISUAL BASIC FOR APPLICATION
CODE FOR RESETTING OF ABSENCE VALUES
TO "000000"

Due to the conversion from variable width to fixed width storage format, null fields resulted within the database for the states of Michigan, Ohio, Pennsylvania, and New York which were populated to "000000" using the following code. This was performed in Microsoft Access using a multiple update query passed to Access via Microsoft Visual Basic for Applications. This update was performed for all four U.S. tables, so Sheet1 variable was set to tblHpd30, tblHpd33, tblHpd36, tblHpd20 in each separate pass applied to the database.

```
Sub MultipleUpdate()
Dim db As DAO.Database
Dim strSQL
Dim fieldnames(23)
Set db = CurrentDb()
For i = 0 To 23
    j = i + 1
    fieldnames(i) = "HR" & j
Next i
'tblHpd30, tblHpd33,tblHpd36, tblHpd20
sheet1 = "tblHpd20"
For k = 0 To 23
    field1 = "[" & fieldnames(k) & "]"
    strSQL = "UPDATE " & sheet1 & " SET " & field1 & _
        "= '000000' WHERE " & field1 & " IS NULL "
    db.Execute (strSQL)
Next k
'update tblHpd??
'SET HR1 = '000000' WHERE HR1 is null
MsgBox "Finished processing."
End Sub
```

APPENDIX F: VISUAL BASIC FOR APPLICATION
CODE FOR CONVERSION OF U.S.
METEOROLOGICAL DATA RECORDED IN
HUNDRETHS OF AN INCH TO TENTHS OF A
MILLIMETRE

U.S. meteorological observations are not provided in the Système Internationale (SI) for hourly rainfall. This is likely due to legacy nature of the data. Thus, recordings must be converted from hundredths of an inch to tenths of a millimeter. This was performed to standardize the U.S. rainfall measurements with the Canadian pluvial recordings. The conversion was performed for each of the imported ASCII text files for the states of Michigan, Ohio, Pennsylvania, and New York in Access. Provided next is the code that was written to undertake the conversion.

```
Sub MultipleUpdate()
Dim db As DAO.Database
Dim strSQL
Dim fieldnames(23)
Dim sheet1(3)
Set db = CurrentDb()
For i = 0 To 23
    j = i + 1
    fieldnames(i) = "HR" & j
Next i
sheet1(0) = "tblHpd30"
sheet1(1) = "tblHpd33"
sheet1(2) = "tblHpd36"
sheet1(3) = "tblHpd20"
For l = 0 To 3
    For k = 0 To 23
        field1 = "[" & fieldnames(k) & "]"
        strSQL = "UPDATE " & sheet1(l) & _
            " SET " & field1 & " = '0' & String(5 - Len(CLng(Left(" & field1 & ", 5) * 2.54)), '0'))" & _
            " & CLng(Left(" & field1 & ", 5) * 2.54) & Mid(" & field1 & ", 6, 2)" & _
            " Where " & field1 & " <> '-99999M'"
        db.Execute (strSQL)
    Next k
Next l
End Sub
```

```
Next l
'update table1
'Set aa = "0" & String(5 - Len(CLng(Left(aa, 5) * 2.54)), "0")_ '& CLng(Left(aa, 5) * 2.54) & _
Mid(aa, 6, 2) 'Where aa <> "-99999M"
MsgBox "Finished processing."
End Sub
```

APPENDIX G: VISUAL BASIC FOR APPLICATION CODE FOR DETERMINING LENGTH OF RECORD FOR U.S. AND CANADIAN METEOROLOGICAL RECORDINGS

The U.S. and Canadian meteorological observations made by meteorological stations were queried to determine length of recorded for each station. This was performed in Microsoft Access using the following Structured Query Language (SQL) statement. Substitution of x with each of the listed table names in Table 23 provides an output representing the length of record at each station in tabular format. Results can then be easily exported to Excel for analysis. With this output one can summarize the length of record for each station and then use these lengths of record for selecting individual station files which meet a standard minimum length of record. During importation into Access, the table names were arbitrarily defined as those shown in the column Table Name.

State/Prov.	Table Name
Ontario	tbl601
Ontario	tbl602
Ontario	tbl603
Ontario	tbl604
Ontario	tbl605
Ontario	tbl606
Ontario	tbl607
Ontario	tbl608
Ontario	tbl609
Ontario	tbl610
Ontario	tbl611
Ontario	tbl612
Ontario	tbl613
Ontario	tbl614
Ontario	tbl615
Ontario	tbl616
Quebec	tbl701
Quebec	tbl702
Quebec	tbl703
Quebec	tbl707
Quebec	tbl708
Michigan	tblHpd20
New York	tblHpd30
Ohio	tblHpd33
Pennsylvania	tblHpd36

Table 23. The table above provides the table names used as input into the application that determines the length of record for each station's recording history.

SQL statement: Selecting the length of record.

```
Select STNID, Max(LENGTH), Min(LENGTH)
From x
Group by STNID
```

APPENDIX H: VISUAL BASIC FOR APPLICATION
CODE FOR SELECTION AND EXPORTATION
OF SPECIFIC U.S. AND CANADIAN
METEOROLOGICAL STATION RECORDINGS

U.S. and Canadian meteorological observations made by meteorological stations were queried to determine length of recorded as demonstrated in Appendix F. After which stations with a length greater than 22 years must be isolated and exported from the Access database to text file format to be read into a program designed to calculate the rainfall erosivity. This selection and exportation was done in Microsoft Access using the following Structured Query Language (SQL) statements passed to Access by means Visual Basic for Applications code. The first set of code performs multiple selection queries based on attributes read from a text file listing station file names (see Table 24). The second set of code exports the selected station queries to comma delimited text file format.

Set 1: Performing isolation queries for specific files listed in text file.

```
Option Compare Database
Function multiple_query()
Dim station_names() As Variant
Dim filenames As String
Dim string1 As String
Dim a As Long
Dim b As Long
Dim i As Long
Dim path As String
Dim tablename
Dim db As DAO.Database
Dim rs As Recordset
Set db = CurrentDb()
Dim qdfNew As QueryDef
filenames = "c:\temp\stationnames_CAN_US.txt"
Open filenames For Input As #1
a = 0
Do While Not EOF(1) 'Do loop while not at the end of 5
```

```

    Line Input #1, currentLine1
    a = a + 1 'Increase a by one
Loop
Close 1
currentLine1 = ""
ReDim station_names(1, a)
b = a
a = 0
Open filenames For Input As #2
Do While Not EOF(2) 'Do loop while not at the end of 5
    Line Input #2, currentLine1
    Mystring = Split(currentLine1, ",")
    station_names(0, a) = Mystring(0)
    station_names(1, a) = Mystring(1)
    a = a + 1 'Increase a by one
Loop
a = 0
Close 2
Dim length As Double
For i = 0 To b - 1
    string1 = station_names(0, i)
    tablename = station_names(1, i)
    'Test length
    length = Len(string1)
    If length = 8 Then
        strSQL = "Select * From " & tablename & _
            " Where STNID = " & string1 & _
            " Order By Date;"
        Set qdfNew = db.CreateQueryDef()
        qdfNew.Name = string1
        qdfNew.SQL = strSQL
        db.QueryDefs.Append qdfNew
    Else
        strSQL = "Select * From " & tablename & _
            " Where STNID = " & "" & string1 & "" & _
            " Order By Date;"
        Set qdfNew = db.CreateQueryDef()
        qdfNew.Name = string1
        qdfNew.SQL = strSQL
        db.QueryDefs.Append qdfNew
    End If
Next i
MsgBox "Done."
End Function

```

Components of the text file read in Set 1. The actual text file listed continuously all the attributes stored in each column. The format for each column is station id, associated table.

Column 1	Column 2	Column 3	Column 4	Column 5
6010738,tbl601	6158733,tbl615	7080452,tbl708	20824600,tblHpd20	30611900,tblHpd30
6012198,tbl602	6158875,tbl615	7080468,tbl708	20829300,tblHpd20	30618400,tblHpd30
6020379,tbl602	6166418,tbl616	20012800,tblHpd20	20841700,tblHpd20	30631400,tblHpd30
6034075,tbl603	6166450,tbl616	20016400,tblHpd20	20855900,tblHpd20	30646400,tblHpd30
6036904,tbl603	7011982,tbl701	20023000,tblHpd20	20921800,tblHpd20	30662300,tblHpd30
6037775,tbl603	7012240,tbl701	20048900,tblHpd20	30004200,tblHpd30	30668500,tblHpd30
6041221,tbl604	7013362,tbl701	20063100,tblHpd20	30004700,tblHpd30	30676800,tblHpd30
6047810,tbl604	7014160,tbl701	20066200,tblHpd20	30027000,tblHpd30	30682500,tblHpd30
6048261,tbl604	7015730,tbl701	20073500,tblHpd20	30033100,tblHpd30	30683900,tblHpd30
6055210,tbl605	7016294,tbl701	20076600,tblHpd20	30068700,tblHpd30	30713400,tblHpd30
6057592,tbl605	7016800,tbl701	20105400,tblHpd20	30076600,tblHpd30	30716700,tblHpd30
6068150,tbl606	7016900,tbl701	20113300,tblHpd20	30078500,tblHpd30	30739800,tblHpd30
6073960,tbl607	7016932,tbl701	20135200,tblHpd20	30086200,tblHpd30	30749700,tblHpd30
6075425,tbl607	7017100,tbl701	20149700,tblHpd20	30101200,tblHpd30	30751300,tblHpd30
6076572,tbl607	7018000,tbl701	20168000,tblHpd20	30118500,tblHpd30	30754900,tblHpd30
6085700,tbl608	7020305,tbl702	20170400,tblHpd20	30120700,tblHpd30	30783000,tblHpd30
6100971,tbl610	7020840,tbl702	20178000,tblHpd20	30152100,tblHpd30	30824800,tblHpd30
6101901,tbl610	7021320,tbl702	20192200,tblHpd20	30162300,tblHpd30	30838300,tblHpd30
6104025,tbl610	7022160,tbl702	20209400,tblHpd20	30170800,tblHpd30	30849800,tblHpd30
6104175,tbl610	7022494,tbl702	20210200,tblHpd20	30194900,tblHpd30	30850600,tblHpd30
6105976,tbl610	7022720,tbl702	20210300,tblHpd20	30196600,tblHpd30	30850700,tblHpd30
6106000,tbl610	7022800,tbl702	20239500,tblHpd20	30197900,tblHpd30	30858600,tblHpd30
6106400,tbl610	7023677,tbl702	20262600,tblHpd20	30198700,tblHpd30	30872000,tblHpd30
6115820,tbl611	7024280,tbl702	20267400,tblHpd20	30219800,tblHpd30	30873900,tblHpd30
6116132,tbl611	7024320,tbl702	20278400,tblHpd20	30227700,tblHpd30	30883900,tblHpd30
6119500,tbl611	7025250,tbl702	20284600,tblHpd20	30245400,tblHpd30	30891000,tblHpd30
6127514,tbl612	7025280,tbl702	20317000,tblHpd20	30252600,tblHpd30	30894400,tblHpd30
6131982,tbl613	7025745,tbl702	20319900,tblHpd20	30258200,tblHpd30	30900000,tblHpd30
6136606,tbl613	7026839,tbl702	20329500,tblHpd20	30295300,tblHpd30	30907200,tblHpd30
6137287,tbl613	7027040,tbl702	20333300,tblHpd20	30318400,tblHpd30	30922900,tblHpd30
6139525,tbl613	7027200,tbl702	20351600,tblHpd20	30385100,tblHpd30	30937400,tblHpd30
6140954,tbl614	7027283,tbl702	20355100,tblHpd20	30397000,tblHpd30	30938900,tblHpd30
6142285,tbl614	7027302,tbl702	20358000,tblHpd20	30398300,tblHpd30	30940000,tblHpd30
6142400,tbl614	7027320,tbl702	20393600,tblHpd20	30402500,tblHpd30	30944200,tblHpd30
6144475,tbl614	7027656,tbl702	20394700,tblHpd20	30407000,tblHpd30	30957600,tblHpd30
6146714,tbl614	7027725,tbl702	20409000,tblHpd20	30410200,tblHpd30	30967000,tblHpd30
6148105,tbl614	7027750,tbl702	20415500,tblHpd20	30417400,tblHpd30	33005800,tblHpd33
6149387,tbl614	7027802,tbl702	20423900,tblHpd20	30420700,tblHpd30	33005900,tblHpd33
6149625,tbl614	7028124,tbl702	20432800,tblHpd20	30442400,tblHpd30	33010700,tblHpd33
6150689,tbl615	7028441,tbl702	20464100,tblHpd20	30455500,tblHpd30	33025600,tblHpd33
6150830,tbl615	7028676,tbl702	20495900,tblHpd20	30461300,tblHpd30	33049300,tblHpd33
6151042,tbl615	7028906,tbl702	20517800,tblHpd20	30512900,tblHpd30	33063900,tblHpd33
6151137,tbl615	7028946,tbl702	20556900,tblHpd20	30534600,tblHpd30	33104200,tblHpd33
6153020,tbl615	7031375,tbl703	20571200,tblHpd20	30537700,tblHpd30	33111300,tblHpd33
6153194,tbl615	7034480,tbl703	20581600,tblHpd20	30559700,tblHpd30	33118200,tblHpd33

Column 6	Column 7	Column 8	Column 9
33158100,tblHpd33	33587800,tblHpd33	36158900,tblHpd36	36606700,tblHpd36
33159200,tblHpd33	33589400,tblHpd33	36170500,tblHpd36	36611100,tblHpd36
33164200,tblHpd33	33612300,tblHpd33	36172600,tblHpd36	36623300,tblHpd36
33165100,tblHpd33	33619600,tblHpd33	36196100,tblHpd36	36641900,tblHpd36
33165700,tblHpd33	33637500,tblHpd33	36216000,tblHpd36	36668100,tblHpd36
33177000,tblHpd33	33638400,tblHpd33	36224500,tblHpd36	36668900,tblHpd36
33178600,tblHpd33	33640500,tblHpd33	36226000,tblHpd36	36672400,tblHpd36
33178800,tblHpd33	33649300,tblHpd33	36226500,tblHpd36	36679200,tblHpd36
33181800,tblHpd33	33661600,tblHpd33	36229800,tblHpd36	36688900,tblHpd36
33190500,tblHpd33	33665000,tblHpd33	36232500,tblHpd36	36691600,tblHpd36
33207500,tblHpd33	33670200,tblHpd33	36234300,tblHpd36	36692700,tblHpd36
33209000,tblHpd33	33678100,tblHpd33	36262900,tblHpd36	36699300,tblHpd36
33209800,tblHpd33	33688200,tblHpd33	36264400,tblHpd36	36699700,tblHpd36
33212400,tblHpd33	33694900,tblHpd33	36268200,tblHpd36	36702900,tblHpd36
33220500,tblHpd33	33717900,tblHpd33	36272100,tblHpd36	36711600,tblHpd36
33227200,tblHpd33	33733300,tblHpd33	36294200,tblHpd36	36718600,tblHpd36
33230500,tblHpd33	33737500,tblHpd33	36301800,tblHpd36	36721700,tblHpd36
33248500,tblHpd33	33738300,tblHpd33	36302800,tblHpd36	36722900,tblHpd36
33251200,tblHpd33	33755900,tblHpd33	36322300,tblHpd36	36731000,tblHpd36
33279100,tblHpd33	33769800,tblHpd33	36329800,tblHpd36	36731400,tblHpd36
33290500,tblHpd33	33793500,tblHpd33	36331100,tblHpd36	36731800,tblHpd36
33295600,tblHpd33	33802000,tblHpd33	36332100,tblHpd36	36741000,tblHpd36
33297400,tblHpd33	33824000,tblHpd33	36333000,tblHpd36	36754000,tblHpd36
33302100,tblHpd33	33835700,tblHpd33	36351500,tblHpd36	36773200,tblHpd36
33304200,tblHpd33	33837800,tblHpd33	36369900,tblHpd36	36784600,tblHpd36
33312000,tblHpd33	33853900,tblHpd33	36400100,tblHpd36	36785500,tblHpd36
33335600,tblHpd33	33855200,tblHpd33	36401900,tblHpd36	36793100,tblHpd36
33337500,tblHpd33	33877400,tblHpd33	36402700,tblHpd36	36793800,tblHpd36
33348300,tblHpd33	33879400,tblHpd33	36404400,tblHpd36	36796500,tblHpd36
33375800,tblHpd33	33921100,tblHpd33	36416600,tblHpd36	36802600,tblHpd36
33400400,tblHpd33	33922400,tblHpd33	36421400,tblHpd36	36805700,tblHpd36
33418900,tblHpd33	33929800,tblHpd33	36430400,tblHpd36	36818400,tblHpd36
33440300,tblHpd33	33931200,tblHpd33	36432500,tblHpd36	36819000,tblHpd36
33445900,tblHpd33	33935700,tblHpd33	36439000,tblHpd36	36827500,tblHpd36
33447300,tblHpd33	33940600,tblHpd33	36443200,tblHpd36	36837900,tblHpd36
33455600,tblHpd33	33942200,tblHpd33	36476300,tblHpd36	36844900,tblHpd36
33467200,tblHpd33	36010600,tblHpd36	36477800,tblHpd36	36846900,tblHpd36
33468600,tblHpd33	36014700,tblHpd36	36489600,tblHpd36	36849100,tblHpd36
33478900,tblHpd33	36020400,tblHpd36	36493400,tblHpd36	36858900,tblHpd36
33486500,tblHpd33	36031300,tblHpd36	36498400,tblHpd36	36859600,tblHpd36
33492400,tblHpd33	36063400,tblHpd36	36499200,tblHpd36	36866800,tblHpd36
33494200,tblHpd33	36072500,tblHpd36	36533600,tblHpd36	36876300,tblHpd36
33497900,tblHpd33	36074300,tblHpd36	36540000,tblHpd36	36887300,tblHpd36
33499200,tblHpd33	36082100,tblHpd36	36560100,tblHpd36	36888500,tblHpd36
33502900,tblHpd33	36107300,tblHpd36	36560600,tblHpd36	36889300,tblHpd36

Column 10	Column 11	Column 12	Column 13
6153300,tbl615	7035290,tbl703	20621500,tblHpd20	30568200,tblHpd30
6155878,tbl615	7035520,tbl703	20630000,tblHpd20	30579600,tblHpd30
6156533,tbl615	7036762,tbl703	20712200,tblHpd20	30580100,tblHpd30
6157831,tbl615	7037400,tbl703	20736600,tblHpd20	30580300,tblHpd30
33504100,tblHpd33	36113900,tblHpd36	36565400,tblHpd36	36890500,tblHpd36
33529700,tblHpd33	36121500,tblHpd36	36567600,tblHpd36	36898200,tblHpd36
33531500,tblHpd33	36126200,tblHpd36	36573100,tblHpd36	36898900,tblHpd36
33539800,tblHpd33	36135400,tblHpd36	36577500,tblHpd36	36902400,tblHpd36
36972800,tblHpd36	20782800,tblHpd20	36148500,tblHpd36	20741900,tblHpd20
6158350,tbl615	20788000,tblHpd20	36152900,tblHpd36	36579000,tblHpd36
33550500,tblHpd33	36581700,tblHpd36	36993800,tblHpd36	30581100,tblHpd30
7074240,tbl707	36591500,tblHpd36	7038040,tbl703	30582100,tblHpd30
7077570,tbl707	36996600,tblHpd36	36137200,tblHpd36	36931200,tblHpd36
36970500,tblHpd36	36904200,tblHpd36	33153600,tblHpd33	36940800,tblHpd36
33119700,tblHpd33	6158520,tbl615	36936700,tblHpd36	33156100,tblHpd33
33125900,tblHpd33	6158665,tbl615	7017BFN,tbl701	33154100,tblHpd33
33140400,tblHpd33	33557300,tblHpd33	30580600,tblHpd30	33574700,tblHpd33
33146600,tblHpd33			

Table 24. Listed in the table above are the station names and tables associated to the stations used for selection and exportation. The actual text file containing these attributes was summarized using multiple columns above. The original text file lists these attributes continuously.

Set 2: After the queries were performed in Set 1, all queried station texts files were exported as comma delimited text files using the following code. The contents of "stationnames_CAN_US.txt" are given above.

```
Option Compare Database
Function test1()
Dim station_names() As Variant
Dim filenames As String
Dim string1 As String
Dim a As Long
Dim b As Long
Dim i As Long
Dim path As String
filenames = "c:\temp\stationnames_CAN_US.txt"
Open filenames For Input As #1
a = 0
Do While Not EOF(1) 'Do loop while not at the end of 1
    Line Input #1, currentLine1
    a = a + 1 'Increase a by one
```

```

Loop
Close 1
currentLine1 = ""
ReDim station_names(0, a)
b = a
a = 0
Open filenames For Input As #2
Do While Not EOF(2) 'Do loop while not at the end of 1 (parsed input prec.
file)
    Line Input #2, currentLine1
    Mystring = Split(currentLine1, ",")
    station_names(0, a) = Mystring(0)
    a = a + 1 'Increase a by one
Loop
a = 0
Close 2
For i = 0 To b - 1
    string1 = station_names(0, i)
    path = "c:\Temp\" & string1 & ".txt"
    DoCmd.OpenQuery string1, acNormal, acEdit
    DoCmd.TransferText acExportDelim, "New_export_mmddyy", string1, path, False, "" _
    DoCmd.Close acQuery, string1
Next i
MsgBox "Finished exported the files for input in the rainfall erosivity utility.", vbOKOnly, _
"Finished exporting."
'Output format, filename – stationnumber.txt
'recordnumber,station,date,type,HR1,
'HR2,HR3,HR4,HR5,HR6,HR7,HR8,HR9,HR10,HR11,HR12,HR13,HR14,HR15,HR17,HR18,
'HR19,HR20,HR21,HR22,HR23,HR24
End Function

```

APPENDIX I: VISUAL BASIC CODE FOR
CALCULATION OF THE ATESHIAN
APPROXIMATION OF THE RAINFALL
EROSIVITY FACTOR

U.S. and Canadian meteorological observations made by meteorological station were queried to determine length of recorded beyond 22 years in Appendix F. These queried tables were then exported (Appendix G) in comma delimited format with no text qualifier for further analysis. A program was created to analyze these outputs and the source code for this program is given below. This utility calculates Ateshian's estimate of the rainfall erosivity factor from hourly precipitation recordings. Requirements for input are a station file in ASCII text comma delimited format with the following format: record number, station number, date, type of recording, recording for hour one, recording for hour two, etc. to hour twenty-four. The user must also provide an adjustment factor for the length of the interval used to store precipitation recordings, the path to which all the text files are stored and the user must select a pre-generated text file containing the text file names with the .txt extension listed sequentially. Provided next is the interface (Fig. 97) developed to accept initial user input and associate code used to calculate the approximation of the rainfall erosivity index.

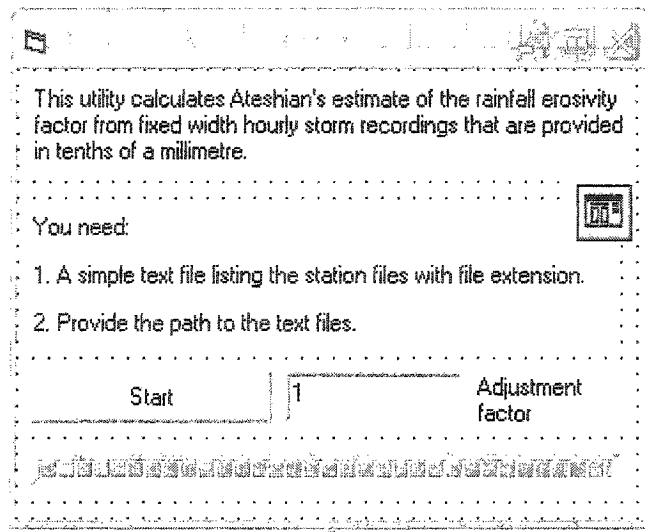


Fig. 97. Graphical user interface of the program designed to calculate Ateshian's estimate of the rainfall erosivity of the USLE. Required inputs for the program are hourly precipitation files.

'Global variable

Dim inputmultiplefactor As Variant

Private Sub Command1_Click()

Dim source_names As String

Dim directory_path1 As String

Dim thefiletitle As String

ProgressBar1.Value = 0

inputmultiplefactor = Text1.Text

CommonDialog1.Flags = CommonDialog1.Flags Or cdlOFNHideReadOnly

CommonDialog1.Filter = "All Files|*.*" 'Set the CommonDialog filter to

MsgBox "Navigate to the location and select the file that contains the storm names.", _
vbInformation, "Attention."

CommonDialog1.ShowOpen 'Open and show the commondialog

source_names = CommonDialog1.filename

thefiletitle = CommonDialog1.FileTitle

If Len(source_names) = 0 Then 'If the length of filenames is zero then no files were selected

MsgBox "No files selected", vbOKOnly, "Error"

Exit Sub

End If

directory_path1 = InputBox("What is the path to the files? Example: c:\Temp\","Attention.")

If directory_path1 = "" Then

MsgBox "Invalid entry. Try again."

Exit Sub

End If

'Read file and store file names and path to array

Dim a As Long 'Counter

a = 0

```

Dim currentLine As String
Open source_names For Input As #1
Do While Not EOF(1)
    Line Input #1, currentLine
    a = a + 1
Loop
Close 1
currentLine = ""
Dim array_names() As String
ReDim array_names(2, a - 1)
Dim name As String
name = ""
a = 0
Open source_names For Input As #2
Do While Not EOF(2)
    Line Input #2, currentLine
    array_names(0, a) = directory_path1 & currentLine 'Input name and dir
    name = ""
    name = Left(currentLine, Len(currentLine) - 4)
    array_names(1, a) = name 'Input file title
    array_names(2, a) = directory_path1 & name & "_maxyear6hr.csv" 'output
    a = a + 1
Loop
Close 2
'Adjust variables
a = a - 1
currentLine = ""
source_names = ""
Dim startdate As Date
Dim enddate As Date
Dim inputfile As String
Dim outputfile As String
Dim linecounter As Double
Dim length As Double
Dim numberdays_startdate_enddate As Double
Dim array_precipitation_values() As Variant
Dim pulleddate As Date
Dim numberhours_startdate_enddate As Double
Dim daydiff_startdate_pulleddate As Double
Dim hourdiff_startdate_pulleddate As Double
Dim increment_hour As Date
Dim bottom As Double
Dim top As Double
Dim pulled_value As Variant
Dim sum_stored_values As Double
Dim sum_stored_values_largest As Double

```

```

Dim stnid As String
Dim date_largest_beginning As Date
Dim date_largest_ending As Date
Dim datetop As Date
Dim datetopplusone As Date
Dim datedifftoptopplusone As Double
Dim sum_in_mm As Double
'Loop through the array of file names
For i = 0 To a
    ProgressBar1.Value = (i + 1) * 100 / (a + 1)
    startdate = 0
    enddate = 0
    inputfile = ""
    outputfile = ""
    linecounter = 0
    length = 0
    sum_in_mm = 0
    'Loop through the input file and find start date and length
    inputfile = array_names(0, i)
    Open inputfile For Input As #3
    Do While Not EOF(3)
        Line Input #3, currentLine
        Mystring = Split(currentLine, ",")
        'Test to see if first date, if so, take date
        If linecounter = 0 Then
            startdate = Mystring(2)
        End If
        linecounter = linecounter + 1
    Loop
    linecounter = linecounter - 1
    length = linecounter
    linecounter = 0
    currentLine = ""
    Close 3
    'Find enddate
    Open inputfile For Input As #4
    Do While Not EOF(4)
        Line Input #4, currentLine
        Mystring = Split(currentLine, ",")
        'Test to see if first date, if so, take date
        If linecounter = length Then
            enddate = Mystring(2)
        End If
        linecounter = linecounter + 1
    Loop
    currentLine = ""

```

```

linecounter = 0
Close 4
Erase Mystring
numberdays_startdate_enddate = 0
'Find number of days between the two dates
numberdays_startdate_enddate = DateDiff("d", startdate, enddate) + 1
numberhours_startdate_enddate = 0
'Find number of hours, zero based
numberhours_startdate_enddate = (numberdays_startdate_enddate * 24) - 1
'Populate array to length of number hours
ReDim array_precipitation_values(1, numberhours_startdate_enddate)
increment_hour = startdate
'Fill the date and hour field and populate all values to missing
For k = 0 To UBound(array_precipitation_values, 2)
    increment_hour = increment_hour + (1 / 24)
    array_precipitation_values(0, k) = increment_hour
    array_precipitation_values(1, k) = "-99999M"
Next k
increment_hour = 0
'Loop through file and populate array
Open inputfile For Input As #5
Do While Not EOF(5)
    Line Input #5, currentLine
    Mystring = Split(currentLine, ",")
    pulleddate = 0
    pulleddate = Mystring(2)
    daydiff_startdate_pulleddate = 0
    daydiff_startdate_pulleddate = DateDiff("d", startdate, pulleddate)
    hourdiff_startdate_pulleddate = 0
    If daydiff_startdate_pulleddate <> 0 Then
        hourdiff_startdate_pulleddate = (daydiff_startdate_pulleddate * 24)
    Else
        hourdiff_startdate_pulleddate = 0
    End If
    For j = 4 To 27
        array_precipitation_values(1, hourdiff_startdate_pulleddate) = Mystring(j)
        hourdiff_startdate_pulleddate = hourdiff_startdate_pulleddate + 1
    Next j
    hourdiff_startdate_pulleddate = 0
Loop
currentLine = ""
linecounter = 0
Close 5
outputfile = ""
outputfile = array_names(2, i)
Open outputfile For Output As #6

```

```

Print #6, "stnid,starttime,endtime,amount_ten_mm,amount_mm"
bottom = 0
top = 0
pulled_value = 0
sum_stored_values_largest = 0
'Loop through the massive array in six hour increment
For j = 0 To (UBound(array_precipitation_values, 2) - 6)
    bottom = j
    top = j + 5
    pulled_value = 0
    sum_stored_values = 0
    'Loop through six hour increment
    For k = bottom To top
        pulled_value = array_precipitation_values(1, k)
        pulled_value = Left(pulled_value, 6)
        If pulled_value = -99999 Then
            pulled_value = 0
        End If
        pulled_value = pulled_value * inputmultiplefactor
        sum_stored_values = sum_stored_values + pulled_value
        pulled_value = 0
    Next k
    'Test whether the value is larger than last store
    'If so, store, if not continue
    If sum_stored_values >= sum_stored_values_largest Then
        sum_stored_values_largest = sum_stored_values
        date_largest_beginning = array_precipitation_values(0, bottom)
        date_largest_ending = array_precipitation_values(0, top)
        sum_stored_values = 0
    End If
    'Test whether top date and next date after top date is one year difference
    'If so dump
    datetop = 0
    datetopplusone = 0
    datetop = array_precipitation_values(0, top)
    datetopplusone = array_precipitation_values(0, top + 1)
    datedifftoptopplusone = 0
    datedifftoptopplusone = DateDiff("yyyy", datetop, datetopplusone)
    stnid = ""
    If datedifftoptopplusone = 1 Or j = (UBound(array_precipitation_values, 2) - 6) Then
        'Pull the stnid
        sum_in_mm = 0
        sum_in_mm = sum_stored_values_largest / 10
        stnid = array_names(1, i)
        If sum_in_mm > 0 Then
            Print #6, stnid & "," & date_largest_beginning & "," & _

```

```

        date_largest_ending & "," & sum_stored_values_largest & "," & sum_in_mm
    End If
    'Reset all the variables
    stnid = ""
    date_largest_beginning = 0
    date_largest_ending = 0
    sum_stored_values_largest = 0
    sum_in_mm = 0
End If
Next j
'Close the output file
Close 6
Erase array_precipitation_values
Next i
'Now, sum the values and calculate the return interval of once in two year,
'six hour storm using Gumbel distribution
'input stnid,starttime,endtime,amount_ten_mm,amount_mm
'Cycles through the array of file names
outputfile = ""
Dim counter2 As Double
currentLine = ""
Dim max_events() As Variant
Dim Sumsquares As Double
Dim sum2 As Double
Dim mean As Double
Dim standarddeviation As Double
Dim TWOYR_6H_RN As Double
Dim return_periodK As Double
Dim stnid_output As String
Dim RT As Double
Dim output_ateshianfile As String
return_periodK = -0.164
output_ateshianfile = directorypath1 & "ateshian_estimates.csv"
Open output_ateshianfile For Output As #9
Print #9, "STNID, ADJ_FACT,RET_P_K,MEAN,SD,N,2YR_6H_RN,RT"
For i = 0 To UBound(array_names, 2)
    outputfile = array_names(2, i) 'Pull the file for analysis
    Open outputfile For Input As #7
    counter2 = 0
    Do While Not EOF(7)
        Line Input #7, currentLine 'Pull the var. width record
        counter2 = counter2 + 1
    Loop
    Close 7
    counter2 = counter2 - 1
    ReDim max_events(4, counter2)

```

```

Open outputfile For Input As #8
counter2 = 0
currentLine = ""
Do While Not EOF(8)
    Line Input #8, currentLine 'Pull the var. width record
    Mystring = Split(currentLine, ",")
    For j = 0 To 4
        max_events(j, counter2) = Mystring(j)
    Next j
    counter2 = counter2 + 1
Loop
Close 8
counter2 = counter2 - 1
Sumsquares = 0
sum2 = 0
standarddeviation = 0
mean = 0
TWOYR_6H_RN = 0
'Calculate the mean of maximum precipitation events RET_P_ADJ
'From one as headers are in the array
For j = 1 To UBound(max_events, 2)
    sum2 = max_events(4, j) + sum2
    Sumsquares = Sumsquares + ((max_events(4, j)) ^ 2)
Next j
mean = sum2 / counter2
standarddeviation = (counter2 * (Sumsquares)) - (sum2 ^ 2)
standarddeviation = standarddeviation / (counter2 * (counter2 - 1))
standarddeviation = Sqr(standarddeviation)
TWOYR_6H_RN = 0
TWOYR_6H_RN = mean + (return_periodK * standarddeviation)
stnid_output = ""
stnid_output = max_events(0, 1)
RT = 0
RT = 0.417 * (TWOYR_6H_RN ^ 2.17)
""STNID, ADJ_FACT,RET_P_K,MEAN,SD,N,2YR_6H_RN,RT"
Print #9, stnid_output & "," & inputmultiplefactor & "," & return_periodK & "," & mean & _
    "," & _
standarddeviation & "," & counter2 & "," & TWOYR_6H_RN & "," & RT
sum2 = 0
Sumsquares = 0
TWOYR_6H_RN = 0
stnid_output = ""
standarddeviation = 0
RT = 0
mean = 0
counter2 = 0

```

```

Next i
Close 9
ProgressBar1.Value = 0
MsgBox "Finished calculating the maximum once in two year, six hour storm.", vbCritical, _
"Attention."
End Sub

Private Sub Text1_Change()
inputmultiplefactor = Text1.Text
If IsNumeric(inputmultiplefactor) <> True Then
    MsgBox "You must enter a numeric value for multiple factor.", _
vbInformation, "Attention."
    Text1.Text = 1
    Exit Sub
End If
End Sub

```


APPENDIX J: VISUAL BASIC CODE FOR HISTOGRAM GENERATION OF THE MAXIMUM AMOUNT OF PRECIPITATION RECEIVED IN A SIX HOUR INTERVAL PER YEAR

A smaller program was built to generate a count of the Julian occurrence of each of the yearly maximum six hour precipitation. The following code associate to the form loops through the maximum yearly six hour precipitation files for each station and counts their day of occurrence. The counts are populated and written to file for analysis. Requirements are an ASCII text file listing the file names containing the yearly maximums with the proper extension and provision of the path to station files. The text files should be comma delimited and ordered in the following manner: stnid, start time, end time, amount of rainfall in tenths of a millimeter, amount of rainfall in millimeters. The graphical user interface of this program is shown in Fig. 98.

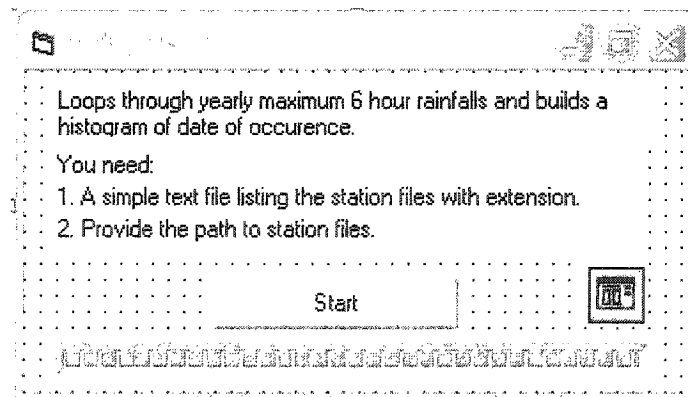


Fig. 98. Graphical user interface of the program designed to calculate the Julian occurrence and corresponding histogram of the yearly maximum six hour rainfalls.

```

Private Sub Command1_Click()
Dim source_names As String
Dim directory_path1 As String
Dim thefiletitle As String
ProgressBar1.Value = 0
CommonDialog1.Flags = CommonDialog1.Flags Or cdlOFNHideReadOnly
CommonDialog1.Filter = "All Files|*.*" 'Set the CommonDialog filter to
MsgBox "Navigate to the location and select the file that contains the monthly precipitation.", _
vbInformation, "Attention."
CommonDialog1.ShowOpen 'Open and show the commondialog
source_names = CommonDialog1.filename
thefiletitle = CommonDialog1.FileTitle

If Len(source_names) = 0 Then 'If the length of filenames is zero then no files were selected
    MsgBox "No files selected", vbOKOnly, "Error"
    Exit Sub
End If
Dim filename As String
length_thefiletitle = Len(thefiletitle)
filename = Left(thefiletitle, Len(thefiletitle) - 4)
directory_path1 = Left(source_names, Len(source_names) - length_thefiletitle)
If directory_path1 = "" Then
    MsgBox "Invalid entry. Try again."
    Exit Sub
End If
'Read file and store file names and path to array
Dim a As Long 'Counter
a = 0
Dim currentLine As String
'Open a file for output
Dim outputfilename As String
outputfilename = directory_path1 & "histogram.csv"
Open outputfilename For Output As #1
'Build the array to store the instance of the 6 hour storm
Dim array_filenames() As Variant
'Find the number of lines in the file
Open source_names For Input As #2
    Do While Not EOF(2)
        Line Input #2, currentLine
        a = a + 1
    Loop
Close 2
currentLine = ""
a = a - 1
ReDim array_filenames(a)
a = 0

```

```

'Populate array with file names
Open source_names For Input As #3
  Do While Not EOF(3)
    currentLine = ""
    Line Input #3, currentLine
    array_filenames(a) = currentLine
    a = a + 1
    currentLine = ""
  Loop
Close 3
currentLine = ""
a = a - 1
Dim theopenfile As String
Dim thehistogramarray(1, 1 To 366) As Variant
For j = 1 To 366
  thehistogramarray(0, j) = j
Next j
Dim dateinput As Date
Dim counter1 As Long
Dim julianday As Variant
'Loop through array of file names
For i = 0 To UBound(array_filenames, 1)
  ProgressBar1.Value = (i + 1) * 100 / (UBound(array_filenames, 1) + 1)
  theopenfile = ""
  theopenfile = array_filenames(i)
  theopenfile = directory_path1 & theopenfile
  currentLine = ""
  counter1 = 0
  Open theopenfile For Input As #4
  Do While Not EOF(4)
    currentLine = ""
    dateinput = 0
    Line Input #4, currentLine
    If counter1 > 0 Then
      Mystring = Split(currentLine, ",")
      dateinput = Mystring(1)
      julianday = Date2Julian(dateinput)
      julianday = Right(julianday, Len(julianday) - 4)
      thehistogramarray(1, julianday) = thehistogramarray(1, julianday) + 1
    End If
    currentLine = ""
    dateinput = 0
    counter1 = counter1 + 1
  Loop
Close 4
theopenfile = ""

```

```

    counter1 = 0
Next i
theopenfile = ""
counter1 = 0
currentLine = ""
dateinput = 0
ProgressBar1.Value = 0
Print #1, "julianday,count"
For i = 1 To UBound(thehistogramarray, 2)
    currentLine = ""
    currentLine = thehistogramarray(0, i) & "," & thehistogramarray(1, i)
    Print #1, currentLine
    currentLine = ""
Next i
Close 1
MsgBox "Finished processing.", vbCritical, "Attention."
End Sub
Public Function Date2Julian(ByVal vDate As Date) As Long
    Date2Julian = CLng(Format(Year(vDate), "0000") _
        + Format(DateDiff("d", CDate("01/01/" _
        + Format(Year(vDate), "0000")), vDate) _
        + 1, "000"))
End Function

```

APPENDIX K: VISUAL BASIC CODE FOR MONTHLY PRECIPITATION CALCULATIONS

Two separate routines were developed to sum the total amount of precipitation occurring in each month at each station and the percentage of precipitation that occurs for pluvial months. Total precipitation for each month was calculated using the first set of code provided below which sums precipitation amounts by month via a looping routine that reads and calculates the station files. After the values are summed the monthly values are averaged over the recording period to later calculate the percentage of rainfall occurring in each month at each station. For the Canadian data, limitations were imposed in that months with less than 20 days of record were not included in the monthly averaging as totals for such months would skew the monthly averages. For the U.S. dataset, those months with missing recordings were also dropped in the analysis of monthly precipitation. Within the yearly window of collection for each station the percentage of precipitation per month was multiplied against the gross rainfall erosivity to provide an estimate of monthly erosivity. This methodology is provided in the second set of code.

Set 1: This program calculates the amount of precipitation occurring in each month. User input includes the provision of a pre-generated ASCII text file listing the names of the of the station files to process including their extension (See Appendix G). The user must also provide the path to these files and a cutoff that restricts the processing of months beyond a set number of recording years for that month. The GUI of this program is given in Fig. 99.

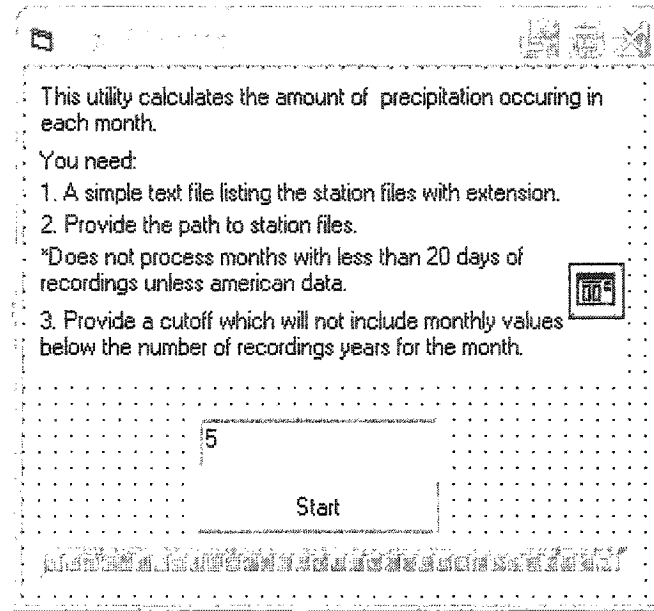


Fig. 99. Graphical user interface of the program designed to calculate the amount of precipitation occurring in each month from hourly precipitation text files.

'Global variable

Dim the _cutoff As Variant

Private Sub Command1_Click()

Dim source_names As String

Dim directory_path1 As String

Dim thefiletitle As String

ProgressBar1.Value = 0

the _cutoff = Text1.Text

CommonDialog1.Flags = CommonDialog1.Flags Or cdlOFNHideReadOnly

CommonDialog1.Filter = "All Files|*.*" 'Set the CommonDialog filter to

MsgBox "Navigate to the location and select the file that contains the precipitation file _
names.", vbInformation, "Attention."

CommonDialog1.ShowOpen 'Open and show the commondialog

source_names = CommonDialog1.filename

thefiletitle = CommonDialog1.FileTitle

If Len(source_names) = 0 Then 'If the length of filenames is zero then no files were selected

MsgBox "No files selected", vbOKOnly, "Error"

Exit Sub

End If

directory_path1 = InputBox("What is the path to the files? Example: c:\Temp\","Attention.")

If directory_path1 = "" Then

MsgBox "Invalid entry. Try again."

Exit Sub

```

End If
'Read file and store file names and path to array
Dim a As Long 'Counter
a = 0
Dim currentLine As String
Open source_names For Input As #1
    Do While Not EOF(1)
        Line Input #1, currentLine
        a = a + 1
    Loop
Close 1
currentLine = ""
Dim array_names() As String
ReDim array_names(2, a - 1)
Dim name As String
name = ""
a = 0
Open source_names For Input As #2
    Do While Not EOF(2)
        Line Input #2, currentLine
        array_names(0, a) = directory_path1 & currentLine 'Input name and dir
        name = ""
        name = Left(currentLine, Len(currentLine) - 4)
        array_names(1, a) = name 'Input file title
        array_names(2, a) = directory_path1 & name & "_monthlyprecip.csv" 'output
        a = a + 1
    Loop
Close 2
'Reset variable
a = a - 1
name = ""
source_names = ""
currentLine = ""
Dim summedmonthvalue As Double
Dim Value As Double
Dim lengthrecord As Double
Dim b As Double
Dim c As Double
Dim firstdate As Date
Dim seconddate As Date
Dim indexedates() As Variant
Dim datedifference As Double
Dim printyear As Integer
Dim printmonth As Integer
Dim printstnid As String
Dim outputfilename As String

```

```

Dim counter_daysinmonthly_recordings As Double
Dim length_file As Integer
Dim limit_num_rec_mnth As Double
'Loop through each of the station files and calculate the precipitation events
'in each month, then dump the value to file
For i = 0 To a
    ProgressBar1.Value = (i + 1) * 100 / (a + 1)
    source_names = ""
    currentLine = ""
    summedmonthvalue = 0
    lengthrecord = 0
    b = 0
    'Open the file and loop through line by line
    'Find length
    source_names = array_names(0, i)
    length_file = 0
    name = ""
    name = array_names(1, i)
    length_file = Len(name)
    name = ""
    'Determine whether Canadian or American
    If length_file = 8 Then
        'Set to American
        limit_num_rec_mnth = 2
    Else
        'Set to Canadian
        limit_num_rec_mnth = 20
    End If
    lengthfile = 0
    Open source_names For Input As #3
    Do While Not EOF(3)
        Line Input #3, currentLine
        b = b + 1
    Loop
    Close 3
    currentLine = ""
    b = b - 1
    'Create and index date array
    ReDim indexdates(b)
    b = 0
    currentLine = ""
    'Populate index dates
    Open source_names For Input As #4
    Do While Not EOF(4)
        Line Input #4, currentLine
        Mystring = Split(currentLine, ",")

```



```

    indexdates(b) = Mystring(2)
    b = b + 1
Loop
Close 4
currentLine = ""
b = b - 1
Erase Mystring
firstdate = 0
seconddate = 0
c = 0
Value = 0
summedmonthvalue = 0
'Open output file
outputfilename = ""
outputfilename = array_names(2, i)
Open outputfilename For Output As #6
Print #6, "STNID,YR,MON,TOT"
counter_daysinmonthly_recordings = 0
'Open the file and loop through line by line
Open source_names For Input As #5
Do While Not EOF(5)
    Line Input #5, currentLine
    Mystring = Split(currentLine, ",")
    counter_daysinmonthly_recordings = counter_daysinmonthly_recordings + 1
    'set first date
    firstdate = Mystring(2)
    Value = 0
    'Loop through Mystring
    For j = 4 To UBound(Mystring, 1)
        'Take only numeric value, not flag
        Value = Left(Mystring(j), 6)
        If Value <> -99999 Then
            summedmonthvalue = summedmonthvalue + Value
        End If
    Next j
    'Check to see if change in month
    'If so, dump value, if not, continue
    'Only check if not b, when b, dump regardless
    'set stationid
    printstnid = ""
    printstnid = Mystring(1)
    printyear = 0
    printyear = Year(Mystring(2))
    printmonth = 0
    printmonth = Month(Mystring(2))
    If c < b Then

```

```

seconddate = 0
seconddate = indexdates(c + 1)
datedifference = 0
datedifference = DateDiff("m", firstdate, seconddate)
End If
If datedifference >= 1 And counter_daysinmonthly_recordings >= limit_num_rec_mnth _
Or c = b And counter_daysinmonthly_recordings >= limit_num_rec_mnth Then
    'Print stnid,year,month,total
    Print #6, printsnid & "," & printyear & "," & printmonth & "," & summedmonthvalue
    'Clear stnid,year,month,total
    printsnid = ""
    printyear = 0
    printmonth = 0
    summedmonthvalue = 0
    Value = 0
    Erase Mystring
    counter_daysinmonthly_recordings = 0
    ElseIf datedifference >= 1 And counter_daysinmonthly_recordings < _
    limit_num_rec_mnth Or c = b And counter_daysinmonthly_recordings < _
    limit_num_rec_mnth Then ' no precip in month
    'Clear stnid,year,month,total
    printsnid = ""
    printyear = 0
    printmonth = 0
    summedmonthvalue = 0
    Value = 0
    Erase Mystring
    counter_daysinmonthly_recordings = 0
End If
c = c + 1 'bump up counter
Loop
c = 0
b = 0
Close 5
Close 6
Next i
ProgressBar1.Value = 0
'The next step is to summarize each of the station monthly
'values, and store by month in an array
Dim station_record() As Variant
Dim monthone As Double '1
Dim monthtwo As Double '2
Dim monththree As Double '3
Dim monthfour As Double '4
Dim monthfive As Double '5
Dim monthsix As Double '6

```

```

Dim monthseven As Double '7
Dim montheight As Double '8
Dim monthnine As Double '9
Dim monthten As Double '10
Dim montheleven As Double '11
Dim monthtwelve As Double '12
'Set a counter for each month
Dim one As Double '1
Dim two As Double '2
Dim three As Double '3
Dim four As Double '4
Dim five As Double '5
Dim six As Double '6
Dim seven As Double '7
Dim eight As Double '8
Dim nine As Double '9
Dim ten As Double '10
Dim eleven As Double '11
Dim twelve As Double '12
currentLine = ""
printstnid = ""
Dim outfile_monthly As String
outfile_monthly = ""
outfile_monthly = directory_path1 & "outfile_monthly.csv"
Open outfile_monthly For Output As #8
Print #8, "stnid,jan,feb,mar,apr,may,jun,jul,aug,sep,oct,nov,dec"
ProgressBar1.Value = 0
For i = 0 To a
    ProgressBar1.Value = (i + 1) * 100 / (a + 1)
    'Retrieve the name of the output file with monthly maximums
    source_names = ""
    source_names = array_names(2, i)
    'Open the file
    Open source_names For Input As #7
    'Populate false array which will hold the monthly values
    'with -99999
    ReDim station_record(12) 'Should erase contents of array
    For j = 1 To 12
        station_record(j) = "-99999M"
    Next
    'Reset the monthly values
    monthone = 0 'Jan
    monthtwo = 0 'Feb
    monththree = 0 'Mar
    monthfour = 0 'Apr
    monthfive = 0 'May

```

```

monthsix = 0 'Jun
monthseven = 0 'Jul
montheight = 0 'Aug
monthnine = 0 'Sep
monthten = 0 'Oct
montheleven = 0 'Nov
monthtwelve = 0 '
'Reset counter
one = 0
two = 0
three = 0
four = 0
five = 0
six = 0
seven = 0
eight = 0
nine = 0
ten = 0
eleven = 0
twelve = 0
Do While Not EOF(7)
    'input stnid,year,month,total
    currentLine = ""
    Line Input #7, currentLine
    Mystring = Split(currentLine, ",")
    If Mystring(2) = 1 Then
        monthone = Mystring(3) + monthone
        one = one + 1
    ElseIf Mystring(2) = 2 Then
        monthtwo = Mystring(3) + monthtwo
        two = two + 1
    ElseIf Mystring(2) = 3 Then
        monththree = Mystring(3) + monththree
        three = three + 1
    ElseIf Mystring(2) = 4 Then
        monthfour = Mystring(3) + monthfour
        four = four + 1
    ElseIf Mystring(2) = 5 Then
        monthfive = Mystring(3) + monthfive
        five = five + 1
    ElseIf Mystring(2) = 6 Then
        monthsix = Mystring(3) + monthsix
        six = six + 1
    ElseIf Mystring(2) = 7 Then
        monthseven = Mystring(3) + monthseven
        seven = seven + 1

```

```

ElseIf Mystring(2) = 8 Then
    montheight = Mystring(3) + montheight
    eight = eight + 1
ElseIf Mystring(2) = 9 Then
    monthnine = Mystring(3) + monthnine
    nine = nine + 1
ElseIf Mystring(2) = 10 Then
    monthten = Mystring(3) + monthten
    ten = ten + 1
ElseIf Mystring(2) = 11 Then
    montheleven = Mystring(3) + montheleven
    eleven = eleven + 1
ElseIf Mystring(2) = 12 Then
    monthtwelve = Mystring(3) + monthtwelve
    twelve = twelve + 1
End If
Loop
Close 7
printstnid = ""
printstnid = Mystring(0)
'Check values
'If the test hasn't been tripped set empty
If one < the_cutoff Then
    monthone = -99999
Else
    monthone = monthone / one
End If
If two < the_cutoff Then
    monthtwo = -99999
Else
    monthtwo = monthtwo / two
End If
If three < the_cutoff Then
    monththree = -99999
Else
    monththree = monththree / three
End If
If four < the_cutoff Then
    monthfour = -99999
Else
    monthfour = monthfour / four
End If
If five < the_cutoff Then
    monthfive = -99999
Else
    monthfive = monthfive / five

```

```

End If
If six < the_cutoff Then
    monthsix = -99999
Else
    monthsix = monthsix / six
End If
If seven < the_cutoff Then
    monthseven = -99999
Else
    monthseven = monthseven / seven
End If
If eight < the_cutoff Then
    montheight = -99999
Else
    montheight = montheight / eight
End If
If nine < the_cutoff Then
    monthnine = -99999
Else
    monthnine = monthnine / nine
End If
If ten < the_cutoff Then
    monthten = -99999
Else
    monthten = monthten / ten
End If
If eleven < the_cutoff Then
    montheleven = -99999
Else
    montheleven = montheleven / eleven
End If
If twelve < the_cutoff Then
    monthtwelve = -99999
Else
    monthtwelve = monthtwelve / twelve
End If
Print #8, printstnid & "," & monthone & "," & monthtwo & "," & monththree & _
"," & monthfour & "," & monthfive & "," & monthsix & "," & monthseven & _
"," & montheight & "," & monthnine & "," & monthten & "," & montheleven & _
"," & monthtwelve
monthone = 0 'Jan
monthtwo = 0 'Feb
monththree = 0 'Mar
monthfour = 0 'Apr
monthfive = 0 'May
monthsix = 0 'Jun

```

```

monthseven = 0 'Jul
montheight = 0 'Aug
monthnine = 0 'Sep
monthten = 0 'Oct
montheleven = 0 'Nov
monthtwelve = 0 'Dec
'Reset counter
one = 0
two = 0
three = 0
four = 0
five = 0
six = 0
seven = 0
eight = 0
nine = 0
ten = 0
eleven = 0
twelve = 0
Next i
Close 8
ProgressBar1.Value = 0
MsgBox "Finished processing and aggregating monthly totals.", vbCritical, "Attention."
'Reset the code so that it adjusts to the length of the station id
End Sub
Private Sub Text1_Change()
the_cutoff = Text1.Text
If IsNumeric(the_cutoff) <> True Then
    MsgBox "You must enter a numeric value for multiple factor.", _
        vbInformation, "Attention."
    Text1.Text = 1
    Exit Sub
End If
End Sub

```

Set 2: This utility calculates the percentage of precipitation occurring in each month. User input requires locating the source of the summed monthly precipitation file (.csv) generated in set 1 using a common dialog box. The input monthly precipitation file must not contain any missing data and contain a header with the following columns, station identification continued by monthly values. The GUI for this program is given in Fig. 100.

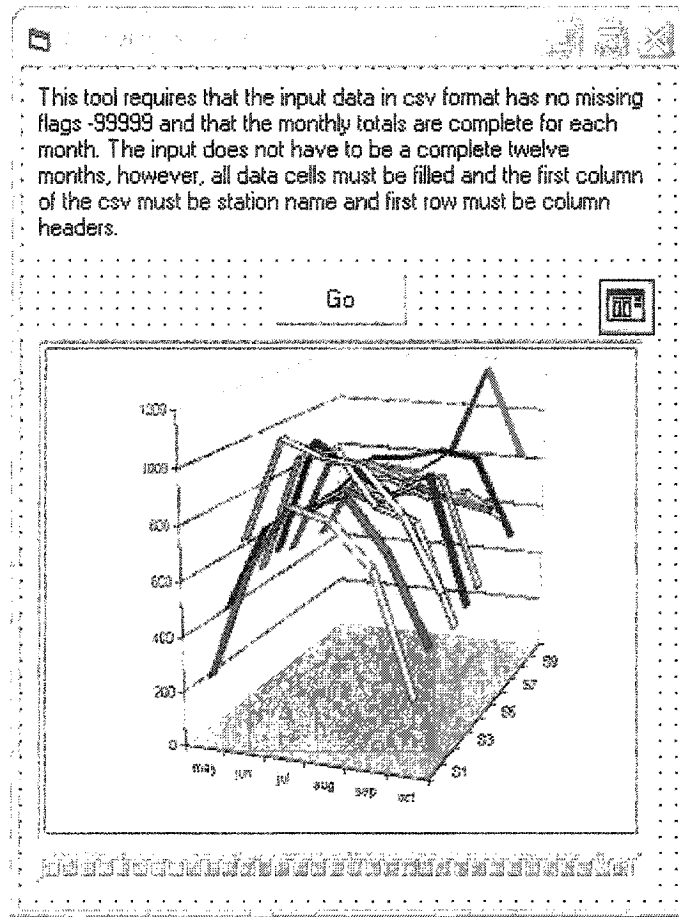


Fig. 100. Graphical user interface of the program designed to calculate the percentage of precipitation occurring in each month from outputs of Set 1.

```

Private Sub Command1_Click()
    Dim source_names As String
    Dim directory_path1 As String
    Dim thefiletitle As String
    ProgressBar1.Value = 0
    CommonDialog1.Flags = CommonDialog1.Flags Or cdIOFNHideReadOnly
    CommonDialog1.Filter = "All Files|*.*" 'Set the CommonDialog filter to
    MsgBox "Navigate to the location and select the file that contains the monthly precipitation.", _
        vbInformation, "Attention."
    CommonDialog1.ShowOpen 'Open and show the commondialog
    source_names = CommonDialog1.filename
    thefiletitle = CommonDialog1.FileTitle
    If Len(source_names) = 0 Then 'If the length of filenames is zero then no files were selected
        MsgBox "No files selected", vbOKOnly, "Error"
        Exit Sub
    End If
    Dim length_thefiletitle As String

```



```

length_thefiletitle = Len(thefiletitle)
Dim filename As String
filename = Left(thefiletitle, Len(thefiletitle) - 4)
directory_path1 = Left(source_names, Len(source_names) - length_thefiletitle)
If directory_path1 = "" Then
    MsgBox "Invalid entry. Try again."
    Exit Sub
End If
'Read file and store file names and path to array
Dim a As Long 'Counter
a = 0
Dim currentLine As String
'Open a file for output
Dim outputfilename As String
outputfilename = directory_path1 & filename & "_perc.csv"
Open outputfilename For Output As #2
'Find the number of lines in the file
Open source_names For Input As #1
    Do While Not EOF(1)
        Line Input #1, currentLine
        a = a + 1
    Loop
Close 1
currentLine = ""
a = a - 1
Dim b As Long 'counter
Dim storage_array() As Variant
Dim outstring As String
Dim sum As Double
Dim leng As Long
'Reopen file for processing
Open source_names For Input As #3
    ProgressBar1.Value = (b + 1) * 100 / (a + 1)
    Do While Not EOF(3)
        currentLine = ""
        Line Input #3, currentLine
        'If it is the first line store headers
        If b = 0 Then
            Print #2, currentLine
            currentLine = ""
        End If
        If b > 0 Then
            Mystring = Split(currentLine, ",")
            ReDim storage_array(1, UBound(Mystring, 1))
            sum = 0
            'Populate array and find sum

```

```

For i = 0 To UBound(Mystring, 1)
    storage_array(0, i) = Mystring(i)
    If i > 0 Then
        sum = sum + Mystring(i)
    End If
Next i
storage_array(1, 0) = Mystring(0)
'Divide each value by sum and output in array
For i = 1 To UBound(Mystring, 1)
    storage_array(1, i) = (storage_array(0, i) / sum)
Next i
outstring = ""
For i = 0 To UBound(storage_array, 2)
    outstring = outstring & "," & storage_array(1, i)
Next i
leng = 0
leng = Len(outstring)
leng = leng - 1
outstring = Right(outstring, leng)
length = 0
Print #2, outstring
outstring = ""
End If
currentLine = ""
b = b + 1
Loop
Close 3
Close 2
currentLine = ""
ProgressBar1.Value = 0
MsgBox "Finished processing.", vbCritical, "Attention."
End Sub

```

APPENDIX L: AML CODE FOR ASSIGNMENT OF TEXTURAL CLASS TO LAYER FILE

```
/* This aml is for classification of soil texture based upon % of sand, silt, and clay assumed by
/*weight.
/* It was originally written by Thierry Fisette of the Eastern Cereal and Oilseed Research Center,
/*Agriculture Canada.
/* Agriculture Canada
/* Modified by Graham Wilkes. February 12, 2004.
/* Find and replace may be necessary in this code
/* as it is hard coded specifically for headings used in this analysis
/* Find and replace performed to change component030204b to test3
/* 1 = sand
/* 2 = loamy sand
/* 3 = silty sand
/* 4 = sandy loam
/* 5 = loam
/* 6 = silt loam
/* 7 = silt
/* 8 = sandy clay loam
/* 9 = clay loam
/* 10 = silty clay loam
/* 11 = sandy clay
/* 12 = clay
/* 13 = silty clay
/* 14 = heavy clay
tables
sel test3
additem test3 temp2 4 4 I
additem test3 tex_gene2 4 5 B
additem test3 structure2 4 5 B
resel tsand GE 85
calc temp2 = tclay * 1.5 + tsilt
resel temp2 LE 15
calc tex_gene2 = 1
nsl
calc temp2 = tclay * 2 + tsilt
resel temp2 LE 30
calc tex_gene2 = 2
sel test3
calc temp2 = tclay * 2 + tsilt
```

```

resel temp2 GT 30
resel tclay LT 7
resel tsilt LT 50
calc tex_gene2 = 3
sel test3
calc temp2 = tclay * 2 + tsilt
resel temp2 GT 30
resel tclay GE 7
resel tclay LE 20
resel tsand GE 52
calc tex_gene2 = 4
sel test3
resel tclay GE 7
resel tclay LE 27
resel tsilt GE 28
resel tsilt LT 50
resel tsand LT 52
calc tex_gene2 = 5
sel test3
resel tsilt GE 50
resel tclay GE 12
resel tclay LE 27
calc tex_gene2 = 6
sel test3
resel tsilt GE 50
resel tsilt LT 80
resel tclay LT 12
calc tex_gene2 = 6
sel test3
resel tsilt GE 80
resel tclay LT 12
calc tex_gene2 = 7
sel test3
resel tclay GT 20
resel tclay LT 35
resel tsilt LT 28
resel tsand GE 45
calc tex_gene2 = 8
sel test3
resel tclay GT 27
resel tclay LT 40
resel tsand GT 20
resel tsand LT 45
calc tex_gene2 = 9
sel test3
resel tclay GT 27

```

```
resel tclay LT 40
resel tsand LE 20
calc tex_gene2 = 10
sel test3
resel tclay GE 35
resel tsand GE 45
calc tex_gene2 = 11
sel test3
resel tclay GE 40
resel tclay LE 60
resel tsand LT 45
resel tsilt LT 40
calc tex_gene2 = 12
sel test3
resel tclay GE 40
resel tsilt GE 40
calc tex_gene2 = 13
sel test3
resel tclay GT 60
calc tex_gene2 = 14
q
```

APPENDIX M: VISUAL BASIC CODE FOR SELECTION OF THE MOST IMPERMEABLE LAYER BASED ON SOIL TYPE

Provided in Fig. 101 is the interface of this utility.

Determines the least permeable layer for the input csv table soil type in question and outputs a comma seperated file to the same directory.

Number of columns in table:

Column number of soil type:

Column number of permeability:

Notes: Columns should not be inputted zero based and the permeability classes range from 1 to 6, with one being the most rapic permeability.

Select table and Go!

Start time:

End time:

Fig. 101. Graphical user interface of the program designed to determine the most impermeable layer for each soil type.

Provided below is the code associated with this utility.

```
Private Declare Sub GetSystemTime Lib "kernel32" (lpSystemTime As SYSTEMTIME)
Private Sub Command1_Click()
Dim tablepath As Variant
Dim mycheck2 As Integer
Dim tablepathout As String
Dim filename As String
Dim SysTime As SYSTEMTIME
Dim SysTimeStart As String
Dim SysTimeEnd As String
CommonDialog1.DefaultExt = ".csv"
CommonDialog1.MaxFileSize = 32000
CommonDialog1.Filter = "comma separated file|*.csv"
CommonDialog1.Flags = cdlOFNHideReadOnly
CommonDialog1.MaxFileSize = 32000
CommonDialog1.ShowOpen
CommonDialog1.CancelError = True
On Error GoTo Line1
tablepath = CommonDialog1.filename
mycheck2 = VarType(tablepath)
If mycheck2 <> 8 Then
    MsgBox "Error ." & mycheck, vbOKCancel, "Err."
End If
MsgBox "The file you have selected for processing: " & tablepath, vbOKOnly, "File to process"
Dim nameout As String
Dim path As String
Dim lengthtablepath As Long
lengthtablepath = Len(tablepath)
filename = CommonDialog1.FileTitle
path = Left(tablepath, lengthtablepath - Len(filename))
tablepathout = path & "out_" & filename
MsgBox "The output path for the file is: " & tablepathout, vbOKOnly, "File output path and _
name."
Open tablepath For Input As #1
    Dim a As Variant
Dim currentLine1 As String
GetSystemTime SysTime
SysTimeStart = SysTime.wHour & ":" & SysTime.wMinute & ":" & SysTime.wSecond & ":" _
& SysTime.wMilliseconds
Label8.Caption = SysTimeStart
Dim permeability_title As String
Dim soiltype_title As String
```

```

a = 0
Do While Not EOF(1) 'Do loop while not at the end of 1
    Line Input #1, currentLine1 'Set line one to currentLine1
    a = a + 1 'Increase a by one
Loop
Close 1
input1 = input1 - 1
Dim array1() As Variant
ReDim array1(input1, a - 2)
Dim Mystring() As String
Open tablepath For Input As #2
currentLine1 = ""
a = 0
Do While Not EOF(2) 'Do loop while not at the end of 1
    Line Input #2, currentLine1 'Set line one to currentLine1
    Mystring = Split(currentLine1, ",")
    If a <> 0 Then
        For i = 0 To input1
            array1(i, a - 1) = Mystring(i)
        Next i
    End If
    If a = 0 Then
        permeability_title = Mystring(input3 - 1)
        soiltype_title = Mystring(input2 - 1)
    End If
    a = a + 1
Loop
Close 2
Dim array2() As Variant
ReDim array2(1, a - 2)
a = 0
For i = 0 To UBound(array1, 2)
    array2(0, i) = array1(input2 - 1, i)
    array2(1, i) = array1(input3 - 1, i)
    a = a + 1
Next i

a = a - 2
Dim soiltype As String
Dim permeability As Integer
Dim soiltype_store As Variant
Dim permeability_store As Variant
'Core code *****
'sorts the input table properly by identified soil column
Dim outarray()
outarray = arraysort(array2)

```



```

Open tablepathout For Output As #3
For i = 0 To a
    soiltype = outarray(0, i)
    permeability = CInt(outarray(1, i))
    If i = 0 Then
        soiltype_store = soiltype
        permeability_store = permeability
        Print #3, soiltype_title & "_X" & "," & permeability_title & "_MIN"
    End If
    If i < a Then
        If soiltype <> outarray(0, i + 1) Then
            If permeability >= permeability_store Then
                soiltype_store = soiltype
                permeability_store = permeability
            End If
            Print #3, soiltype_store & "," & permeability_store
            soiltype_store = outarray(0, i + 1)
            permeability_store = outarray(1, i + 1)
        End If
        If soiltype = outarray(0, i + 1) Then
            soiltype = outarray(0, i)
            If permeability > permeability_store Then
                permeability_store = permeability
                soiltype_store = soiltype
            End If
        End If
    End If
    If i = a Then
        If soiltype <> outarray(0, i - 1) Then
            soiltype_store = soiltype
            permeability_store = permeability
            Print #3, soiltype_store & "," & permeability
        ElseIf soiltype = outarray(0, i - 1) Then
            If permeability >= permeability_store Then
                soiltype_store = soiltype
                permeability_store = permeability
            End If
            Print #3, soiltype_store & "," & permeability_store
        End If
    End If
Next i
Close 3
'*****The core*****
GetSystemTime SysTime
SysTimeEnd = SysTime.wHour & ":" & SysTime.wMinute & ":" & SysTime.wSecond & ":" _
& SysTime.wMilliseconds

```

```

Label9.Caption = SysTimeEnd
MsgBox "Done."
Line1:
Text3.Text = 0
Text3.Enabled = False
Text2.Text = 0
Text2.Enabled = False
Text1.Text = 0
Text1.Visible = True
Command1.Enabled = False
End Sub

```

```

Private Sub Form_Load()
Text2.Visible = False
Text3.Visible = False
Text2.Enabled = False
Text3.Enabled = False
End Sub

```

```

Private Sub Text1_Change()
Dim mycheck As Boolean
input1 = Text1.Text
mycheck = IsNumeric(input1)
If mycheck = False Then
    MsgBox "The number of columns you have provided is not numeric. Please provide a _
numeric value for number of columns.", vbOKOnly, "Attention."
    Text1.Text = 0
End If
Text2.Visible = True
Text2.Enabled = True
End Sub
Private Sub Text2_Change()
Dim mycheck2 As Boolean
input2 = Text2.Text
mycheck2 = IsNumeric(input2)
If mycheck2 = False Then
    MsgBox "The column number for soil type you have provided is not numeric. Please provide
a numeric value for soil type column number.", vbOKOnly, "Attention."
    Text2.Text = 0
End If
Text3.Visible = True
Text3.Enabled = True
End Sub

```

```

Private Sub Text3_Change()
Dim mycheck3 As Boolean

```

```

input3 = Text3.Text
mycheck3 = IsNumeric(input3)
If mycheck3 = False Then
    MsgBox "The column number for permeability you have provided is not numeric. _
Please provide a numeric value for permeability column number.", vbOKOnly, "Attention."
    Text3.Text = 0
End If
Command1.Enabled = True
End Sub

```

```

' ShellSort an array of any type
Sub ShellSort(arr As Variant, column As Double, Optional lastEl As Variant, _
    Optional descending As Boolean)
    Dim value() As Variant
    Dim index As Long, index2 As Long
    Dim firstEl As Long
    Dim distance As Long
    Dim numEls As Long
    ReDim value(input1)
    ' account for optional arguments
    If IsMissing(lastEl) Then lastEl = UBound(arr, 2)
    firstEl = LBound(arr, 2)
    numEls = lastEl - firstEl + 1
    ' find the best value for distance
    Do
        distance = distance * 3 + 1
    Loop Until distance > numEls
    Do
        distance = distance \ 3
        For index = distance + firstEl To lastEl
            For i = 0 To input1
                value(i) = arr(i, index)
            Next i
            index2 = index
            Do While (arr(column, index2 - distance) > value(input2)) Xor descending
                For i = 0 To input1
                    arr(i, index2) = arr(i, index2 - distance)
                Next i
                index2 = index2 - distance
            If index2 - distance < firstEl Then Exit Do
            Loop
            For i = 0 To input1
                arr(i, index2) = value(i)
            Next i
        Next
    Next

```

```

    Loop Until distance = 1
End Sub
Function arraysort(values())
    Dim i
    Dim j
    Dim smallest_value
    Dim smallest_j
    Dim min
    Dim max
    Dim temp
    min = LBound(values, 2)
    max = UBound(values, 2)
    For i = min To max - 1
        smallest_value = values(0, i)
        smallest_j = i
        For j = i + 1 To max
            ' See if values(j) is smaller. changed to strComp to work with strings.
            If StrComp(values(0, j), smallest_value, vbTextCompare) = -1 Then
                ' Save the new smallest value.
                smallest_value = values(0, j)
                smallest_j = j
            End If
        Next 'j
        If smallest_j <> i Then
            ' Swap items i and smallest_j.
            For intA = 0 To UBound(values, 1)
                temp = values(intA, smallest_j)
                values(intA, smallest_j) = values(intA, i)
                values(intA, i) = temp
            Next 'intA
        End If
    Next 'i
    arraysort = values
End Function

```

APPENDIX N: VISUAL BASIC CODE FOR THE SELECTION OF THE MOST IMPERMEABLE LAYER BASED ON SOIL TYPE

```

/* This aml is for classification of soil structure based upon % of sand, silt, and clay assumed by
weight.
/* It was originally written by Thierry Fisette of ECORC, Agcan.
/* Graham Wilkes. February 12, 2004.
/* Modified by Graham Wilkes. February 12, 2004.
/* Find and replace may be necessary in this code
/* as it is hard coded specifically for headings used in this analysis
/* 1 = sand
/* 2 = loamy sand
/* 3 = silty sand
/* 4 = sandy loam
/* 5 = loam
/* 6 = silt loam
/* 7 = silt
/* 8 = sandy clay loam
/* 9 = clay loam
/* 10 = silty clay loam
/* 11 = sandy clay
/* 12 = clay
/* 13 = silty clay
/* 14 = heavy clay
tables
sel component030204b
additem component030204b temp2 4 4 I
additem component030204b tex_gene2 4 5 B
additem component030204b structure2 4 5 B
additem component030204b org_matter2 8 8 F 2
resel tsand GE 85
calc temp2 = tclay * 1.5 + tsilt
resel temp2 LE 15
calc tex_gene2 = 1
nset
calc temp2 = tclay * 2 + tsilt
resel temp2 LE 30
calc tex_gene2 = 2
sel component030204b
calc temp2 = tclay * 2 + tsilt
resel temp2 GT 30
resel tclay LT 7
resel tsilt LT 50

```

```

calc tex_gene2 = 3
  sel component030204b
calc temp2 = tclay * 2 + tsilt
resel temp2 GT 30
resel tclay GE 7
resel tclay LE 20
resel tsand GE 52
calc tex_gene2 = 4
  sel component030204b
resel tclay GE 7
resel tclay LE 27
resel tsilt GE 28
resel tsilt LT 50
resel tsand LT 52
calc tex_gene2 = 5
  sel component030204b
resel tsilt GE 50
resel tclay GE 12
resel tclay LE 27
calc tex_gene2 = 6
  sel component030204b
resel tsilt GE 50
resel tsilt LT 80
resel tclay LT 12
calc tex_gene2 = 6
  sel component030204b
resel tsilt GE 80
resel tclay LT 12
calc tex_gene2 = 7
  sel component030204b
resel tclay GT 20
resel tclay LT 35
resel tsilt LT 28
resel tsand GE 45
calc tex_gene2 = 8
  sel component030204b
resel tclay GT 27
resel tclay LT 40
resel tsand GT 20
resel tsand LT 45
calc tex_gene2 = 9
  sel component030204b
resel tclay GT 27
resel tclay LT 40
resel tsand LE 20
calc tex_gene2 = 10

```

```

sel component030204b
resel tclay GE 35
resel tsand GE 45
calc tex_gene2 = 11
  sel component030204b
resel tclay GE 40
resel tclay LE 60
resel tsand LT 45
resel tsilt LT 40
calc tex_gene2 = 12
  sel component030204b
resel tclay GE 40
resel tsilt GE 40
calc tex_gene2 = 13
sel component030204b
resel tclay GT 60
calc tex_gene2 = 14
/* Calculates structure2 based on texture
  sel component030204b
resel tex_gene2 LE 2
calc structure2 = 1
sel component030204b
resel tex_gene2 LE 5
resel tex_gene2 GE 3
calc structure2 = 2
sel component030204b
resel tex_gene2 GE 6
resel tex_gene2 LE 7
resel tsilt LE 80
calc structure2 = 3
/*nset
/*calc structure2 = 4
sel component030204b
resel tex_gene2 GE 8
calc structure2 = 4
q

```

APPENDIX O: VISUAL BASIC CODE FOR THE SELECTION OF THE HIGHEST SPATIALLY REPRESENTATIVE SOIL TYPE FOR EACH MAP UNIT LISTED IN INPUT TABLE

Provided in Fig. 102 is the interface of the program designed to calculate the most spatially representative soil type per map unit listed in the input table.

The screenshot shows a Visual Basic application window titled "SELECTING THE HIGHEST SPATIALLY REPRESENTATIVE SOIL TYPE FOR EACH MAP UNIT LISTED IN INPUT TABLE". The interface includes a text box with instructions: "Selects the first or second highest spatially representative soil type for the mapunit from csv table and outputs a comma seperated file to the same directory." Below this are three input fields: "Number of columns in table:" with a value of 0, "Column number of K value:" with a value of 0, and "Column number of percent occupation:" with a value of 0. A "Notes" section states: "Columns should not be inputted zero based and in the case where there is 50/50 split, the soil type with the highest K value will be selected. Map unit should be the first column in the table." At the bottom are two buttons: "Bail" and "Select table and go!".

Fig. 102. Graphical user interface of the program designed to select and output the soil type that is predominant in map unit.

Provided next is the Visual Basic code which is core to the utility.

```
Public input1 As Variant
Public input2 As Variant
Public input3 As Variant
Private Type SYSTEMTIME
    wYear As Integer
    wMonth As Integer
    wDayOfWeek As Integer
    wDay As Integer
    wHour As Integer
    wMinute As Integer
    wSecond As Integer
    wMilliseconds As Integer
End Type
Private Declare Sub GetSystemTime Lib "kernel32" (lpSystemTime As SYSTEMTIME)
Private Sub Command1_Click()
    Dim tablepath As Variant
    Dim mycheck2 As Integer
    Dim tablepathout As String
    Dim filename As String
    Dim SysTime As SYSTEMTIME
    Dim SysTimeStart As String
    Dim SysTimeEnd As String
    CommonDialog1.DefaultExt = ".csv"
    CommonDialog1.MaxFileSize = 32000
    CommonDialog1.Filter = "comma seperated file|*.csv"
    CommonDialog1.Flags = cdIOFNHideReadOnly
    CommonDialog1.MaxFileSize = 32000
    CommonDialog1.ShowOpen
    CommonDialog1.CancelError = True
    'On Error GoTo Line1
    tablepath = CommonDialog1.filename
    mycheck2 = VarType(tablepath)
    If mycheck2 <> 8 Then
        MsgBox "Error :" & mycheck, vbOKCancel, "Err."
    End If
    MsgBox "The file you have selected for processing: " & tablepath, vbOKOnly, "File to process"
    Dim nameout As String
    Dim path As String
    Dim lengthtablepath As Long
    lengthtablepath = Len(tablepath)
    filename = CommonDialog1.FileTitle
    path = Left(tablepath, lengthtablepath - Len(filename))
    tablepathout = path & "out_" & filename
```

```

MsgBox "The output path for the file is: " & tablepathout, vbOKOnly, "File output path _
and name."
Open tablepath For Input As #1
Dim a As Variant
Dim currentLine1 As String
GetSystemTime SysTime
SysTimeStart = SysTime.wHour & ":" & SysTime.wMinute & ":" & SysTime.wSecond & ":" _
& SysTime.wMilliseconds
Dim holds_headers() As Variant
a = 0
Do While Not EOF(1)
    Line Input #1, currentLine1
    a = a + 1
Loop
Close 1
Dim array1() As Variant
ReDim array1(input1, a - 2)
Dim Mystring() As String
ReDim holds_headers(input1)
Open tablepath For Input As #2
currentLine1 = ""
a = 0
Do While Not EOF(2)
    Line Input #2, currentLine1
    Mystring = Split(currentLine1, ",")
    If a <> 0 Then 'store core
        For i = 0 To input1
            array1(i, a - 1) = Mystring(i)
        Next i
    End If
    If a = 0 Then 'store header
        For i = 0 To input1
            holds_headers(i) = Mystring(i)
        Next i
    End If
    a = a + 1
Loop
Close 2
a = a - 2
Dim percent_occupation As Double
Dim mapunit As String
Dim mapunit_store As String
Dim percent_occupation_store As Double
Dim stored_row As Variant
Dim k_factor As Double
Dim k_factor_store As Double

```

```

Dim outline As Variant
Dim storeline() As Variant
'Core code *****
'sorts the input table by first column (which should be mapunit)
Dim outarray()
outarray = arraysort(array1)
Open tablepathout For Output As #3
ReDim storeline(input1)
For i = 0 To a
    mapunit = outarray(0, i)
    percent_occupation = outarray(input3, i)
    k_factor = outarray(input2, i)
    If i = 0 Then
        mapunit_store = mapunit
        percent_occupation_store = percent_occupation
        k_factor_store = k_factor
        For j = 0 To input1
            outline = outline & "," & holds_headers(j)
            storeline(j) = outarray(j, i)
        Next j
        outline = Right(outline, Len(outline) - 1)
        Print #3, outline
        outline = ""
    End If
    If i < a Then
        If mapunit <> outarray(0, i + 1) Then
            If percent_occupation >= percent_occupation_store Then
                mapunit_store = mapunit
                percent_occupation_store = percent_occupation
                k_factor_store = k_factor
                For j = 0 To input1
                    storeline(j) = outarray(j, i)
                Next j
            End If
            For j = 0 To input1
                outline = outline & "," & storeline(j)
            Next j
            outline = Right(outline, Len(outline) - 1)
            Print #3, outline
            outline = ""
            mapunit_store = outarray(0, i + 1)
            percent_occupation_store = outarray(input3, i + 1)
            k_factor_store = outarray(input2, i + 1)
        End If
        If mapunit = outarray(0, i + 1) Then
            If percent_occupation > percent_occupation_store Then

```

```

    percent_occupation_store = percent_occupation
    mapunit_store = mapunit
    k_factor_store = k_factor
    For j = 0 To input1
        storeline(j) = outarray(j, i)
    Next j
ElseIf percent_occupation = percent_occupation_store And k_factor >= _
k_factor_store Then
    percent_occupation_store = percent_occupation
    mapunit_store = mapunit
    k_factor_store = k_factor
    For j = 0 To input1
        storeline(j) = outarray(j, i)
    Next j
End If
End If
End If
If i = a Then
    If mapunit <> outarray(0, i - 1) Then
        mapunit_store = mapunit
        percent_occupation_store = percent_occupation
        k_factor_store = k_factor
        For j = 0 To input1
            outline = outline & "," & outarray(j, i)
        Next j
        outline = Right(outline, Len(outline) - 1)
        Print #3, outline
        outline = ""
    ElseIf mapunit = outarray(0, i - 1) Then
        If percent_occupation > percent_occupation_store Then
            mapunit_store = mapunit
            percent_occupation_store = percent_occupation
            k_factor_store = k_factor
            For j = 0 To input1
                storeline(j) = outarray(j, i)
            Next j
        ElseIf percent_occupation = percent_occupation_store And k_factor >= _
k_factor_store Then
            percent_occupation_store = percent_occupation
            mapunit_store = mapunit
            k_factor_store = k_factor
            For j = 0 To input1
                storeline(j) = outarray(j, i)
            Next j
        End If
    End If
    For j = 0 To input1

```

```

        outline = outline & "," & storeline(j)
    Next j
    outline = Right(outline, Len(outline) - 1)
    Print #3, outline
End If
End If
Next i
Close 3
GetSystemTime SysTime
SysTimeEnd = SysTime.wHour & ":" & SysTime.wMinute & ":" & SysTime.wSecond & ":" _
& SysTime.wMilliseconds
MsgBox "The routine has finished.", vbOKOnly, "Attention."
'Line1:
Text3.Text = 0
Text3.Visible = False
Text2.Text = 0
Text2.Enabled = False
Text1.Text = 0
Text1.Visible = True
Command1.Enabled = False
End Sub

Private Sub Form_Load()
Text2.Visible = False
Text2.Enabled = False
Text3.Visible = False
Text3.Enabled = False
ProgressBar1.Value = 0
End Sub
Private Sub Text1_Change()
Dim mycheck As Boolean
input1 = Text1.Text
mycheck = IsNumeric(input1)
If mycheck = False Then
    MsgBox "The number of columns you have provided is not numeric. Please provide a _
numeric value for number of columns.", vbOKOnly, "Attention."
    Text1.Text = 0
End If
input1 = input1 - 1
Text2.Visible = True
Text2.Enabled = True
End Sub

Private Sub Text2_Change()
Dim mycheck2 As Boolean

```

```

input2 = Text2.Text
mycheck2 = IsNumeric(input2)
If mycheck2 = False Then
    MsgBox "The column number for K value you have provided is not numeric. Please provide _
a numeric value for the K value column number.", vbOKOnly, "Attention."
    Text2.Text = 0
End If
input2 = input2 - 1
Text3.Visible = True
Text3.Enabled = True
End Sub

```

```

Function arraysort(values())
Dim i
Dim j
Dim smallest_value
Dim smallest_j
Dim min
Dim max
Dim temp
min = LBound(values, 2)
max = UBound(values, 2)
For i = min To max - 1
    ProgressBar1.Value = (i + 1) * 100 / (max + 1)
    smallest_value = values(0, i)
    smallest_j = i
    For j = i + 1 To max
        'See if values(j) is smaller. changed to strComp to be case sensitive vbBinaryCompare.
        If StrComp(values(0, j), smallest_value, vbBinaryCompare) = -1 Then
            ' Save the new smallest value.
            smallest_value = values(0, j)
            smallest_j = j
        End If
    Next j
    If smallest_j <> i Then
        ' Swap items i and smallest_j.
        For intA = 0 To UBound(values, 1)
            temp = values(intA, smallest_j)
            values(intA, smallest_j) = values(intA, i)
            values(intA, i) = temp
        Next 'intA
    End If
    If i = 3.5 * (Int(i / 4)) Then
        ProgressBar1.Refresh
    End If
    If i = 3 * (Int(i / 4)) Then

```

```

        ProgressBar1.Refresh
    End If
Next 'i
arraysort = values
ProgressBar1.Value = 0
End Function

Private Sub Text3_Change()
Dim mycheck3 As Boolean
input3 = Text3.Text
mycheck3 = IsNumeric(input3)
If mycheck3 = False Or input3 = "" Then
    MsgBox "The column number for percent occupation you have provided is not __
numeric. Please provide a numeric value for the percent occupation column number__
.", vbOKOnly, "Attention."
    Text2.Text = 0
    input3 = 0
End If
input3 = input3 - 1
Command1.Enabled = True
End Sub

```

APPENDIX P: DATASETS OF SOIL LOSS

Listed below in tabular format are soil loss risk class grids for several modeling scenarios applied in this study for the year 2001. Each of the soil loss modeling scenario grids with the given input parameters are located on the CD indicated. These gridded datasets are provided as files in binary floating point format located on the CD specified. Binary floating point grids can be imported into ArcInfo using the floatgrid function. Included with each of the binary floating point datasets is a header file and projection file. The datasets are discrete nominal classifications of soil erosion and should be symbolized with unique values. Class 6 – Very low, $< 6 \text{ t ha}^{-1} \text{ yr}^{-1}$, Class 11- low, $6\text{-}11 \text{ t ha}^{-1} \text{ yr}^{-1}$, Class 22- moderate, $11\text{-}22 \text{ t ha}^{-1} \text{ yr}^{-1}$, Class 33- high, $22\text{-}33 \text{ t ha}^{-1} \text{ yr}^{-1}$, Class 99- extreme, $> 33 \text{ t ha}^{-1} \text{ yr}^{-1}$. Classes 11 through 99 are generally considered to be intolerable levels of erosion on most Canadian soils, with class 99 being the most extreme. Masking indicates the limitation to field areas experiencing erosion based on the domination of either sheet or rill erosion.

<i>R factor</i>	<i>Masking</i>	<i>K factor</i>	<i>LS factor</i>	<i>C factor</i>	<i>P factor</i>	<i>CD</i>
Mean annual	Sheet	Annual	25% Connectivity	Conventional tillage	Constant	1
Mean annual	Rill	Annual	25% Connectivity	Conventional tillage	Constant	1
Mean annual	Sheet	Annual	25% Connectivity	Conservation tillage	Constant	2
Mean annual	Rill	Annual	25% Connectivity	Conservation tillage	Constant	2
Mean annual	Sheet	Annual	25% Connectivity	No till	Constant	3
Mean annual	Rill	Annual	25% Connectivity	No till	Constant	3
Mean annual	Sheet	Annual	100% Connectivity	Conventional tillage	Constant	4
Mean annual	Rill	Annual	100% Connectivity	Conventional tillage	Constant	4
Mean annual	Sheet	Annual	100% Connectivity	Conservation tillage	Constant	5
Mean annual	Rill	Annual	100% Connectivity	Conservation tillage	Constant	5
Mean annual	Sheet	Annual	100% Connectivity	No till	Constant	6
Mean annual	Rill	Annual	100% Connectivity	No till	Constant	6

Table 25. Soil erosion modeling scenarios provided on compact disk.

CD 1

CD 2

CD 3

CD 4

CD 5

CD 6