A DECISION SUPPORT SYSTEM
FOR SOIL CONSERVATION PLANNING

by

HUBERT MONTAS

A Thesis Submitted to the Faculty of Graduate Studies and Research of McGill University, in partial fulfilment of the requirements for the degree of Master of Science

Department of Agricultural Engineering
MacDonald College of McGill University
Montreal, Quebec

September, 1990

ABSTRACT

M.Sc. Agricultural Engineering

HUBERT MONTAS

A DECISION SUPPORT SYSTEM
FOR SOIL CONSERVATION PLANNING

A Decision Support System for the design and planning of soil conservation systems on a watershed scale was conceived and applied to southwestern Quebec. The system integrated Geographical Information System, distributed parameter hydrologic modeling and Expert System technologies. Maps of appropriate soil conservation practices were produced for two small rural basins representative of the study region. The effect of the selected practices on runoff and sediment was assessed using the ANSWERS model. Erosion sites were targeted using a once-in-25 year design storm. It was observed that small portions of the study basins produced large amounts of eroded sediment. The expert system was designed to select appropriate conservation practices for the 1-ha cells which had more than one tonne of erosion as a result of the design storm. The results demonstrated that the selected conservation practices would reduce sediment yield and average erosion rates by 50% in each of the study basins.

RESUME

M.Sc. Génie Rural

HUBERT MONTAS

UN SYSTEME D'AIDE A LA DECISION
POUR PLANIFIER LA CONSERVATION DES SOLS

Un Système d'Aide à la Décision pour la conception et la planification de systèmes de conservation du sol à l'échelle du bassin versant a été conçu et appliqué au sud-ouest du Québec. Ce système intégrait les technologies du Système d'Information Géographique, du modèle hydrologique à paramètres distribués et du Système Expert. Des cartes représentant les pratiques appropriées de conservation du sol ont été générées pour deux petits bassins versants agricoles représentatifs de la région d'étude. L'effet des pratiques choisies sur les écoulements de surface et l'érosion a été évalué en utilisant le modèle ANSWERS. Les sources d'érosion ont été mises en évidence à l'aide d'un orage dont l'intervalle de récurrence était de 25 ans. Il a été observé que de petites portions des bassins d'étude produisaient beaucoup de sédiments. Le système expert a été conçu pour choisir des pratiques de conservation appropriées pour chaque cellule d'un hectare dont la perte de sol due à l'orage de référence était supérieure à une tonne. Les résultats ont démontrés que les pratiques de conservation sélectionnées réduiraient l'apport sédimentaire du bassin et le taux d'érosion moyen de 50%.

ACKNOWLEDGEMENTS

I am grateful to my thesis supervisor and research director, Dr C.A. Madramootoo for his thorough support, guidance and serious supervision of this work.

I also wish to express my thanks to Peter Enright, Research Assistant, for his help with data collection and his positive nature which made working with him a pleasure.

Timothy Quinn is thanked for his help in data analysis and for his metaphorical language which brightened some of the dry summer days of 1989. Messrs. F. Beaulieu, R. Honkoop, K. Wiyo and S. Broughton also helped tremendously with data collection and analysis. I offer my thanks to each and everyone of them.

A very special thanks to my dearest friend Fanaye, for her patience, understanding and sense of humour.

Above all, I wish to thank my family for the encouragement and support that they provided.

The financial support of the Natural Sciences and Engineering Research Council and of the Fonds pour la Formation de Chercheurs et d'Aides à la Recherche is also gratefully acknowledged.

TABLE OF CONTENTS

Page

LIST OF FIGURES

Page

LIST OF TABLES

Page

NOMENCLATURE

A	difference between the maximum and steady-state infiltration rates in Holtan's equation
A	area over which soil detachment occurs
AI	artificial intelligence
ANSWERS	areal nonpoint source watershed environmental response simulation model
C	crop parameter in the USLE
C.	abbreviation of clay in Tables 3.1 and 3.2
C(i)	observed sediment concentration
CP'_A	coefficient of predictability
DBMS	database management system
DEM	digital elevation model
DETF	detachment of soil by surface flow
DETR	detachment by rainfall
DF	depth of the control zone in Holtan's equation
DTM	digital terrain model
DSS	decision support system
EC	electrical conductivity
ES	expert system
FC	steady-state infiltration rate in Holtan's equation
FMAX	infiltration capacity of the control zone in Holtan's equation
g.S.L.	abbreviation of gravelly sandy loam in Table 3.2
GIS	geographical information system
GSL	gross sediment loading
HRU	hydrologic response unit

HU	surface roughness height
i	a summation index
K	soil erodibility
L.f.S.	abbreviation of loamy fine sand in Table 3.1
MBMS	model base management system
n	Manning's roughness coefficient
n	a summation index
NPS	nonpoint source (usually pollution)
NSL	net sediment loading
O(i)	observed runoff value
O.M.	organic matter
P	cropping and management factor in the USLE
P	infiltration exponent in Holtan's equation
PIV	potential infiltration volume in Holtan's equation
PER	percentage ground cover
PIT	potential interception
Q	overland flow rate or stream discharge
R	rainfall and snowmelt factor of the USLE
R^2 or r^2	coefficient of determination
RC	roughness coefficient for surface retention
S	overland slope
S.	sand in Table 3.2
S.g.L.	sandy gravelly loam in Table 3.2
S.L.	sandy loam in Table 3.1
S(i)	simulated runoff value
SCS	United States Soil Conservation Service

SDR	sediment delivery ratio
S.H.C.	saturated hydraulic conductivity
TF	capacity of surface flow to transport sediments
TIN	triangulated irregular network, a form of DEM
TP	total pore volume in the control zone in Holtan's equation
USLE	universal soil loss equation
V.f.S.L.	very fine sandy loam in Table 3.1

1. INTRODUCTION

Intensive monocrop agriculture ensures a plentiful supply of food but at the same time destroys soil productivity. High applications of pesticides and fertilizers increase yields, but also contribute to the contamination of surface and subsurface waters. One of the aims of contemporary agricultural research is to find methods of keeping the benefits of modern farming practices without their drawbacks.

Improving water quality and providing a sustainable basis for agriculture are some basic objectives of soil and water conservation engineering. The selection of measures that reduce erosion from intensely cultivated fields are a key element of this discipline. A typical soil conservation plan consists of changes in land use and/or crop management and the implementation of conservation structures. The appropriate practices are determined by land use, topography and soil types, as well as by economic and social factors. Experienced soil conservation engineers are, however, scarce in Canada. Consequently there is a need for computer-based tools that permit engineers and planners to assess land use, perform erosion analyses and develop appropriate conservation plans with greater ease and reliability.

Decision Support Systems (DSS) show great promise for strategic planning of soil conservation efforts. This technology is used by managers and planners in the business sector to select appropriate development plans and perform strategic market analyses. A DSS can similarly aid in the selection of appropriate soil conservation practices for agricultural watersheds.

Expert Systems (ES), Geographical Information Systems (GIS) and detailed process models are additional technologies that can be used for the improvement of water quality and abatement of non-point source pollution through conservation planning. These technologies can be integrated in the framework of a DSS and provide combined capabilities greater than if each tool was used separately.

This thesis demonstrates the design and implementation of a DSS for making soil conservation plans at the watershed scale. The system integrates ES, GIS and detailed process model technologies. The DSS was used to produce soil conservation maps for two watersheds of southwestern Quebec.

1.1. OBJECTIVE

The objective of this thesis was the development of a Decision Support System (DSS) for soil conservation planning. The target system consisted of: (i) a spatial database (GIS) that accessed information on land use, soil type, stream network and topography of agricultural watersheds; (ii) a distributed parameter hydrology and sediment transport model, ANSWERS and; (iii) an Expert System (ES).

1.2. SCOPE

The DSS was applicable to watersheds of up to 20 km^2 due to limitations in the GIS and ANSWERS. It focused on alleviating erosion by water since ANSWERS simulates only this type of soil loss. Eight soil conservation practices were considered by the expert system.

The soil conservation DSS is not intended for commercial use at this stage, and therefore does not have an intuitive user interface. Operation of the system requires some level of programming ability.

2.REVIEW OF THE LITERATURE

Erosion is the removal of surface particles by wind or water (Kirkby, 1980). Erosion by water is caused by two agents: raindrops (splash) and runoff (wash). Raindrop impacts detach and move small soil particles and break down the soil surface aggregates causing a crust to develop. Runoff further causes four types of erosion: sheet; rill; gully and channel erosion (Schwab et al., 1981). Detached particles are picked up by runoff and transported downstream. The transport capacity of surface flow depends on its velocity and depth as well as on the size distribution of the detacned particles. According to Hurni (1988), soil erosion by water from cultivated land is the most threatening degradation process for sustainable soil productivity.

The degradation of the soil due to erosion is evidenced by lower crop yields. Schertz et al. (1985) observed yield reductions of up to 49% for corn and 29% for soybeans between severely and moderately eroded plots in a three year experiment.

Runoff from agricultural land poses further threats to health by conveying toxic chemicals. Fertilizers and pesticides from cropped areas are dissolved in runoff or adsorbed on the sediments it transports. Nitrogen compounds and bacteria from feedlots similarly make their way to streams and lakes. According to Beasley et al. (1984), water is the primary carrier of pollutants from most farmlands.

Soil conservation aims to improve water quality and provide a sustainable basis for agriculture through the control of soil erosion. Conservation planning is a three step process: 1) targeting areas of high soil loss; 2) selecting appropriate practices; 3) implementing the selected measures. A Decision Support System can be used to help perform steps one and two of this process.

2.1. Decision Support Systems

A Decision Support System is a grouping of computer-based tools aimed at easing the problem-solving process. Sprague et al. (1982) noted the following specific traits of DSS: i) they are generally aimed at problems that are badly structured or underspecified; ii) they combine models, analytical tools and data processing functions; iii) they focus on features that make them easy to use; iv) they are flexible and adaptable to changes in decision-making approaches. These four specific aspects of DSS set them apart from previous computer-based tools such as management information systems (MIS) and electronic data processing (EDP) which focused on information retrieval rather than problem-solving.

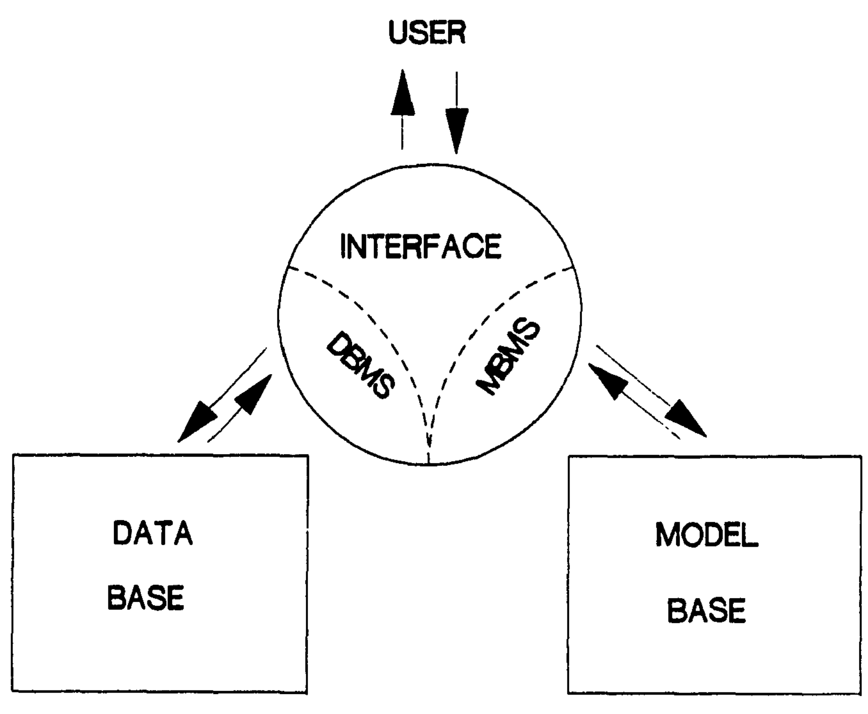


Figure 2. 1: Decision Support System Components

A DSS generally consists of three components: database, model base and user interface (Figure 2.1). The database stores all the data necessary to carry the decision making process. This data defines the problem solving space within which a solution is sought. This data is accessed and managed through the DataBase Management System (DBMS).

The model base stores quantitative and qualitative models. The quantitative models permit numerical analysis of the data stored in the database. Quantitative models may be deterministic or stochastic, linear or non-linear. The qualitative models permit search and judgemental analysis to be performed on the data. These models are often derived from artificial intelligence technology (eg. expert systems).

The user interface permits dialogue between the user and the database and model components. This component provides support for user queries and is responsible for the transmission of model results.

Davis (1988) outlined the use of a DSS in the decision making process: The decision maker must determine how an organization or physical system can be expected to behave under a variety of different circumstances. Management objectives, organizational issues, historical data, operational conditions, external factors, resource considerations, and so forth, are analyzed and combined quantitatively to provide various indicators of performance, risk and cost. Management then uses human experience and insight, to weed out unacceptable alternatives and to propose new ones. This pattern strongly resembles the soil conservation process. Likewise it consists in an initial assessment phase, characterized by quantitative analysis, followed by a selection phase based on qualitative approaches.

For soil conservation purposes the behaviour of the physical system (ie. watershed) can be assessed through a mathematical model. The ground data, stored in the database, consists of the physical properties of crops and soils and the management practices of the farmers. The quantitative indicators of performance are erosion levels and water quality indices. The human experience, or a qualitative model thereof, can be used to propose appropriate soil conservation practices.

Many researchers agree on the point that integrating databases with quantitative and qualitative models will provide tools of unprecedented power (Borgelt, 1988; Heatwole et al., 1987; Whittaker et al., 1986; Robinson et al., 1986). This integration is the definition of a DSS. For soil conservation decision making the database may be a Geographical Information System (GIS), the quantitative model may be a detailed process distributed-parameter model of hydrologic processes and the qualitative model may be an Expert System (ES)

2.1.1. Examples of DSS used in Soil and Water Management

Arnold and Sammons (1988) implemented a DSS to assist users of the SWRRB hydrologic model in selecting input parameters. This DSS could get weather and soils data from large databases to supply default input values for the model. Furthermore, the DSS could call two expert systems : CURVENUM that specialized in selecting appropriate SCS runoff curve numbers and a second expert system that determined the USLE P factor from cropland practices and topography. Integrated DSS were found to decrease the time and money spent during the preparation of input data to process models.

Chen (1986) implemented an intelligent interface to estimate uncertain input data for a water quality model. His DSS consisted of an expert system, water quality model and user interface. User entered parameters were filtered through the knowledge base and replaced by acceptable values when too high, too low or missing. The model was then run with the accepted values and its output was verified by both the user and the expert system. This DSS helped the Shanghai Environment Protection Bureau of China in the planning of pollution control strategies for the Huangpu River.

DSS used for land use planning often integrate an expert system with a geographical information system. The expert system is then a qualitative decision model whilst the geographical information system serves as a database. Reisinger and Davis (1986) implemented such a system for planning timber harvests and evaluating terrain. GEODEX and URBYS are two additional systems dedicated to urban land use planning (Robinson and Frank, 1987).

2.2. Geographical Information Systems

A geographical information system (GIS) is a database management system (DBMS). The information that it contains is spatially referenced and represents geographical features of various areas of interest. A typical GIS consists of an input interface, a database management system, spatial data storage and an output interface (Figure 2.2). The three functions integrated within a GIS are data entry, data treatment and data output.

According to Avery (1985) a state of the art GIS should be capable of: (i) accepting data input in many different forms including maps, aerial photographs, satellite images and survey sheets; (ii) storing and maintaining the entered information with the necessary spatial relationships; (iii) performing data manipulation operations such as querying, overlaying and combining in a timely manner; (iv) some level of modeling (including elevation modeling) that takes into account data interrelationships and causes and effect responses of the appropriate factors; (v) presenting outputs in a variety of ways including tables, screen images and paper plots.

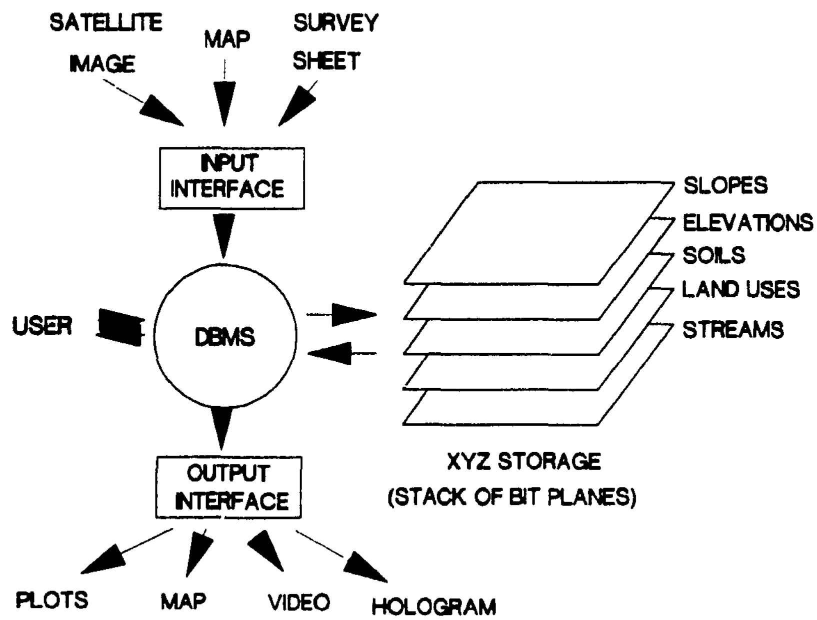


Figure 2.2: Geographical Information System Components

Information within a GIS is usually stored as stacked planes or layers. Each layer represents one particular feature. A GIS for agricultural purposes could for example consist of a layer of soils information, a layer of land use information, a layer of streams information and a layer of topographical information. This separation of features into distinct layers makes it easy to edit specific information independently of the data stored in other layers. It also permits the creation of composite maps through the combination of data from different layers.

An important aspect of a geographical information system is the form in which it stores information. Two basic encoding methods are utilized: raster mode and vector mode. Raster mode is a storage paradigm in which information is stored as square or rectangular cells. A given feature of a region is therefore encoded as a two-dimensional array of cells. The value assigned to each cell is the average value of the feature over the area of the cell. Raster storage is easy to handle on the computer because of the capability of most programming languages to manipulate arrays. Storing information as grids of cells may however be wasteful when large homogeneous areas are considered. Three methods of overcoming this problem are chain codes, block codes and quadtrees (Burrough, 1987).

Vector mode is a storage method that directly stores the physical x, y and z coordinates of the features of interest. For punctual features such as elevation benchmarks, a single set of coordinates is stored. For linear objects such as roads or streams a list of coordinates is stored. For areal objects a list of the coordinates making the boundary of the object is stored. At comparable levels of precision, vector encoding is more storage efficient than raster encoding. With vector encoding one can furthermore specify precisely the position of any punctual object whereas raster mode stores only approximate positions. Overlaying is however a much more complex operation in vector mode than it is in raster mode.

Another important aspect of any GIS is the means it possesses for modeling information. A Digital Elevation Model (DEM) is an integral part of most GIS applications. Ridge lines, watershed boundaries, surface slope direction and steepness are all potential products of an elevation model. Elevation models are produced from topographic information such as contour lines and spot elevations. Three methods of deriving a DEM are mathematical surface patches, triangulated irregular networks (TIN) and distance weighted interpolation (Burrough, 1987; Monmonier, 1982).

Previously available only on mainframes, GIS can now be implemented on a microcomputer. Borgelt (1988) listed 19 GIS packages for microcomputer systems. Half of the reviewed systems were raster based including IDRSI and OSU-MAP which are low-cost systems. The popular vector-based ARC/INFO GIS which is a medium priced system was also discussed. The capital cost of a microcomputer GIS varies from 50$ to 65,000$.

GIS is becoming the key element in soil conservation planning. Modeling abilities make GIS useful for targeting sources of pollution. In addition, data management capabilities make GIS useful aids to data entry for distributed parameter models.

2.2.1. Geographic Information Systems Used for Soil Conservation and Improving Water Quality

Shanholtz et al.(1987) described the development of VirGIS the Virginia Geographic Information System. This system was developed to target major sources of NonPoint Source (NPS) pollution within the Chesapeake Bay region in the United States. VirGIS is a raster based GIS with a cell size of one hectare. The data held inside VirGIS consist of soil type, land use and topography. This GIS currently manages data for 3.25 million hectares of the Chesapeake Bay region.

Dillaha et al. (1987) used VirGIS, the USLE and a simple sediment delivery ratio (SDR) to target high pollution potential areas within the Chesapeake Bay region. They compared the results obtained with their simple function to ANSWERS predictions. The results showed that the simple function was not very accurate but could be improved by considering wooded areas and increasing the SDR of cells through which a stream passes.

Yagow et al. (1987) described the use of an erodibility index overlay and a water quality index overlay to target sources of high nonpoint source pollution potential using VirGIS. A comparison of the targeted areas with professional judgment showed total agreement for two of the four soil and water conservation districts considered.

RGISM is the Raster Geographic Information System for Mapping. It was developed in FORTRAN 77 by Peterson and Long (1984),(as reported by Gilliland et al.1987). This GIS is implemented as separate programs which provide a modular nature. The system provides basic GIS data manipulation and retrieval functions. A simple data structure makes it possible to add specific purpose functions to the system.

Gilliland and Baxter-Potter (1987) used RGISM to predict nonpoint-source pollution potential of a 2.59 km^2 agricultural watershed in Nebraska. A feedlot, corn field and pasture were the dominant land uses in this area. The grid-cell size used for this study was of 400 m^2. The researchers programmed three different techniques as RGISM program modules: the SCS Curve Number technique, the USLE, and a loading function for the prediction of bacterial densities in runoff. Their results showed the great spatial variability of runoff, erosion and bacteria sources.

LRIS is the acronym for Land Resource Information System (Adams et al., 1982). This GIS was developed as a part of the Lake Erie Wastewater Management Study (LEWMS) to assess the impact of agricultural land uses on phosphorus pollution of the Great Lakes. LRIS is a variable cell-size (4-36 hectares) GIS. It includes data on land use, soil characteristics, and hydrologic and political boundaries. LRIS was used by Logan et al. (1982) to target diffuse sources of phosphorus in the lake Erie basin. They used the USLE to assess the impact of soil conservation scenarios on soil loss.

Tan and Shih (1989) used the ARC/INFO vector based GIS to assess the location of abandoned artesian wells in Florida. These wells contaminate potable water reservoirs with saline water. The study included 655 km^2 of land use information from 1944, 1958 and 1987. The GIS was used to digitize and overlay this information. A resolution of six metres was chosen.

Vieux et al. (1988) used ARC/INFO to generate a triangulated irregular network elevation model (TIN) for a watershed in Nebraska. This TIN formed part of the input to a finite element runoff model.

Needham et al. (1989) demonstrated the use of a GIS as an aid for data input to distributed parameter models. ARC/INFO was used to create a grid representing a watershed, derive SCS runoff curve numbers, calculate slope and aspect of the land surface and calculate average parameter values for each grid cell created. The grid served as input to the AgNPS model of runoff and erosion (Young, 1987 as reported by Feezor et al., 1989). The GIS was further used to map model output and overlay land use on regions of high nitrogen loss.

2.3. Assessing Erosion Using Quantitative models

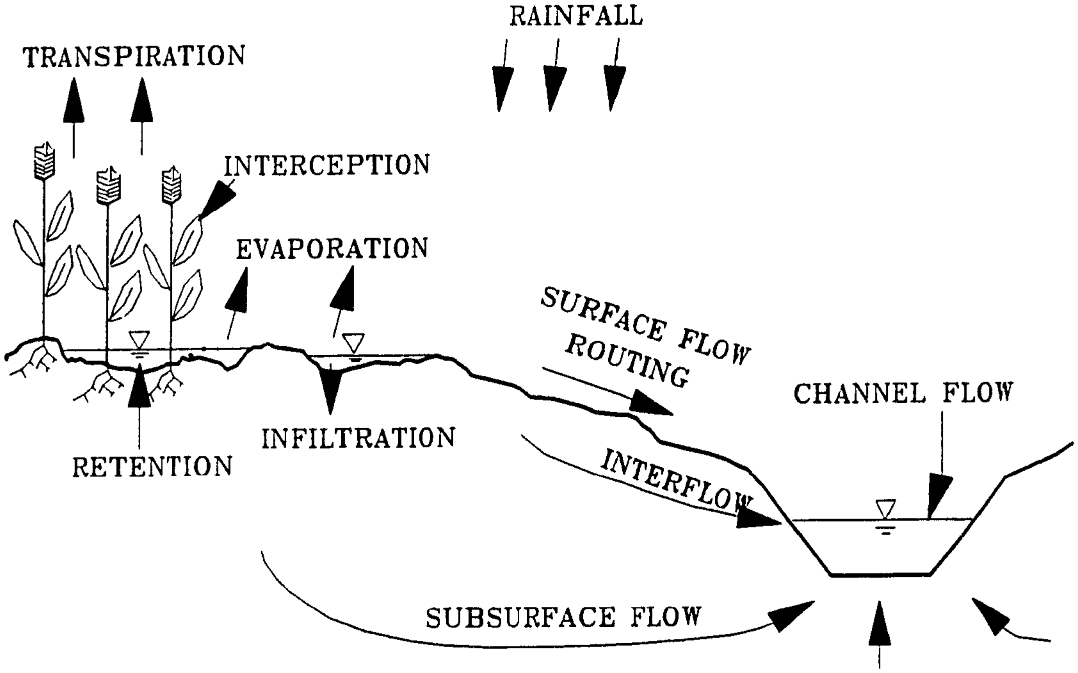
2.3.1. Hydrologic Models

Hydrology is the science that studies water circulation and distribution and the associated transport processes. The hydrologic cycle is the continuous process in which water evaporates from surface water bodies, forms clouds, moves through the air and produces rain and snow (Bedient and Huber, 1988). Some important components of this cycle are illustrated in Figure 2.3.

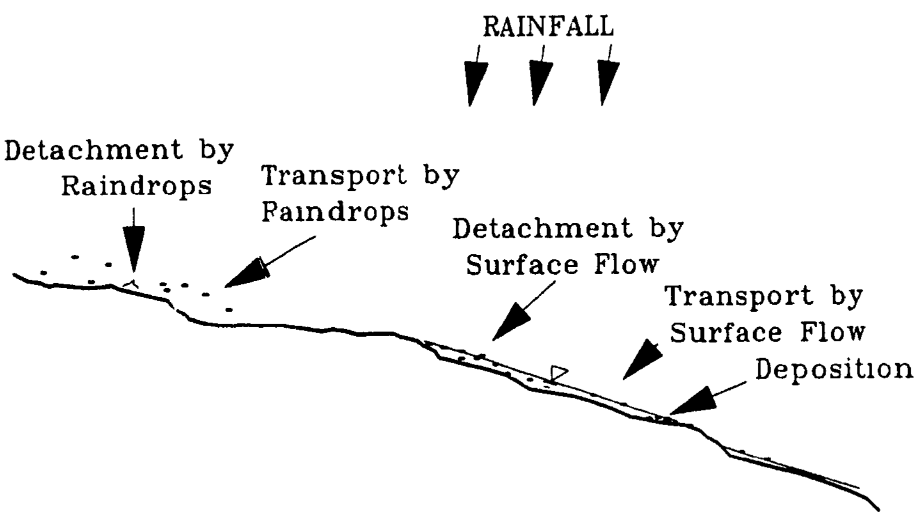
Hydrologic models are mathematical representations of the processes of the hydrologic cycle. Their general aim is the prediction of runoff from rainfall data. For soil erosion studies the runoff prediction components of hydrologic models are linked to soil loss and transport components.

Hydrologic models are separated into black-box models and physically based models. Black-box models are regression equations fitted to arbitrary parameters. These models provide a rough approximation of the complexity of hydrologic processes and are simple to use. This simplicity makes them useful for simulations of runoff on a continuous (year round) basis. The rational method and the SCS curve number method are two black-box models used to predict peak runoff rates. Madramootoo et al. (1989) found that the rational method overpredicts peak flow for small flat agricultural watersheds. Madramootoo and Enright (1988) found that the SCS technique usually underpredicts the maximum runoff rate.

Physically based models rely on a detailed mathematical description of the processes of the hydrologic cycle. These models are based on physical relationships involving measurable parameters. Physical consistency makes this type of model applicable to a wider range of conditions than



a) Water Circulation and Distribution



b) Sediment Transport Processes

Figure 2.3: Processes of the Hydrologic Cycle

regression models. Another advantage is that the model can be updated as new theories are developed. The state of the art in physically based models are watershed scale distributed parameter models.

The distributed parameter approach to modeling is based on the concept of an hydrologic response unit (HRU). An HRU is a region which behaves homogeneously with respect to runoff generation. HRUs are therefore characterized by a constant land use, soil type and topography. Two approaches exist for breaking a watershed up into HRUs. The simplest approach is to use a square grid and specify watershed properties for each cell that lies within grid lines. This method lends itself to finite difference modeling of hydrologic processes. The second method consists of subdividing the watershed into elements of irregular shape. This method is most appropriate for finite element modeling. Irregularly shaped HRUs can reduce the size of the input parameter specification since homogeneous adjacent cells need not be coded separately. The computational complexities associated with the finite element method may, however, outweigh this benefit.

Hydrologic models used for erosion assessment contain additional relationships describing soil detachment and transport by water. The Universal Soil Loss Equation (Wischmeier and Smith 1978), or one of its derivatives, is often used for this purpose. This equation was developed to estimate the average annual erosion for a given agricultural field. It consists in a product of 6 factors. These factors have been tabulated by Wischmeier and Smith (1978) for various regions of the United-States. The USLE can also be used to select appropriate land use as described by Hudson (1981). Saheli et al. (1989) evaluated the USLE for the province of Quebec. Their study was conducted over a four year period and included four combinations of land use and tillage. Their results showed a good correlation of the measured value of the USLE parameter C with the tabulated C values presented by Wischmeier and Smith (1978). Madramootoo (1988) presented detailed maps of the USLE rainfall and snowmelt factor *R* that are applicable to the provinces of Quebec and Ontario.

The input requirements of detailed process watershed scale distributed parameter hydrology and sediment transport models generally consist of a detailed description of land use, soil types and topography of the region of interest.

2.3.2. Examples of Detailed Process Watershed Scale Distributed Parameter Hydrologic Models

ANSWERS is the acronym for Areal Nonpoint Source Watershed Environment Response Simulation (Beasley et al., 1980a). This model utilizes a grid based representation of the watershed and thus uses a finite difference solution scheme. ANSWERS computes infiltration using a modified version of Holtan's infiltration equation. The model then routes runoff through cells using Manning's and the continuity equations. Sediment detachment by rainfall and runoff are calculated using the equations of Meyer and Wischmeier (1969) modified by Foster (1976). The sediment transport capacity of overland flow is computed using an adaptation of Yalin's equation.

ANSWERS was used to identify watersheds with high pollution potential in Allen County, Indiana (Beasley et al., 1980b). ANSWERS permitted the identification of the local sources of pollution within each watershed and permitted the ranking of groups of farmers for cost sharing conservation initiatives.

Breve et al.(1989) evaluated ANSWERS for the Georgia coastal plains. The study watershed had an area of 0.344 ha, an average slope of 2.5% and a loamy sand soil. Data obtained for thirteen rainfall events and 3 erosion events were used. The results showed that when surface crusting is taken into account and antecedent soil moisture is properly estimated ANSWERS can predict runoff within 30%. Evaluation of the erosion component was however inconclusive.

Von Euw et al. (1989) performed a sensitivity analysis on ANSWERS and evaluated its erosion and runoff components on an 800 ha watershed located in Ontario. The study region had a rolling topography with a 2% average slope. The land use consisted of 64% tilled crop land, 16% pasture and 20% forested. Over 30% of the watershed was tile drained. The sensitivity analysis for ten input variables showed that the predicted sediment yield is most influenced by the steady-state infiltration rate of the soil for low intensity events (10 mm/h for 2 hours) and additionally by Manning's roughness coefficient and the surface slope for events of higher intensity (32.4 mm/h for one hour). Their results however showed that ANSWERS underpredicts sediment yield and is not very good at predicting either peak flow or flow volume.

Dickinson et al.(1989) studied the effect of the time interval used in the input of rainfall data in ANSWERS. They found that a shorter time interval (5 minutes as compared to one hour) increases runoff depth, peak runoff rate, maximum erosion rate and total sediment yield by factors of up to 2.3, 12.2, 1.7 and 10.3 respectively. The greatest increase always appeared when the time step was reduced from 30 to 15 minutes.

FESHM is the acronym for Finite Element Storm Hydrograph Model. As its name indicates this model relies on a finite element scheme for solving runoff generation, routing and sediment transport equations. FESHM simulates runoff generation through the use of Holtan's equation and routing through the continuity and Manning's equations (Ross, 1979). The watershed is divided into flow planes of irregular shapes. The flow planes are further divided into strips in which the flow is assumed to be perpendicular to the direction of flow in the channel. The strips are broken into HRUs with homogeneous soils and crops.

Hession et al.(1987) evaluated the runoff generation and routing components of FESHM on a 361 ha watershed in Virginia. This watershed was farmed to 68% and forested to 32%. Forty-two percent of the watershed area had slopes greater than 15%. The soil types were well drained loams and sandy loams. The evaluation was done using 111 significant runoff events from a 17 year database. The results showed no difference in peak flow at the 0.05 significance level.

AgNPS is the Agricultural NonPoint Source pollution model (Young, 1987 as reported by Feezor et al., 1989). This model relies on a grid-based representation of the watershed. The maximum number of cells is 3200. The model predicts runoff using the SCS curve number technique. It also predicts sediment yield, total phosphorus and nitrogen loadings and the chemical oxygen demand at the stream outlet (Feezor et al., 1989).

GAMES is the Guelph model for evaluating the effect of Agricultural Management systems on Erosion and Sedimentation (Cook et al., 1985). This model distributes the watershed parameters into field-sized cells of irregular dimensions. GAMES computes estimates of erosion using the USLE. Sediment transport is estimated by sediment delivery ratios calculated for each cell. GAMES does not simulate runoff generation or routing in detail.

Madramootoo et al.(1988) used GAMES to target sources of pollution in two tributaries of a 10,000 ha watershed in southwestern Quebec. Their results showed that 16.5% and 10% of the land area in the two subwatersheds required conservation work. They stated that a major input requirement of the model is the preparation of overlay maps in which the field-sized cells are defined.

Producing input files for distributed parameter models is recognized to be a major constraint by many researchers. Geographical Information Systems (GIS) can be used for this task (Hession et. al., 1987, Feezor et al, 1989)

2.4. Selecting Soil Conservation Practices

An appropriate soil conservation practice is one which reduces the soil loss to an acceptable level. Soil conservation experts use both judgment and formulae, like the USLE, to select appropriate practices. The decision is made once the causes of erosion are determined. The factors considered are: crop type, crop management, soil type and field topography. A field with steep topography should for instance not be intensively cropped and tilled up and down the row but rather terraced, grazed or contour-tilled.

2.4.1. Human Selection of Conservation Practices

There exists a number of methods for conserving soil. A classification of soil conservation practices is displayed in Figure 2.4. The three main effects of conservation measures are: the reduction of raindrop impacts on the soil; the reduction of runoff volume and velocity; the increase of the soil's resistance to erosion (Troeh et al., 1980).

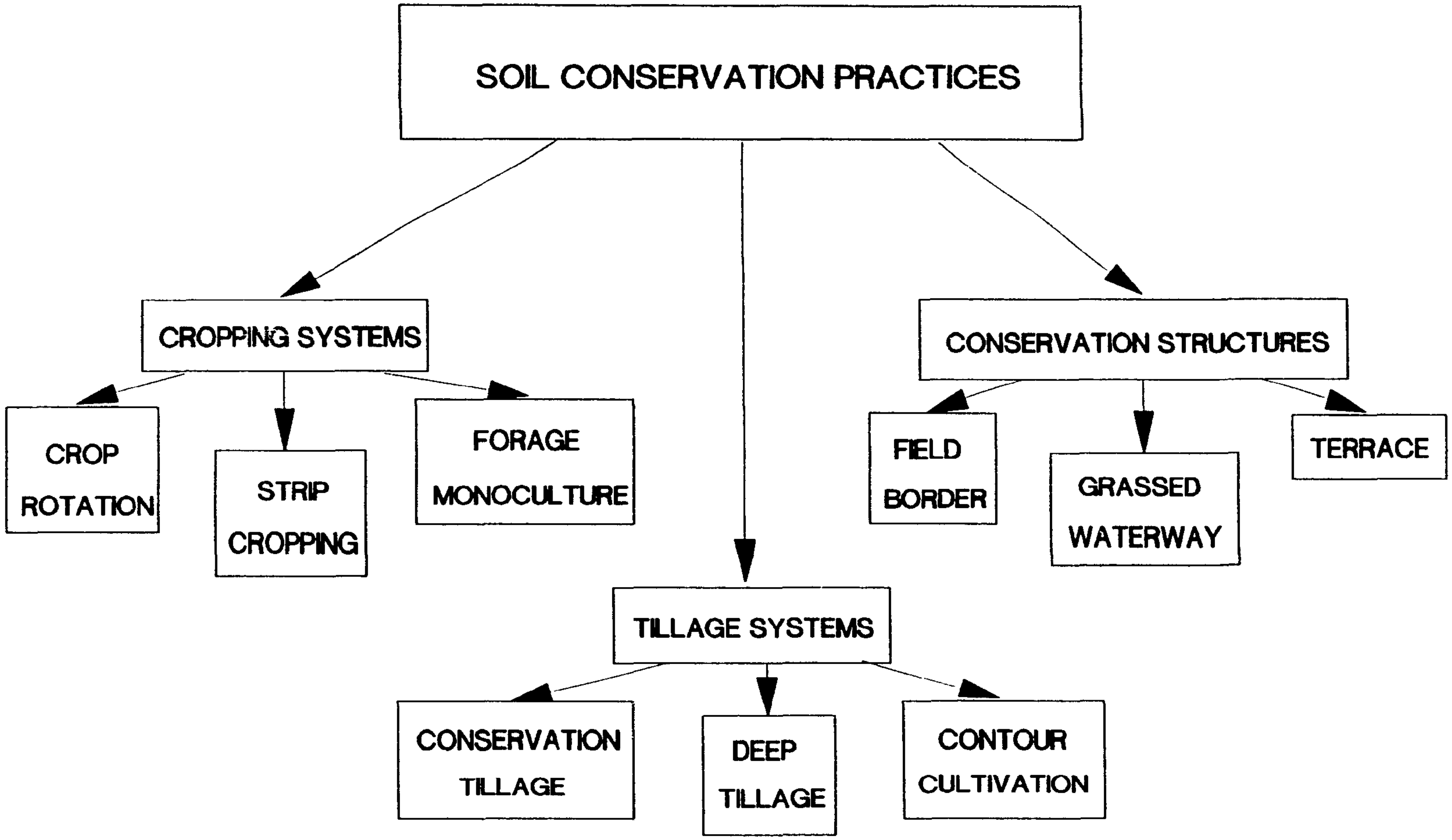


Figure 2 . 4: Classification of Soil Conservation Practices

2.4.1.1. Tillage Systems

Conservation tillage is a non-inverting shallow tillage operation that performs surface roughening while retaining crop residues. Stubble mulch tillage, minimum tillage and zero-tillage are three types of conservation tillage. These operations are applicable to sloping, well drained and permeable coarse and medium textured soils. In their three year study, McGregor et al.(1975) observed soil losses seven times lower for no-till continuous soybeans as compared to conventional-till soybeans. Ketcheson (1977) reported soil loss reductions from 4.17 Mg/ha to 0.12 Mg/ha when no-till was implemented on a Guelph silt loam.

Deep tillage refers to operations that disturb the soil at depths varying from 30 to 60 cm. Three deep tillage operations are subsoiling, vertical mulching and deep plowing. These operations are used to break the impervious pans of compacted soils and to bring finer-textured subsoils back to the surface of highly erodible topsoils. Jasa and Dickey (1989) obtained reductions of 70% in total runoff from subsoiled treatments and an appreciable reduction in the maximum runoff rate.

Contour cultivation consists of planting and tilling crops along contour lines rather than parallel to field edges. The ridges produced by this practice act as barriers to water flow hence promoting infiltration and reducing the velocity and volume of runoff. Contour cultivation can be implemented on sites where a slope of 5% does not exceed a length of 100 metres. Onstad (1972) observed consistently lower soil losses from a contoured field than from a field tilled up and down the slope during his six year study. Contour cultivation is also effective in reducing pesticide loss as shown by Kenimer et al. (1989).

2.4.1.2. Cropping Systems

Crop rotation is a cropping system in which a repetitive sequence of crops is grown on the same land. Crop rotation conserves the soil when companion crops, cover crops and green manures are introduced into the cropping cycle. Cover and companion crops protect the soil when the main crop is harvested or before it emerges. Green manure crops are forages that get plowed into the soil at the end of the growing season to improve its structure and stability against erosion. In a ten year study, Moldenhauer et al (1967) obtained reductions in soil loss and runoff of 30% and 37% respectively for a 3 year rotation of oats, corn and alfalfa-brome hay on a silty clay loam soil.

Strip cropping is another cropping system used for soil conservation. It is applied on sloping land. The idea is to cultivate along contour lines across the main overland flow direction. The land is cropped in strips and a crop rotation scheme is followed.

Monoculture is a cropping system in which the same crop is grown on the same land for a number of successive years. Forage crop monocultures are justified on land too steep to support other crop types. Tree crops are usually grown in monoculture. If erosion is noticed in an orchard then the cropping system should allow for more ground cover (ie. litter or grass).

2.4.1.3. Conservation Structures

Field borders, grassed waterways and terraces are conservation structures used to control soil erosion. Grassed field borders reduce the velocity of the runoff leaving a field and hence decrease its erosiveness. Dillaha (1989) reported removal rates of 87% and 75% for field borders with lengths of 9.1 and 4.6 metres respectively. Vegetative filter strips are also useful for removing plant nutrients from runoff. This study however pointed out that field borders, as designed today, are effective only where shallow uniform surface flow is the dominant form of runoff.

Grassed waterways are conservation structures used to heal or prevent gullies (Bosworth et al., 1982). Terraces are used to break steep slopes into smaller level segments.

2.4.2. Expert Systems as Qualitative Models of Human Reasoning

Artificial Intelligence (AI) is an emerging field of engineering and computer science, with potential applications in many domains of human activity. Applied agriculture will benefit from AI developments through field robots, automated machinery and intelligent decision-making management tools.

Expert Systems are the most widespread development of AI, with more than 150 presently under development or being used (Schmoldt et al., 1986). An expert system is a computer program that is capable of carrying out reasoning and analysis functions in narrowly defined subject areas at proficiency levels approaching that of a human expert (McKinion et al., 1985). Expert systems generally consist of three parts : a knowledge base, a fact base and an inference engine (Figure 2.5). The knowledge base is the store of domain specific knowledge encoded in the form of production rules (eg. **IF** condition(s) **THEN** consequence(s)). The fact base holds data relevant to the study case. The inference engine matches facts from the fact base with the condition part of the rules in the knowledge base to either verify that a given consequence is true (satisfied by the database under the current interpretation and variable assignment) or to deduce new facts. The latter process is called forward chaining whilst the former is referred to as backward chaining.

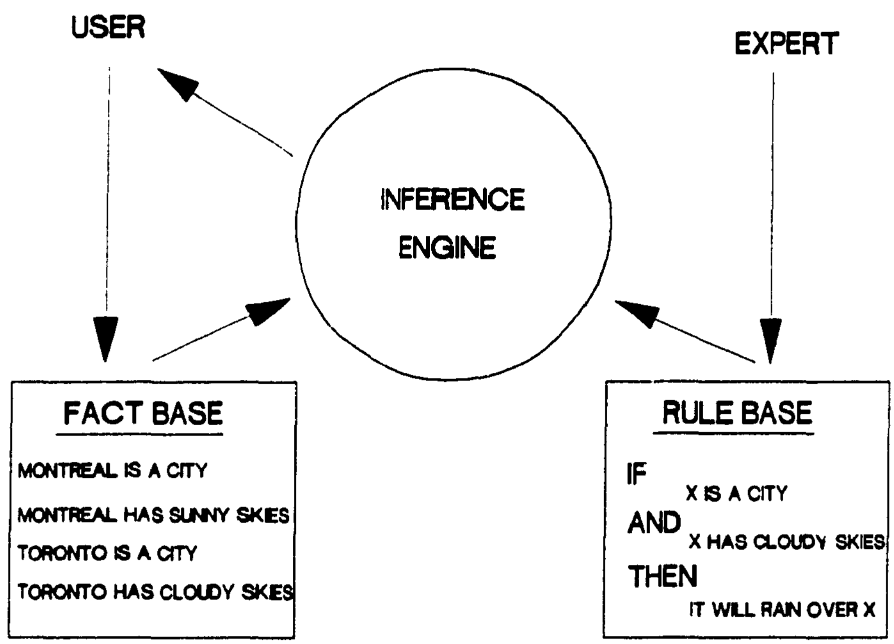


Figure 2.5: Expert System Components

In general, backward chaining is used to test hypotheses and is therefore useful in theorem proving, and for the validation of medical diagnosis. Forward chaining on the other hand generates new facts through deduction from the database until the facts base is saturated. Forward chaining is used in design situations to generate plans.

Expert systems can be more powerful than outlined above through the use of heuristics (meta-rules), non-monotonic reasoning strategies (closed-world-assumption, predicate completion and circumscription, bayesian logic and default logic) and interfaces for knowledge acquisition and user support.

Developing an artificial intelligence application based on logical principles requires that knowledge be formalized before it is implemented. Knowledge formalization is the process by which real world situations and knowledge about these situations are expressed in a declarative form. Genesereth and Nilsson (1987) outlined this process which consists in conceptualizing the problem, choosing a language of expression, selecting an interpretation and writing facts that satisfy the interpretation using sentences expressed in the chosen language. The result of this process, used for expert system development, are the rules and facts expressing the knowledge and situation of the study problem.

The problem conceptualization step of the formalization process, is the definition of an applicable universe of discourse. The universe of discourse is the statement of a coherent set of objects, relations and functions that pertain to the study problem. Predicate calculus is often selected for the expression of this knowledge. This language is characterized by sentences expressed as strings of characters, logical operators, quantifiers, functions and relations. Available logical operators include: $\wedge$ (logical and), V (logical or), $\neg$ (logical not) and => (implication). Quantifiers include $\forall$ (the universal quantifier) and $\exists$ (the existential quantifier). Functions include +, -, * and /. Relational operators include >, <, <> and =. Predicate calculus makes it possible to express many forms of knowledge.

Unfortunately, predicate calculus is not available as a programming language. The predicate calculus expression of domain knowledge must therefore be translated into a more common language such as LISP or Prolog. LISP is the acronym of List Processing. This language was invented in the late 1950's by John McCarthy (as reported by Abelson et al., 1987).

It was initially developed for performing symbolic manipulations on mathematical expressions. Today, LISP is the main computer programming language used for artificial intelligence research in the United States. Syntax and semantics of this language are covered in Winston and Horn (1989) and Steele (1984).

Prolog is the acronym of Programming in Logic. This computer language was developed in France in the early 1970's for artificial intelligence and theorem proving purposes (Van Caneghem, 1986). Prolog is based on a subset of the predicate calculus language called Horn clauses. Prolog is hence declarative rather than imperative and is therefore a good medium for expressing and manipulating knowledge. It is also very close syntactically to predicate calculus and therefore permits knowledge formalized into the latter language to be easily programmed into the computer. Principles of the Prolog language are given by Clocksin and Mellish (1984) and its use for expert system development is outlined by Townsend (1987) and Borland (1988).

2.4.2.1. Examples of Expert Systems Used in Agriculture

Heatwole (1987) developed the FARMPLAN expert system to generate land use plans for agricultural soil conservation. This expert system determined whether a given cropping system and cropping practice were acceptable based on USLE predictions and feasibility to the farmer. The expert system was linked to VirGIS, from which it got the site specific information needed for validating the land management plan.

Engel et al. (1988) implemented an expert system that integrated an erosion model. The expert system used a technique known as blackboarding to integrate the knowledge of various experts. The integration with an erosion model gave the system both qualitative and quantitative capabilities.

Clarke and Vyn (1989) described the development of an expert system for conservation tillage. This system was capable of recommending appropriate conservation tillage practices for both soybean and corn production. The system considered zero-till, ridge-till, disc, chisel, and moldboard plowing techniques. The target system would integrate the knowledge from multiple sources of expertise using the blackboard architecture.

Schmoldt and Martin (1986) developed PREDICT (Pinus Resinosa Expert Diagnostic Consultation Tool) to help foresters diagnose pest problems in red pine stands. PREDICT could identify 28 pathogens using more than 400 inference rules. The system could be used in forward chaining to generate a list of potential insects and pathogens. This permitted the prevention of diseases. When used in backward chaining, the system helped to diagnose pest infections and devise curative methods.

Roach et al. (1987) developed POMME (Pest and Orchard Management Expert) using the PROLOG computer language. This expert system incorporated a model of apple diseases and was used to help growers manage their orchards. Using 550 rules, POMME was able to suggest spraying dates and give advices on drought control and the treatment of winter injuries, cedar apple rust, San Jose scale and apple scab. Experts in plant pathology agreed that POMME would reduce the workload of apple growers. In its current version, POMME was, however, too large to be distributed on diskettes.

COMAX is the acronym for COtton MAnagement eXpert and was the first integration of an expert system with a simulation model (GOSSYM) for daily use in farm management (Lemmon, 1986). COMAX used 50 rules to infer an optimum cotton crop management scenario on a day-to-day basis. The management schemes consisted of a) irrigation requirements, which were based on predictions made from weather stations data; b) nitrogen requirements, based on GOSSYM simulations of the growth of cotton; c) harvest date, based on GOSSYM and weather predictions.

CHESS 1 (Citrus Harvest Expert System for Interpreting Simulation Output) is an expert system dedicated to the interpretation of simulations of Florida citrus harvest operations (Khuri et al., 1988). A goal of the research on CHESS 1 was to verify the accuracy of expert systems as compared to human expert advice. Six cases were presented that combined all possibilities for management recommendations on activities scheduling and balancing of machinery utilization. It was found that human experts and the expert system were in agreement. CHESS 1 could therefore be used to advise non-expert citrus harvest managers.

2.5. Summary

Decision Support Systems have not been previously used for aiding the process of soil conservation planning. GIS, Expert Systems and detailed hydrologic models have been used separately by many researchers but attempts have seldom been made to integrate these tools. The integration of these technologies into the framework of a soil conservation DSS should therefore be attempted. The GIS would serve as a data source for the expert system and detailed model. The model would be used to target sources of erosion and assess the effectiveness of soil conservation practices. The expert system would aid planners in selecting soil conservation practices.

3. STUDY REGION

Two small watersheds located in southwestern Quebec were selected for the application of the Decision Support System (Figure 3.1). One basin is located approximately 20 km west of Macdonald College, in St-Dominique, Quebec. The other is located approximately 35 km north-west of the campus, in Très-Saint-Rédempteur, close to Rigaud, Quebec. These watersheds were chosen based on their land use, soil types and topography which are typical of the St-Lawrence lowlands region. Most of the basins in this region are rural and agriculture is their dominant land use. Corn, hay, dairy farms and pastures are very common. Forested areas are present wherever the land is too steep to support agriculture.

The St-Lawrence lowlands are characterized by a generally flat topography scattered by small mountains made of igneous intrusions. Most of the soils consist of relatively young materials deposited over marine sediments from the Champlain Sea. The marine sediments are heavy grey and green clays.

The climate of the area is continental and temperate. The average annual precipitation is 946 mm (Environment Canada, 1987). Rainfall accounts for 75% of the yearly precipitation. Summer thundershowers account for 22% of the rainy days. The one-in-five and one-in-25 year one hour rainfalls are 32 and 56 mm respectively.

3.1. St-Dominique Watershed

The St-Dominique basin is typical of a southwestern Quebec agricultural watershed. This basin has an area of 8.13 km^2 (Figure 3.2). The main watercourse is 5.2 km long and has two small branches. The average surface slope, along the stream, is 0.19%.

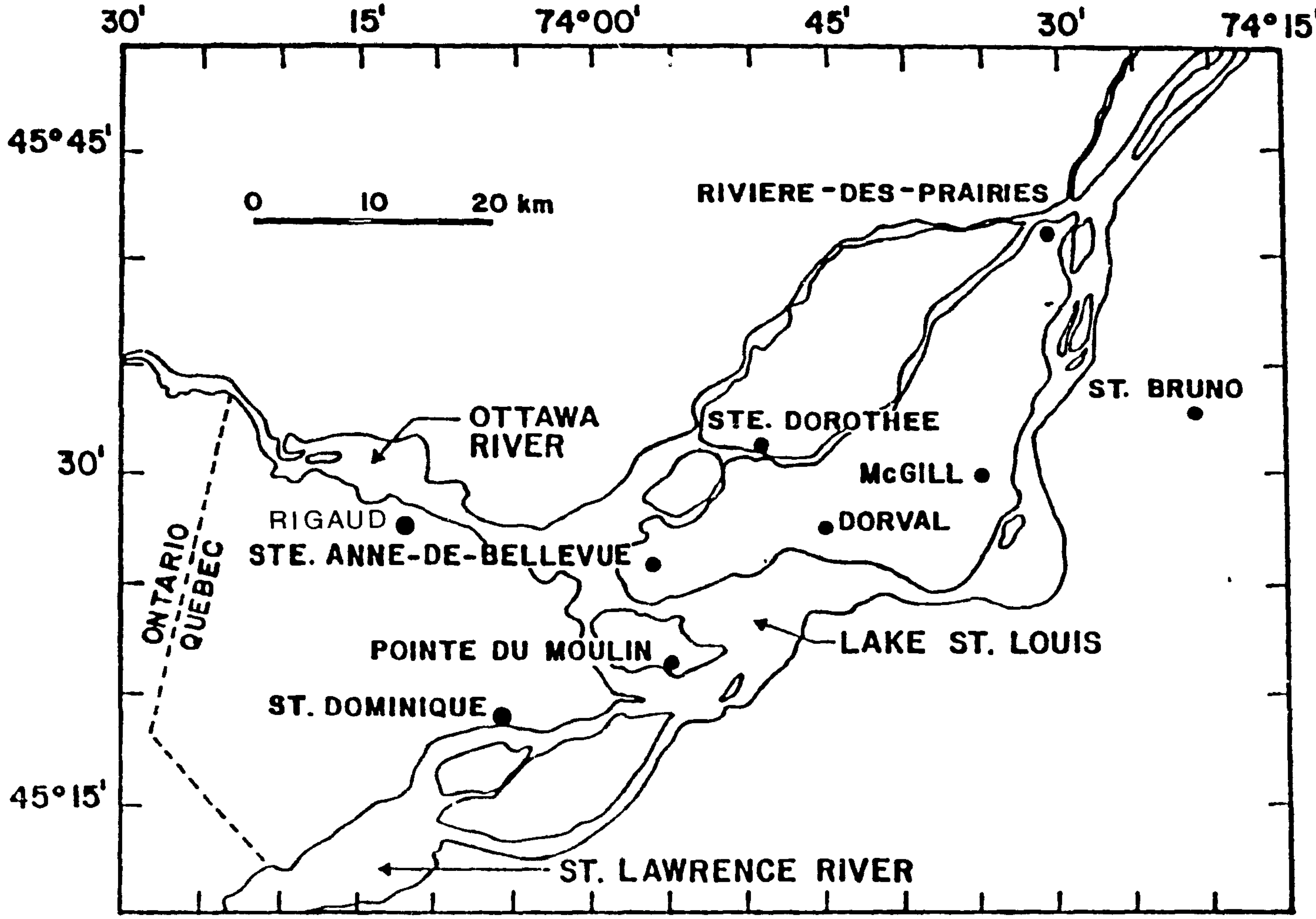


Figure 3.1. Location Map of the Study Watersheds

According to the provincial soils map and to soil surveys, seven soil types are present in this basin. Courval sandy loam is present in the centre of the southern half of the basin, as a strip running from north to south. Below this strip is a small region of Rideau clay. West from the strip is Soulanges very fine sandy loam and east from it is Ste-Rosalie clay. The northern half of the basin is occupied by St-Zotique sandy loam, Vaudreuil loamy fine sand and Muck. The main soil textural class of this basin is sandy loam. This soil is present in a shallow phase over marine clay. The sandy loam phase is typically 30 to 80 cm thick.

The St-Dominique watershed is intensively cultivated. Corn is the predominant land use (21.5% of the area) and is followed by hay and pasture (17.0 and 14.5% respectively). A tree nursery and a sod farm are also present. Less than 17% of the basin area is either in woods or bush. Table 3.1 summarizes the land use and soil types of the St-Dominique watershed.

Table 3.1: Land Use and Soil Types of The St-Dominique Basin

Land Use (1989)	Percentage	Soil Type[1]	Percentage
Corn	21.5	St-Zotique S.L.	33.2
Hay	17.0	Soulanges V.f.S.L.	18.5
Pasture	14.5	Courval S.L.	12.9
Tree Nursery	14.1	Vaudreuil L.f.S.	9.1
Sod Farm	10.0	Ste-Rosalie C.	19.0
Woods	9.8	Rideau C.	3.9
Bush	7.1	Muck O.M.	3.4
Vegetables	3.7		
Small Grains	2.3		

[1] Source: Lajoie and Stobbe, 1951.

About 30% of the St-Dominique watershed is tile drained.

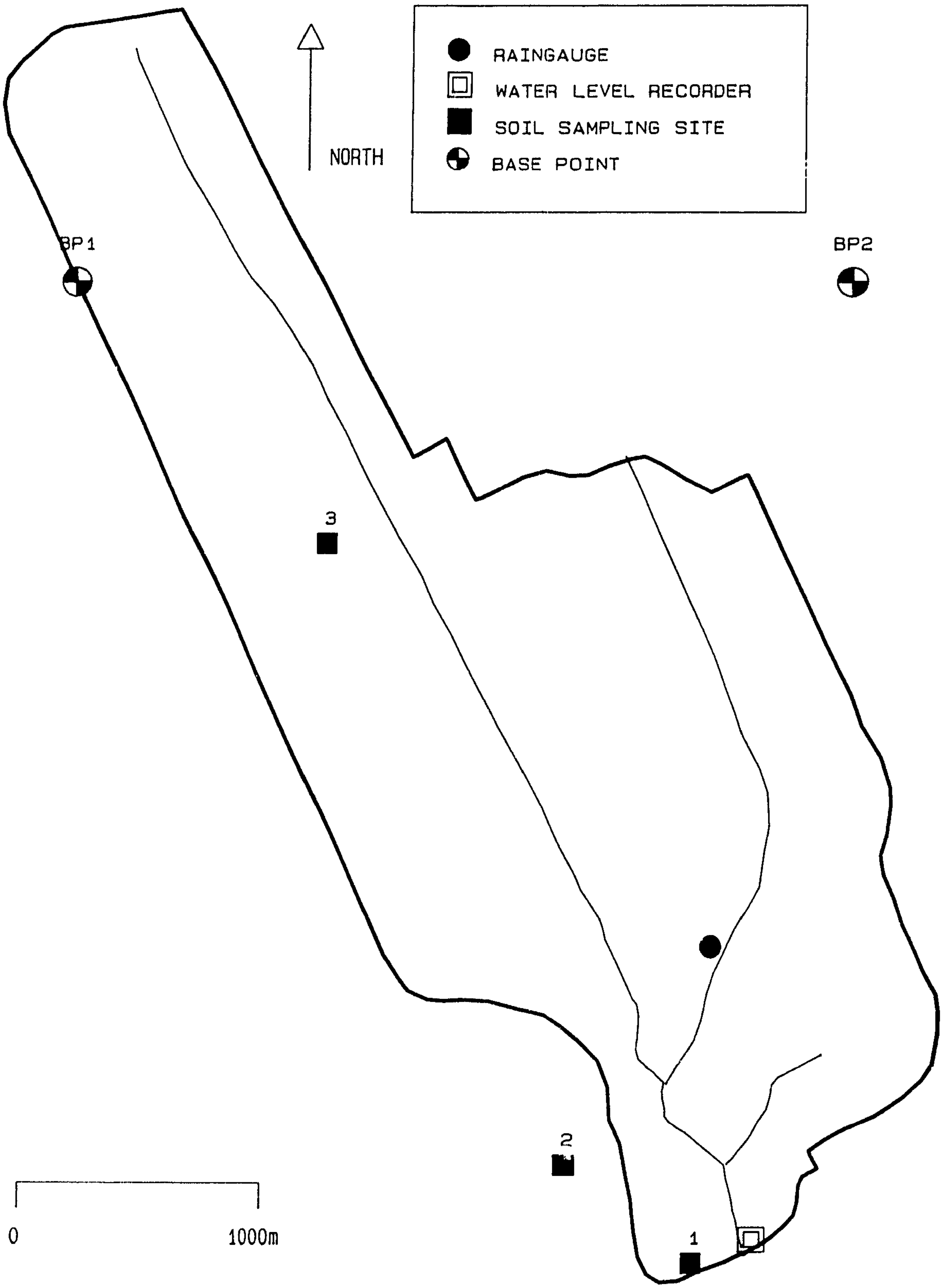


FIGURE 3.2 The St-Dominique Watershed

3.2. Rigaud Watershed

The Rigaud watershed is also a typical rural basin of the Southwest of the Quebec province (Figure 3.3). It extends into Mount Rigaud, a small mountain made of igneous intrusions. The eastern half of this basin is consequently steeper than the rest. The watershed area is 16.6 km^2. The main stream is 12.6 km long and has 12 branches. The average slope taken along the main stream is 1.2%.

According to the provincial soils map, six soil types are present in this basin. The dominant soil type in the eastern portion of the watershed is a Rigaud gravelly sandy loam (33.9%). Perrot stony gravelly loam, Uplands sand and some rough and stony land are also present in smaller quantities. The western section contains Ste-Rosalie clay and Rideau clay. These clays occupy 50.4% of the basin.

Fifty-eight percent of the watershed is farmed. The most common crop is hay (29.4%), followed by corn (19.6%). Woods occupy most of the non-agricultural portion of the watershed. Two small lakes are also found.

Table 3.2: Land Use and Soil Types of the Rigaud Watershed

Land Use (1989)	Percentage	Soil Type[1]	Percentage
Corn	19.6	Perrot s.g.L.	5.2
Grass	1.5	Rideau C.	14.4
Hay	29.4	Rigaud g.S.L.	33.9
Bush	2.5	Rough Stony	8.8
Lake	1.1	Ste-Rosalie C.	35.9
Pasture	6.6	Uplands S.	1.8
Tree Plantation	0.6		
Vegetables	0.5		
Woods	38.2		

[1] Source: Lajoie and Stobbe, 1951.

Approximately 34% of this watershed is tile drained.

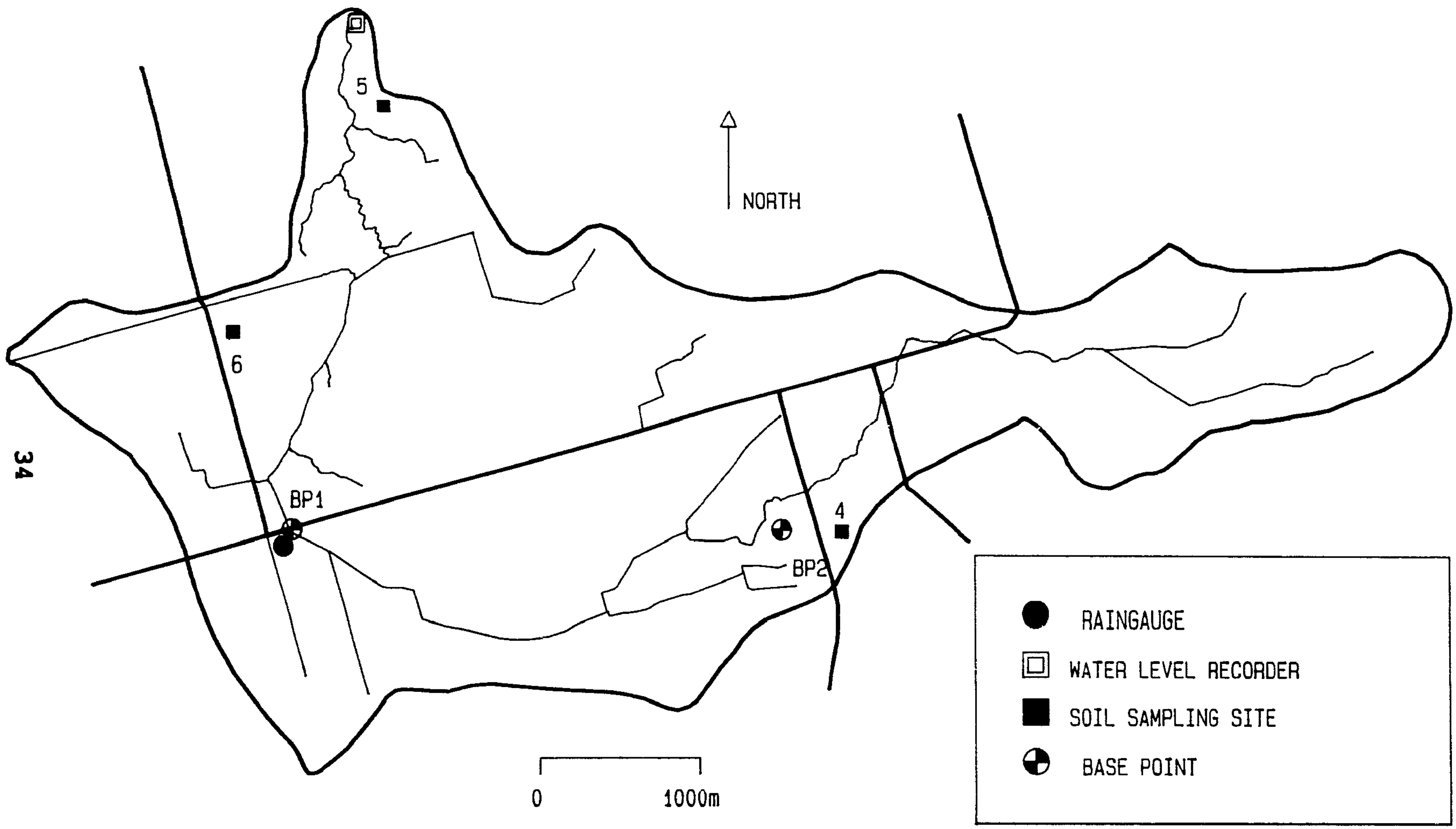


FIGURE 3.3 The Rigaud Watershed

4. HYDROMETEOROLOGICAL DATA AND WATERSHED PROPERTIES

The St-Dominique and Rigaud watersheds were instrumented for hydrologic research in 1985 and 1989 respectively. Sediment sampling at the outlet started in 1989 for both basins. Soil sampling and land use surveys were performed to assess the properties of the basins. A survey of the main channel of the St-Dominique watershed was also performed. The locations of the instruments and soil sampling sites are shown in Figures 3.2 and 3.3.

4.1. Rainfall and Runoff Measurements

Rainfall data were obtained from tipping-bucket rain gauges. A single recording rain gauge was installed in each watershed. These rain gauges were located as close to the watershed centroids as possible.

Channel water levels were recorded continuously at the outlet of each watershed. Stage readings (cm) from the water level recorders were converted to stream discharges (m^3/s) using the following relationships: $Q = 6.0092\ stage^{2276}$ and $Q = 0.000108\ stage^{2214}$ for St-Dominique and Rigaud, respectively. Discharge data were processed on an hourly basis.

The stream-discharge relationships, presented above, were developed throughout the study years by measuring stream velocity at different times during the rising and falling stages of a runoff event. The discharges were calculated as the product of the flow velocity with the cross-sectional area. The stages were also recorded. The rating curves were obtained by a least square regression of the logarithm of the discharge on the logarithm of the stage.

4.1.1. St-Dominique

Twenty runoff events were observed from 1985 to 1989 at the St-Dominique watershed. The total rain, runoff, peak flow and runoff/rainfall ratio of these events are presented in Table 4.1.

Table 4.1: Observed Runoff Events at St-Dominique

DATE (yr-mo-da)	TOTAL RAIN (mm)	RUNOFF (mm)	PEAK FLOW (m^3/s)	RUNOFF/ RAINFALL
85-09-27	52.5	3.93	0.433	0.07
85-10-10	26.8	4.26	0.644	0.16
85-11-13	33.6	17.38	1.333	0.52
86-07-26	50.2	5.44	1.181	0.10
86-08-15	22.6	1.88	0.278	0.08
86-08-27	28.6	4.84	0.626	0.17
86-09-11	64.1	29.28	1.307	0.26
86-09-30	43.4	17.69	2.518	0.41
87-05-23	18.4	3.59	0.590	0.11
87-06-08	51.2	17.71	2.180	0.35
87-07-14	45.0	2.76	0.700	0.06
87-07-18	44.5	3.22	0.719	0.07
87-07-24	35.7	1.64	0.433	0.05
87-10-28	29.9	2.25	0.378	0.07
88-04-28	41.8	14.47	1.281	0.35
88-11-02	44.2	6.40	0.680	0.14
88-11-06	19.4	3.17	0.440	0.16
89-20-10	63.0	3.26	0.150	0.05
89-11-14	52.5	13.43	1.241	0.26
89-11-16	36.2	21.42	3.668	0.59

Source of 1985-1988 data: Enright (1988)

Large runoff depths and high peak flows occur mainly in the fall and early spring. The largest amount of runoff observed is 29.3 mm which occurred on September 11, 1986. This was a complex event which generated two successive stream rises. The peak flow for this event was therefore relatively low. The largest observed peak flow occurred on November 19, 1989. This was a simple event with a single rise in water level. The peak flow for this event was 3.67 m^3/s.

Spring and fall events however have generally low rainfall intensities which are expected to produce very little runoff and a lot of subsurface flow. The observed result is due to many factors including interflow, macropore flow, surface sealing, surface cover and evapotranspiration. Since the dominant soil type of the St-Dominique watershed is a shallow sandy loam over heavy clay, a large amount of the water that infiltrates the soil does not reach the stream through deep subsurface flow but through shallow interflow. This means that rainfall events with low intensity can contribute rapidly to stream discharge through interflow hence producing more runoff than expected.

Macropore flow occurs in cracked clays soils during dry summer months. The surface connected macropores increase the infiltration rate of these soils.

Surface sealing, on the other hand, lowers the steady-state infiltration rate of the soils, thereby producing higher peaks. This effect is reflected in the higher runoff/rainfall ratio of every second and third spring or fall storm. In the fall of 1985, for example, the runoff/rainfall ratio of the first event was 0.07 and rose to 0.16 and 0.52 for the two following events. Surface sealing is more important in the spring and fall when the soil is not protected by any cover.

4.1.2.Rigaud

Four runoff events were observed at Rigaud during 1989. The total rainfall, runoff, peak flow and runoff coefficient of these events are presented in Table 4.2.

Table 4.2: Observed Runoff Events at Rigaud

DATE (yr-mo-da)	TOTAL RAIN (mm)	RUNOFF (mm)	PEAK FLOW (m^3/s)	RUNOFF/ RAINFALL
89-06-10	37.5	2.30	0.469	0.06
89-10-20	60.4	3.76	0.549	0.06
89-11-14	53.7	9.77	1.888	0.18
89-11-16	26.0	21.45	9.963	0.82

The results of the event of November the 16th are a little high. The stage-discharge relationship is known to be valid up to about 1.75 m^3/s. The calculated value of 9.96 m^3/s is way out of this range. Back-water effects from the downstream culvert may control water flow at such high values of stage. This event should therefore not be taken as representative of the behaviour of the Rigaud watershed. Further studies of the hydraulics of high stage flow in this channel should be performed.

4.2. Sediment Yield

Water samples were taken manually at each watershed from May to November, whenever a runoff event occurred and on a weekly basis. Plastic bottles were used to sample the stream at a depth equal to 40% of the current water level. These samples represented instantaneous sediment loadings in the stream.

An automatic water sampler was installed at Rigaud. This instrument was set to start sampling automatically at a preset water level. Once this level was reached, the unit sampled every hour. The sampled volume was approximately of 100 ml for each pumping cycle. The hourly samples were collected in a 4 litre plastic bottle to form an integrated sample. To avoid contamination by previous samples the instrument was programmed to empty the intake line completely at the end of each sampling cycle.

Exactly 100 ml of each water sample was dried in an oven to obtain the gross sediment concentration. The electrical conductivity of the water sample was measured to obtain the salt load in the water. The gross sediment concentration of each sample was then corrected for suspended salts to obtain the net sediment concentration of the runoff water. The correction for salt is expressed as:

$$NSL = GSL - 0.00064 * EC \qquad (1)$$

Where:

NSL is the net sediment loading in g/l
GSL is the gross sediment concentration in g/l
EC is the electrical conductivity of the water sample in mmhos/cm

The sediment yield for the event was calculated from the instantaneous and integrated sediment concentrations. Sediment concentration was assumed to vary linearly between the observed values. If an integrated sample was obtained then the concentration of this sample was used throughout the interval. The following formula was used to calculate the yield:

$$Yield = 3600 * \sum_{i=0}^{n} Q(i) * C(i) \qquad (2)$$

Where:

Yield is the sediment yield in kg
Q(i) is the observed stream discharge at hour i in m^3/s
C(i) is the observed or linearly interpolated sediment concentration at hour i in g/l
n is the duration of the event in hours

The results obtained for St-Dominique and Rigaud are presented in Tables 4.3 and 4.4. The values of sediment yield are only approximate since it is improbable that the actual sediment concentration in the stream rose and fell linearly with time.

The highest observed concentrations are 2.19 and 0.81 g/l respectively for St-Dominique and Rigaud. They both occurred during the event of the 20th of October. This was the first event during the fall of this year and runoff probably carried sediments that had previously been detached by wind, farm machinery and earlier runoff events. The second highest concentrations occurred in the event of the 19th of November. This event also corresponds to the highest observed values of sediment yield and of runoff volume and peak flow. Both watersheds produced above 100 metric tonnes of sediment during this event. This corresponds to 60% of the yearly yield calculated based on the observed events. This shows that a small number of events may contribute disproportionate amounts of sediments and hence that soil conservation should focus on these events, rather than on yearly averages, to alleviate erosion.

It is also noted that on average, the erosion is not very high. A total of 175 t/year corresponds to roughly 200 kg of soil loss per hectare of agricultural land in each watershed. It is however expected that this soil does not come uniformly from the entire watershed but is generated by localized highly erodible sites. The measured data did not permit targeting of these sites.

Table 4.3: Sediment Concentration and Yield at the Outlet of the St-Dominique Watershed for Three Observed Runoff Events

DATE (yr-mo-da)	TIME (ho:mi)	FLOW RATE (m^3/s)	SEDIMENT CONCENTRATION (g/l)	SEDIMENT YIELD (t)
89-10-20	10:00	0.07	0.24	
	15:30	0.17	2.19	
	16:00	0.17	2.19	
89-10-21	16:30	0.10	0.13	21.8
89-11-14	15:45	0.50	0.34	
89-11-15	13:00	1.19	0.13	
	18:45	0.93	0.05	21.6
89-11-16	12:45	1.52	0.83	
	16:45	3.23	0.95	
89-11-17	13:30	0.75	0.11	132.1

Table 4.4: Sediment Concentration and Yield at the Outlet of the Rigaud Watershed for Four Observed Runoff Events

DATE (yr-mo-da)	TIME (ho:mi)	FLOW RATE (m^3/s)	SEDIMENT CONCENTRATION (g/l)	SEDIMENT YIELD (t)
89-06-11	15:00	0.12	0.24	
89-06-13	16:00	0.05	0.27	6.7
89-10-20	8:45	0.05	0.00	
	13:50	0.21	0.42	
	14:20	0.21	0.81	
	16:30	0.40	0.32	
	17:00	0.48	0.32	
89-10-21	17:00	0.20	0.11	
89-10-22	13:30	0.12	0.07	12.1
89-11-15	11:30	1.58	0.23	
	15:30	1.06	0.27	
	15:30-0:00	--	avg:0.20*	35.4
89-11-16	0:00-10:30	--	avg:0.20*	
	10:30	0.33	0.05	
89-11-16,17	10:30-11:30	--	avg:0.31*	
89-11-17	11:30	0.61	0.21	119.0

* Composite sample obtained by automated water sampler

4.3. Soils Properties

The field capacity, porosity, bulk density, saturated hydraulic conductivity, and infiltration rate were measured in the two watersheds. Three sampling sites at St-Dominique (1, 2 and 3) and 3 sites at Rigaud (4, 5 & 6) were used (Figs 3.2 and 3.3). Data for a Courval sandy loam were obtained from another research site at St-Polycarpe which is nearby the two study watersheds. The soil types found at each site are summarized in Table 4.5.

Table 4.5 : Soil Types and Sampling Sites of the Two Watersheds

Soil Type	Textural Class	Sampling Sites
Ste-Rosalie	Clay	6
Rideau	Clay	1 & 5
Soulanges	Very Fine Sand Loam	2
Courval	Sandy Loam	St-Polycarpe
St-Zotique	Sandy Loam	3
Rigaud	Gravelly Sandy Loam	4

A few soil types (ie. Perrot, Rough Stony, Uplands, Vaudreuil and Muck) were not sampled, as they were inaccessible. These soils, however, represent a very small percentage of the study region.

The soil sampling method consisted of taking undisturbed soil cores at an average depth of 5 cm at each site. Twelve small cores (5 cm long x 10 cm dia.) used for the water retention experiment were taken at each site. Three larger cores (10 cm long x 10 cm dia.) were also taken for measuring saturated hydraulic conductivity. Soil sampling activities took place during July of 1989.

4.3.1. Porosity and Field Capacity

The water retention characteristics of the soils were measured using a Haine's apparatus for suctions of approximately 0, 1, 2, 5 and 10 kPa. A pressure plate apparatus was used to obtain water contents at pressures of 0, 10, 20, 50 and 100 kPa. The porosity of the soil was calculated as its volumetric moisture content at saturation. The field capacity was calculated as the volumetric water content at 1/10 of a bar (10 kPa). Table 4.6 summarizes the measured porosities and field capacities for each soil type.

Table 4.6. Porosities and Field Capacities

Soil Type	Sites	Porosity (%)	Field Capacity (%)
Ste-Rosalie C.	6	69.8	47.7
Rideau C.	5	60.0	34.0
Soulanges V.F.S.L.	2	44.5	29.4
Courval S.L.	St-Polycarpe	46.3	24.1
St-Zotique S.L.	3	54.0	34.6
Rigaud G.S.L.	4	70.0	34.2

4.3.2. Saturated Hydraulic Conductivity and Bulk Density

The saturated hydraulic conductivity was measured using the falling head method. Each sample was subjected to three test runs. One set of cores was used for both hydraulic conductivity and bulk density measurements. After the hydraulic conductivity measurements, the soil cores were dried during 24 to 48 hours at 105°C in order to determine bulk density. The measured values are presented in Table 4.7.

Table 4.7 : Saturated Hydraulic Conductivities and Bulk Densities

Soil Type	sites	# of samples	Hydraulic Conductivity (cm/h)	Bulk Density (g/cm^3)
Ste-Rosalie	6	18	0.9224	1.341
Rideau	5	3	0.9823	1.328
Soulanges	2	5	0.2750	1.535
Courval	St-Polycarpe	3	0.5710	1.409
St-Zotique	3	3	0.0063	1.572
Rigaud	4	3	0.1738	1.193

4.3.3. Infiltration Rate

Infiltration tests were performed at sites 4 to 6, and at St-Polycarpe during August 1989, and at sites 1 to 3 during early October of 1989. Thirty-centimetre diameter double-ring infiltrometers were used to measure the cumulative infiltration vs time relationship of each soil. A minimum of three tests was performed at each site. Each test lasted from 20 to 120 minutes depending on the time taken to obtain a steady-state rate and on the availability of water. The parameters of Holtan's equation were fitted to the observed data using a BASIC program. In many cases the final steady state infiltration rate was very high compared to the saturated hydraulic conductivity. This was probably due to macropore flow. Cracking could have been induced when the infiltrometers were inserted, or simply as a result of dry weather. Another reason may be horizontal flow below the base of the infiltrometers (inserted 10 cm into the soil). In many soils, a layer of corn residues which had been plowed under the soil surface was observed. These residues probably raised the horizontal hydraulic conductivity of the soil in that layer causing infiltrated water to flow laterally rather than vertically. Test results which exhibited high steady state infiltration rates were discarded.

Table 4.8 summarizes the test results. The coefficient of determination between the observed cumulative infiltration and the prediction of the Holtan equation is higher than 0.98 for every soil. This indicates that Holtan's equation is a good estimator of the infiltration characteristics of the soils. It must, however, be noted that most parameters have much higher values than those published in the ANSWERS user's manual (Beasley et al., 1981).

Table 4.8. Holtan Infiltration Parameters

Soil Type	FC (mm/h)	*A* (mm/h)	*P*	DF (mm)	r^2
Ste-Rosalie	17.33	10.92	2.25	445	.987
Rideau	123.14	1231.28	2.19	125	.994
Soulanges	16.20	39.29	1.39	509	.990
Courval	13.90	454.85	2.09	165	.980
St-Zotique	75.47	20.55	2.21	84	.999
Rigaud	861.34	381.09	2.35	565	.990

FC is the steady-state infiltration rate
A is the difference between maximum and steady state infiltration rates
P is the exponent of the infiltration equation
DF is the depth of the control zone
r^2 is the coefficient of determination

4.3.4. Soil Erodibility

Soil erodibilities were estimated for all the soil types using the equation presented by Wischmeier and Smith (1978). This empirical equation relates the erodibility to the texture (clay, silt, very fine sand and organic matter fractions), permeability (b) and structure (c) of the soil:

$$K = 2.7\ M^{1.14}\ 10^{6}\ (12\text{-om}) + 0.042\ (b-2) + 0.033\ (c-3) \quad \text{(3a)}$$

Where:

$$M = (\text{silt} + \text{vfsand}) * (100 - \text{clay}) \quad \text{(3b)}$$

and:

K is the erodibility of the soil in t/ha h/mm ha/Mj

om	is the organic matter content (%)
silt	is the silt content (%)
vfsand	is the percentage of very fine sand present
clay	is the percentage of clay in the soil
b	is an indicator of soil structure (1=fine granular to 4=blocky)
c	is an indicator of soil permeability (1=rapid to 6=very slow)

Soil textures and structures used in this equation were obtained from Lajoie and Stobbe (1951). Permeabilities were taken from the saturated hydraulic conductivity test results (Table 4.7).

Table 4.9. Calculated Soil Erodibilities

Soil Type	Very Fine Sand (%)	Silt (%)	Clay (%)	O.M. (%)	Structure	Permeability	USLE K (t*h/mm/MJ)
Ste-Rosalie	20	47	33	8.7	granular	moderately fast	.12
Rideau	23	38	39	7.6	fine granular	moderately fast	.10
Soulanges	28	32	10	3.9	fine granular	moderate	.38
Courval	29	18	9	4.2	crumbs	moderately slow	.31
St-Zotique	30	31	10	10.2	crumbs	very slow	.22
Rigaud	52	42	6	8.3	fine granular	slow	.35

4.4. Crops

Most parameters representing the properties of the crops found in the two study watersheds were gathered from the literature. Percentage of cover was assumed to vary during the year. A value of 100% was chosen from June 15 to September 15, and lower for the rest of the year: 0% for row crops, 10% for hay and pasture, 20% for trees in nursery and 50% for natural woods and bush. The parameters are summarized in Table 4.10.

Table 4.10. Crop Parameters

Crop	PIT (mm)	PER Spring (%)	PER Summer (%)	RC	HU (mm)	n	CP
Corn	0.80	0	100	0.33	70.0	0.090	0.27
Grass	0.75	100	100	0.40	38.1	0.450	0.02
Hay	1.80	10	100	0.43	45.0	0.240	0.01
Bush	1.80	50	100	0.40	38.1	0.250	0.00
Lake	0.10	0	0	0.01	0.1	0.081	0.00
Pasture	0.40	10	100	0.43	45.0	0.130	0.04
Sod Farm	0.75	0	100	0.43	45.0	0.450	0.01
Small Grain	0.65	0	100	0.33	70.0	0.060	0.27
Tree Nursery	1.80	20	100	0.43	45.0	0.023	0.66
Vegetables	1.00	0	100	0.42	30.0	0.080	0.50
Woods	1.80	50	100	0.43	45.0	0.240	0.00

PIT is potential interception of the plant
PER is percent coverage of the soil by the crop
RC is runoff retention roughness coefficient due to tillage
HU is roughness height used in calculating water retention
n is Manning's roughness coefficient of surface flow
CP is the product of USLE C and P factors for fall conditions

Sources: Beasley et al.(1981), Engman (1986), Wischmeier and Smith (1978)

4.5.Channel Data

The most important channel properties are slope, width and roughness. The slope of the main channel of the St-Dominique watershed was surveyed by Enright (1988). This channel has a slope of 0.24% from the outlet to a point 2 km upstream. The slope then becomes 0.044% for 3 km, and up to 0.97% for the last 700 m of the channel. Such a survey could not be performed in the larger Rigaud basin due to time and weather constraints.

The bottom width of the streams of both watersheds varies along their length. A bottom width of 3 m was judged to be a good average for both watersheds.

The Manning's roughness coefficient also varied along the length of the streams and with channel stage. A value of 0.048 was adopted in this study. This value corresponds to a natural stream with some pools and shoals, clean, low stages and some ineffective slopes and sections (Schwab et al., 1981).

5. MATERIALS AND METHODS

The objective of this study was the development and application of a soil conservation DSS. The target DSS consisted of a GIS, the ANSWERS model and an expert system. The development of the DSS consisted of three steps: i) Set up the Geographical Information System; ii) validate the ANSWERS hydrologic model for the study region; iii) develop a soil conservation expert system. The application of the DSS consisted of the generation of maps of the appropriate soil conservation practices for two small rural watersheds in western Quebec.

5.1. Geographical Information System Setup

5.1.1. Description of the Geographical Information System

A watershed based spatial database developed by the author in 1988, was used to store digital representations of the watersheds. This GIS is raster based and stores six layers of data: streams, land use, soil types, elevation, slope and aspect. The data are stored internally as a two-dimensional array of strings and externally in ASCII files. The internal array is 100 cells large in the east-west direction and 71 cells long in the north-south axis which means that watersheds of up to 71 km^2 can be managed. A practical limit of 20 km^2 is however advised for efficiency reasons.

The original software written in QuickBASIC v4.5 (Microsoft, 1988) was updated during this study. The final version was stored at the Hydrology and Water Management Laboratory of Macdonald College managed by P.E. Enright and Dr C.A. Madramootoo. This version consisted of a core module, 10 utility programs and 2 interface programs. The core module managed data entry from a 60 x 90 cm digitizer and output to a pen plotter of equal size. This module performed rasterization of the vector and point data obtained from the digitizer. It also permitted the creation of overlays and colour output maps. In addition to the individual layer information, the system required two base points (see Figures 3.2 and 3.3). These points are spatial references that allow maps of different scales to be used, independent of their orientation on the digitizer. Base points are further used by the core module to align the raster grid. It is important that the line joining the two base points be parallel to the universal transverse mercator if the digitized data are to be georeferenced. Georeferencing is, however, of lesser importance when watersheds are studied independently of their regional context.

The utility programs include programs to acquire topographic information, edit watershed data on an individual cell basis and perform statistical analyses. Topographic data are acquired and processed into a Digital Elevation Model (DEM), outside of the core module because of the numerous manipulations required. Five separate programs are used to manage this data. The first program is used to acquire contour lines, spot elevations and other topographic data from the digitizer. A rectangular region larger than the watershed is entered to provide accurate interpolations at the basin boundaries. The second program performs interpolation of the elevation data along ridge lines (eg. watershed boundary and streams). A second interpolation program is then used to interpolate elevations for each one hectare cell in the watershed and surrounding area. This interpolation is performed using inverse distance cubed weighting which is generally judged adequate for natural terrain data. The fourth program calculates the slope of each cell within the rectangular region using planes of best fit. This program then stores this data in a format accessible by the core module.

The last program is used to manually edit the aspect of the slopes of watershed cells.

Keyboard edition programs are used to manually edit land use, soil types and streams of a watershed. Soil and land use editing is necessary for some fields which are not wider than 100 m. The cells representing such fields tend to be disconnected especially when the field is at an angle with respect to the watershed grid. Stream editing is also used to ensure continuity of the channels. This feature is very important in hydrologic modeling.

The statistics programs calculate the percentages of various land uses, soil types and slopes in the basins and the combination of these parameters. These programs are useful in assessing the importance of such land use or soil type in a given study basin. Furthermore, the combination statistics are useful in assessing the heterogeneity of the watersheds.

The interface programs are used to transfer watershed data to ANSWERS and the expert system. The first program generates an ANSWERS elemental datafile from data stored in the GIS. The second program generates four Prolog databases that represent the x-y locations, topography, land uses and soil types of watershed cells.

5.1.2. Setup and Verification Procedures

Base points, basin outlines, streams, land use, soil types and topography of the St-Dominique and Rigaud basins were entered in the GIS. Base points were selected for each watershed (Table 5.1). These points were chosen because they were identifiable on every map of the watersheds. The selected base points further ensured that the raster grid would be aligned with the mercator grid.

Table 5.1. Selected Base Points for the Two Watersheds

Watershed Name	Point	Description
St-Dominique	BP1	Intersection of CP rail line with western boundary of the watershed
	BP2	Intersection of chemin Chenier with railway East of BP1
Rigaud	BP1	Intersection of principal road of St Telesphore with Ruisseau Blanc
	BP2	860 metres South of intersection between principal road and montee du Bois Franc.

The stream networks and basin outline of each watershed were identified on topographic maps of the regions: 1:25,000 for St-Dominique and 1:20,000 for Rigaud. They were then digitized and stored in the database.

The land uses were determined from field surveys. Identified land uses were then transferred on base maps of the watersheds and digitized.

The soil types were digitized from a 1:63,360 map of the Vaudreuil and Soulanges counties (Lajoie and Stobbe, 1951).

The topography layers were developed from the topographic maps used to determine basin outlines. Contour lines and spot elevations were obtained from these maps. Channel profiles and cross-sections were obtained from Enright (1988) for St-Dominique and from the local MAPAQ office for Rigaud. Surface elevation close to the streams were derived from the channel cross-sections. All of these data were digitized into ASCII elevation files with an X,Y,Z format. Data as far as 1 km outside of the watersheds were also included to increase the reliability of the interpolation at the edges of the basins.

The GIS was used to generate raster maps of the land use, soil types, elevation and slope of each watershed. A cross-section of the DEM of St-Dominique was also performed to verify the correctness of the interpolation scheme. Association tables representing the relative importance of different combinations of crop type, soil and slope were produced to assess the heterogeneity of the watersheds.

5.2. ANSWERS Validation

5.2.1. Description of ANSWERS

ANSWERS is a physically based distributed parameter watershed model that simulates runoff and sediment transport. Parameters representing the properties of crops and soil types are distributed within rectangular grid cells. A grid size of 1 to 4 hectares is generally chosen. The model is applicable to watersheds of up to 100 km^2, but the microcomputer version can handle only 1700 cells. The practical limit is therefore 17 km^2, if 1 ha cells are used.

ANSWERS simulates runoff, overland flow routing, and channel flow as well as sediment detachment and transport. Interception, retention and infiltration are taken into consideration. Infiltration is calculated from a modified form of Holtan's equation:

$$FMAX = FC + A * (PIV / TP)^{P} \quad \ldots\ldots\ldots\ldots (4)$$

Where:

FMAX is the infiltration capacity of the surface
FC is the steady-state infiltration rate of the soil
A is the difference between the maximum and the steady-state infiltration rate of the soil
PIV is the volume of water needed to fill the control volume to saturation
TP is the total volume of pore space within the control volume
P is the infiltration exponent.

This equation is based on the concept of a control volume of soil situated at the surface of the profile. The thickness of this layer is the control zone depth, DF. Water infiltrates into this volume and drains out of it.

Surface flow is routed from cell to cell using the continuity equation together with Manning's flow equation. The portion of flow going from a given cell into each of the adjacent downstream cells is computed based on the direction of the cell slope. Channel flow is calculated using Manning's equation with the assumption of a rectangular channel cross-section.

ANSWERS simulates subsurface drain flow using a design drainage coefficient for the region (10 mm/day in western Quebec). Other forms of subsurface flow are lumped into a groundwater release fraction (GWR) parameter. At each simulation time step a volume equal to the product of GWR by the volume of water stored in the soil is released into the stream.

Sediment detachment by rainfall and surface flow are calculated using adaptations of the equations presented by Meyer and Wischmeier (1969). The rate of detachment by rainfall is given by:

$$DETR = 0.108\ C\ P\ K\ A\ R^2 \quad [kg/min] \quad \ldots\ldots \quad (5)$$

and the rate of detachment by overland flow is given by:

$$DETF = 0.90\ C\ P\ K\ A\ S\ Q \quad [kg/min] \quad \ldots\ldots \quad (6)$$

Where:

C,P & K are the USLE Crop, Practice and Soil erodibility factors

A	is the area over which flow or rainfall occurs in m^2
R	is the rainfall intensity in mm/min
S	is the overland slope in m/m
Q	is the overland flow rate per unit width in m^2/min

Potential transport of sediments by overland flow, TF (kg/min-m) is calculated using an equation based partly on Yalin's (1963) work:

$$TF = 161\, S\, Q^{0.5} \quad \text{if } Q < 0.046\ m^2/min \quad \ldots.(7)$$

and

$$TF = 16{,}230\, S\, Q^2 \quad \text{if } Q > 0.046\ m^2/min \quad \ldots.(8)$$

ANSWERS further assumes that deposited sediments must be re-detached in order to be available for surface flow, and that channels and subsurface drains are not erodible.

ANSWERS solves the flow and sediment transport equations using an explicit backward-difference technique. The time step used in the integration is one minute.

The output from ANSWERS consists of a runoff hydrograph at the watershed outlet, a graph of sediment concentration versus time at the stream outlet and a detailed map of erosion and deposition throughout the watershed.

5.2.2.Validation Procedures

ANSWERS was validated for the St-Dominique and Rigaud watersheds, after performing a sensitivity analysis. This analysis was used to assess the relative importance of most input parameters on runoff and sediment concentration predictions. The rainfall event of September 30th 1986 and data representing the St-Dominique watershed were used for the sensitivity analysis. Twenty parameters were varied by 25%

and 50%. The effects of the most influential parameters on runoff and sediment were tabulated and plotted.

The soil, crop and channel parameters presented in Chapter 4 were used as input to the model. A design drainage coefficient of 10 mm/day and a GWR of 0.004 were assumed. Antecedent soil moisture of nearly 20% was measured during the summer months. A value of 40% was assumed in spring and fall. Elemental cell descriptions were obtained from the GIS.

Twenty runoff events that occurred between 1985 and 1989 in the St-Dominique watershed and 4 events that occurred in 1989 in the Rigaud watershed were used to validate the hydrolog portion of the model. The sediment transport component was validated using sediment concentration data from 1989. There were 3 events from St-Dominique and 4 events from Rigaud with measured sediment data.

ANSWERS was validated by comparing predicted and observed hydrologic parameters and hydrographs. These parameters were: peak flow, time to peak, runoff volume, sediment concentration and sediment yield.

Predicted and observed runoff hydrographs were compared using the coefficient of performance CP'_A (James and Burgess, 1982):

$$CP'_A = \sum_{i=1}^{n} (S(i) - O(i))^2 \Big/ \sum_{i=1}^{n} (O(i) - O_{avg})^2 \quad . . . . . (9)$$

Where:

- $O(i)$ is the i^{th} observed runoff value
- O_{avg} is the mean of the observed runoff values
- $S(i)$ is the i^{th} simulated runoff value
- n is the duration of the event in hours

This coefficient approaches zero as the observed and predicted hydrographs get closer. CP'_A was also used to compare the predicted and observed peak flows, times to peak and runoff volumes.

5.3. Expert System Development

The problem of soil conservation practice selection was conceptualized by defining an applicable universe of discourse. This step consisted of the statement of a coherent set of objects, relations and functions that pertain to soil conservation planning in the study region. The objects considered by the soil conservation expert system were selected to match those stored by the GIS and used by the ANSWERS model. These objects were: watershed cells, land uses, soil types, slopes and land management practices.

Each cell object consisted of an x,y location and a cell ID number. All cell objects were expected to have the same dimension of 1 ha.

Land use objects were either corn, small grain, hay, pasture, vegetable, nursery, wood or grass. The rowcrop unary relation was used to classify the land use objects. This relation was true for corn, small grain and vegetables but false for the other land uses. The croptype binary relation was used to associate each cell ID with a land use.

Soil Type objects were Ro, R, S, Cv, Za, Rg, Pg, U, V and RS (codes refer to Table 3.4). Three unary relations were defined on these objects. The cohesive relation identified cohesive soils and was true for R and Ro. The impervious relation identified soils with low steady-state infiltration rates and was true for Ro, S and Cv. The third relation was sand_over_clay and was true for Cv, S, V, and Za. The soiltype binary relation was used to associate each cell ID with a soil code.

The slope objects were the numbers representing the percentage of slope and the aspect of the terrain. A 3-ary relation called slope associated cell IDs with their slope and aspect. A binary relation called topography classified slopes into steep slope (> 5%), moderate slope (between 1 and 5%) and level_land (< 1%). Topography was also used to identify depressional cells which might represent gullies. Topography further associated the slope classification to each cell ID.

Land management objects were crop rotation, strip cropping, planned grazing, conservation tillage, deep tillage, contour farming, filter strip, grassed waterway and terrace. The binary relation advised-practice was established by the expert system when inferring appropriate soil conservation practices for watershed cells. This relation associated a cell ID with an appropriate conservation practice.

A unary relation called streamcell was used to identify cells through which a stream passed. This permitted the identification of field parcels which were adjacent to a stream.

These objects and relations were judged sufficient for expressing a reasonable amount of soil conservation knowledge. More land management practices could be considered and a finer definition of soil textural classes could be used. A finer classification of topographical elements would also improve our conceptualization. Spatial relations such as near, far or upslope could as well be defined. These improvements could be implemented in later versions.

The interpretation of the selected objects and relations is generally obvious. The precise definition of each term was chosen to comply with the SCS standards presented in the National Handbook of Conservation Practices (USDA, 1985).

Using predicate calculus, each watershed cell was represented by an object as defined above:

Watershed_cell(x, y, ID)

The actual cell definitions came from the GIS database. An instance of a cell could for example be:

Watershed_cell(3, 25, 62)

The land use, soil type, topography and advised land management of this cell could similarly be:

croptype(62, corn)
soiltype(62, cv)
topography(62, moderate_slope)
advised-practice(62, planned grazing)

The soil conservation knowledge was expressed in the form of logical sentences. The sentences were used to advise on what cropping system, practice or conservation structure should be used to reduce erosion. The rules considered the land use, soil type, topography and current practice objects as previously defined. Each rule was based on the premise that the considered cell had an erosion problem. Eleven soil conservation practice selection rules were defined. These rules are presented below. The knowledge used to form these rules is summarized in Table 5.2. Plus signs are used to represent conditions that must be present and minus signs

TABLE 5 . 2: Selection Criteria for Soil Conservation Practices

PRACTICE \ FACTORS	ROWCROP	PASTURE	IMPERVIOUS SOIL	COHESIVE SOIL	SAND OVER CLAY	LEVEL LAND	FAIR SLOPE	STEEP SLOPE	DEPRESSION	ADJACENT TO STREAM
CONSERVATION TILLAGE	⊕					⊕				
DEEP OR					⊕	⊕				
TILLAGE			⊕			⊕				
CONTOUR FARMING	⊕			⊕			⊕			
CROP ROTATION	⊕			⊖		⊕				
PLANNED OR				⊖				⊕		
GRAZING		⊕								
STRIP CROPPING	⊕			⊖			⊕			
FILTER STRIP						⊕				⊕
GRASSED WATERWAY									⊕	
TERRACE				⊕				⊕		

conditions that must be absent. All the conditions on any given row must be satisfied for a practice to be applicable.

(1) Where row crops are grown on level land and low cover conditions are predominant, the erosion problem may be due to raindrop impact. Conservation tillage should be practiced to leave residues on the surface and hence protect the soil:

$$\forall\ x,y,ID,Crop$$
$$\begin{aligned} & watershed\_cell(x,y,ID) \\ \wedge\ & croptype\ (ID,\ Crop) \\ \wedge\ & rowcrop(Crop) \\ \wedge\ & topography\ (ID,\ level\ land) \end{aligned}$$
$$\Rightarrow advised\text{-}practice(ID,\ conservation\ tillage)$$

(2) If excessive erosion occurs on level land the problem may be a low infiltration capacity. If the soil consists of a layer of sand over a layer of clay then deep tillage should be practiced to increase infiltration:

$$\forall\ x,y,ID,Soil$$
$$\begin{aligned} & watershed\_cell(x,y,ID) \\ \wedge\ & topography\ (ID,\ level\ land) \\ \wedge\ & soiltype\ (ID,\ Soil) \\ \wedge\ & sand\_over\_clay(Soil) \end{aligned}$$
$$\Rightarrow advised\text{-}practice(ID,\ deep\ tillage)$$

(3) Where the soil is impervious it is generally necessary to increases its infiltration capacity. If the field surface is level then deep tillage should be practiced:

$$\forall\ x,y,ID,Soil$$
$$\begin{aligned} & watershed\_cell(x,y,ID) \\ \wedge\ & soiltype(ID,\ Soil) \\ \wedge\ & impervious(Soil) \\ \wedge\ & topography\ (ID,\ level\ land) \end{aligned}$$
$$\Rightarrow advised\text{-}practice(ID,\ deep\ tillage)$$

(4) An erosion problem on a fair slope is due to runoff velocity. For row crops grown on cohesive soils, the problem may be cured by tilling on the contour:

$\forall$ x,y,ID,Crop,Soil

watershed_cell(x,y,ID)
$\wedge$ topography(ID, fair slope)
$\wedge$ croptype(ID, Crop)
$\wedge$ rowcrop(Crop)
$\wedge$ soiltype(ID,Soil)
$\wedge$ cohesive(Soil)
=> advised-practice(ID, contour farming)

(5) Where row crops are grown on level land, erosion may be due to poor soil conditions due to intense cultivation. This is especially true for non-cohesive soils. A rotation should be practiced in such cases:

$\forall$ x,y,ID,Crop,Soil

watershed_cell(x,y,ID)
$\wedge$ topography(ID, level land)
$\wedge$ croptype(ID, Crop)
$\wedge$ rowcrop(Crop)
$\wedge$ soiltype (ID, Soil)
$\wedge \neg$ cohesive(Soil)
=> advised-practice(ID, deep tillage)

(6) Non-cohesive soils on steep slopes should not be cultivated but lightly grazed:

$\forall$ x,y,ID,Soil

watershed_cell(x,y,ID)
$\wedge$ soil type(ID, Soil)
$\wedge \neg$ cohesive(Soil)
$\wedge$ topography (ID, steep slope)
=> advised practice(ID, planned grazing)

(7) Excessive erosion in a pasture is often the result of overgrazing. A rotation grazing system should be implemented in this case:

$\forall$ x,y,ID,Crop
watershed_cell(x,y,ID)
$\wedge$ croptype(ID, Crop)
$\wedge$ Crop = PASTURE
=> advised practice(ID, planned grazing)

(8) Runoff velocity on fair slopes can generally be controlled by contour farming. In the case where the soil is not cohesive, however, strip cropping should be practiced:

$\forall$ x,y,ID,Crop,Soil
watershed_cell(x,y,ID)
$\wedge$ topography (ID, fair slope)
$\wedge$ croptype(ID, Crop)
$\wedge$ rowcrop(Crop)
$\wedge$ soiltype (ID, Soil)
$\wedge \neg$ cohesive (Soil)
=> advised practice(ID, strip cropping)

(9) Where erosion takes place in the vicinity of a stream, and the land is relatively level, vegetative filter strips can be used to filtrate runoff and deposit sediments:

$\forall$ x,y,ID, watershed_cell(x,y,ID)
$\wedge$ streamcell(ID)
$\wedge$ topography(ID, level land)
=> advised practice(ID, filter strip)

(10) Gullying occurs where concentrated flow conditions exist. A grassed waterway should be implemented in such locations:

$\forall$ x,y,ID, watershed_cell(x,y,ID)
$\wedge$ topography(ID, depression)
=> advised practice(ID, grassed waterway)

(11) Terraces are used to solve the problem of erosion on steep slopes and cohesive soils:

$\forall$ x,y,ID,Soil

watershed_cell(x,y,ID)

$\wedge$ topography(ID, steep slope)

$\wedge$ soiltype(ID, Soil)

$\wedge$ cohesive(Soil)

=> advised practice(ID, terrace)

The soil conservation expert system was implemented using the Turbo Prolog version 2.0 compiler (Borland, 1988). This programming language was chosen over a shell or another language for three reasons: i) the inference mechanism (backward-chaining) is integral to the language which saves programming efforts; ii) external databases are managed by the language; iii) graphics are fully supported.

5.4. Application of the Decision Support System

The decision support system was applied to the generation of soil conservation plans for the two watersheds of the study region. Erosion was assessed for a design storm in each basin using the ANSWERS model and the data stored in the GIS. The expert system was then used to select soil conservation practices for all cells that had more than 1000 kg/ha of erosion for that storm. The selected soil conservation practices were validated by using ANSWERS to simulate erosion with conservation practices in place.

The storm of July 19, 1989 which occurred in Harrow, Ontario was selected to target erosion sources within the basins. This event was selected because an event recorded with the same precision and return period was not available for southwestern Quebec. The maximum one-hour intensity was 43 mm/h which has a ten year recurrence interval in the Montreal region. The total accumulation was 247 mm over 27 hours which exceeds the 1 in 25 year storm in Montreal. The hyetograph for this event is shown in the Appendix.

The same data used for the validation of ANSWERS were used to target erosion sources in the two basins. No seasonal adjustment was necessary since most physical properties of the watersheds had been measured during either July or August.

The soil loss of each cell was transferred from the ANSWERS output file to a PROLOG database. The expert system read erosion values for each cell and formulated appropriate conservation practices when 1000 kg/ha were exceeded. The conservation practices were selected based on the rules derived in the previous section. The expert system then wrote the advised soil conservation practices to an output file.

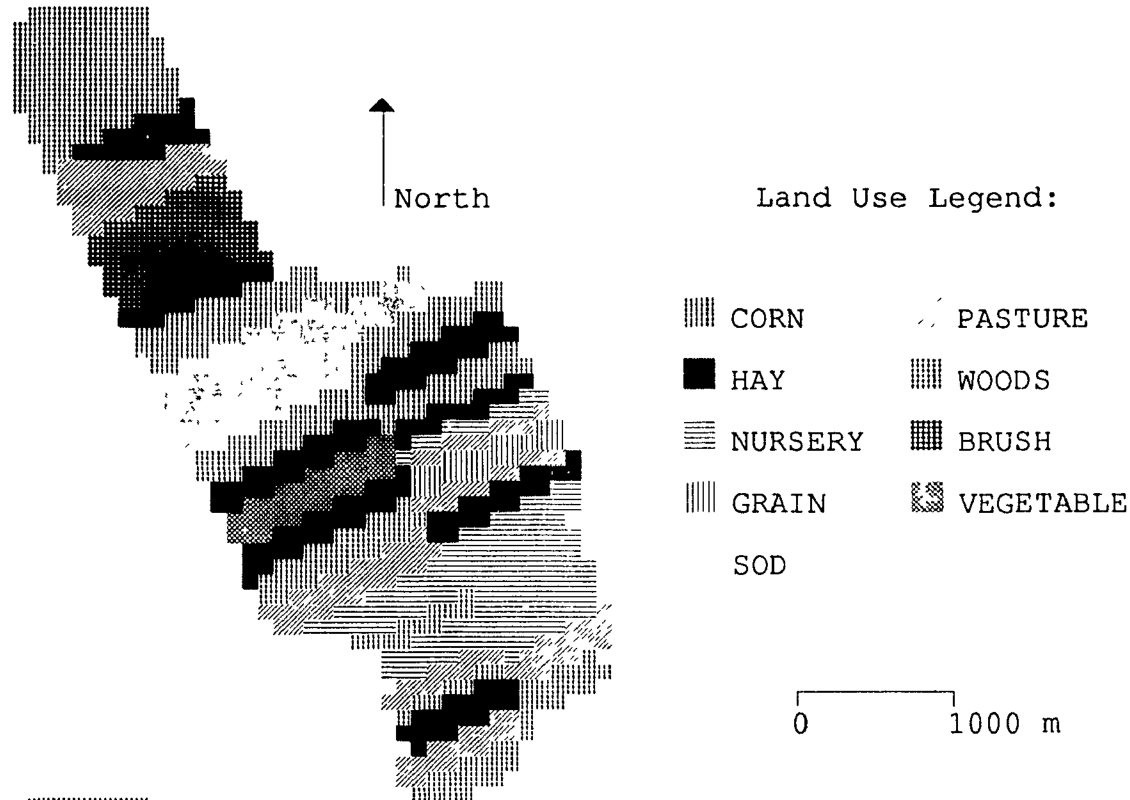
The effect of the conservation practices on soil loss was then simulated with ANSWERS. The practices were modeled according to their effects on crops, soil properties, soil cover and topography. New soil type and land use codes were assigned to the cells in which conservation practices were applied. The simulation results were then compared with the previous results to assess the effectiveness of the selected soil conservation practices.

6. RESULTS AND DISCUSSION

6.1. Geographical Information System Setup

The streams, soils, land use and topography of the St-Dominique and Rigaud watersheds were entered in the GIS. The St-Dominique watershed and adjoining area were digitized into 868 cells of one hectare. The total area of the GIS representation is therefore 6.8% larger than the original basin which has an area of 8.13 km^2. The Rigaud watershed is represented as 1618 cells. The difference in area is in this case of 2.5%. These differences are due to the raster mode used for encoding the watershed. The error in total area generally decreases as the cell size is reduced relative to the basin size. A cell size of one hectare was used in this study based on the results of VirGIS experiments. Smaller cells could have been used but would have resulted in larger data files. Reducing the width of a cell by a factor of two quadruples the storage. Land use surveys further indicated that most agricultural fields are wider than 100 metres.

The GIS representations of the land use and soil types of the St-Dominique watershed are shown in Figure 6.1. The land use map shows the predominance of agriculture within the basin. A tree nursery and a sod farm are also present. A few fields are 100 metres wide and are represented as rows one cell wide. Most fields are however wider than 100 metres. The soils map shows the spatial variability of soil types in the watershed. Clay soils occupy the eastern portion of the basin. Vaudreuil loamy sand is present in the northern portion of the basin. Well decomposed organic matter (muck) is present in a



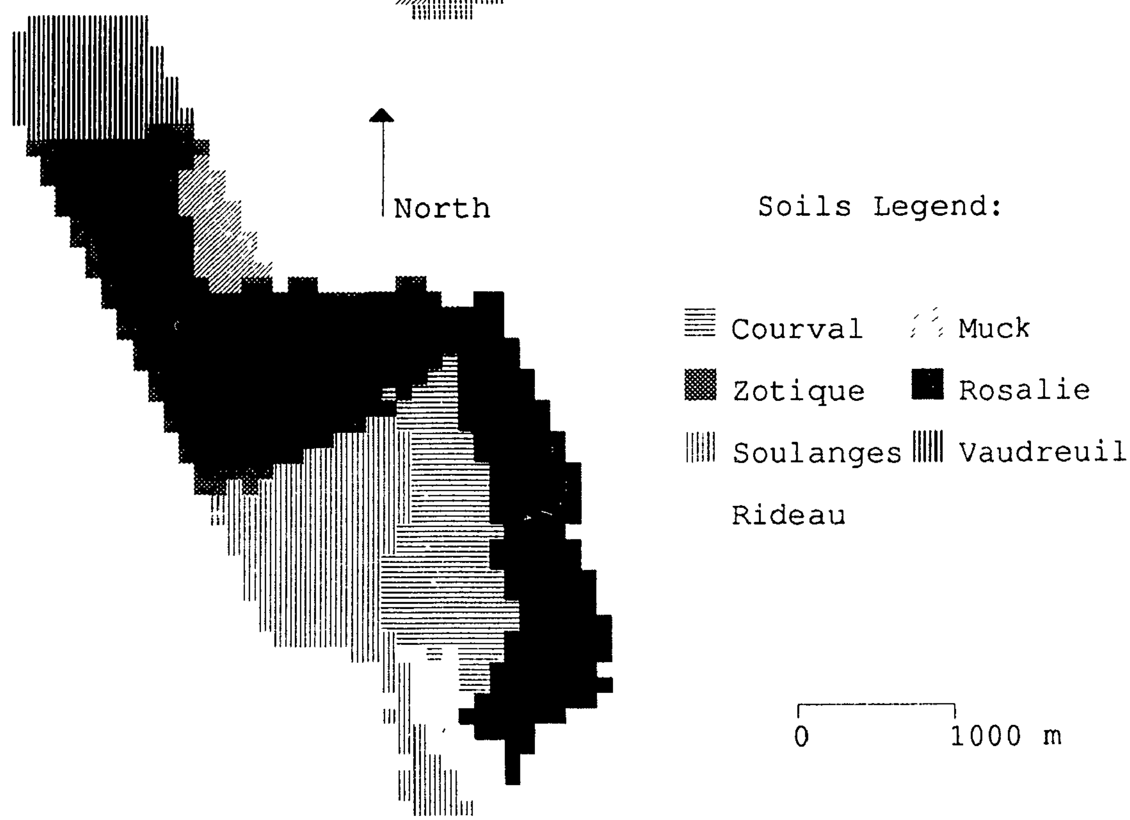
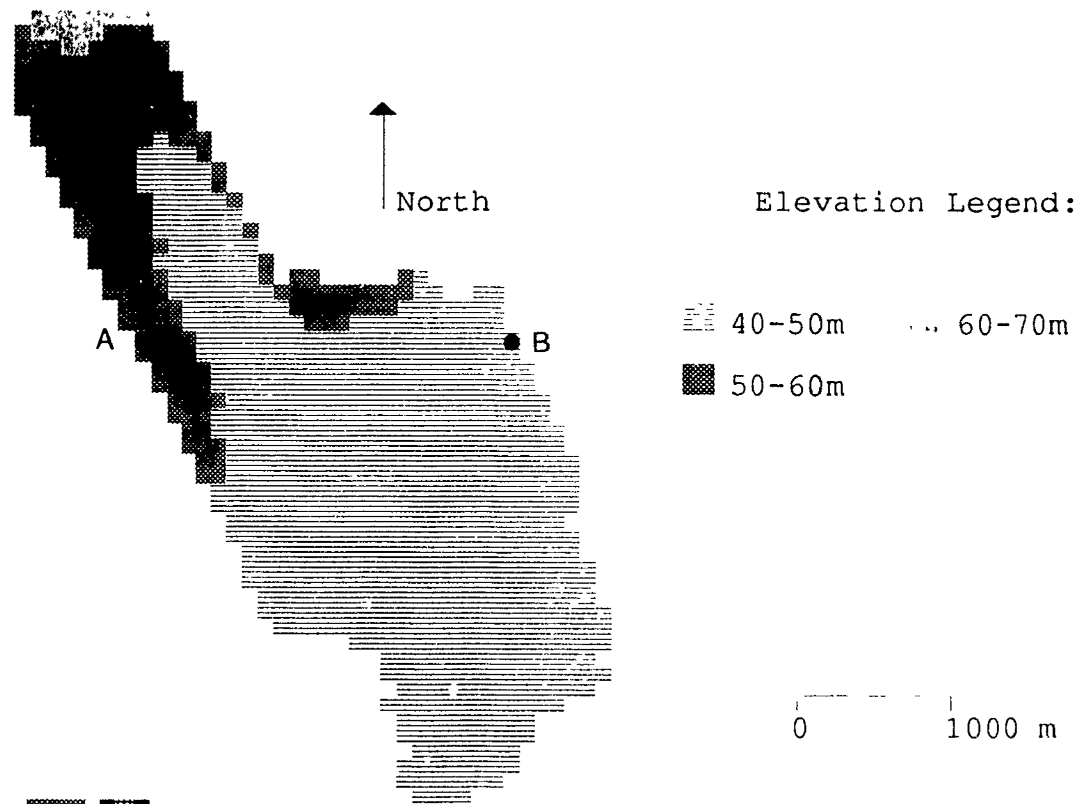


Figure 6.1: Land Use and Soils of the St-Dominique Basin

small percentage below the Vaudreuil soil. The rest of the catchment is occupied by sandy loam soils.

The elevation and slope of the St-Dominique watershed are presented in Figure 6.2. The top map shows the elevation of each cell in increments of 10 m. This digital representation shows that the basin is level except for its northern portion. It must be noted that elevations are stored externally with a precision of 1 cm but are presented here with a 10 m interval for clarity. The slopes are represented on the map at the bottom of Figure 6.2. Most of the slopes are less than 1%. Higher slopes are found in the northern part of the basin. The GIS was used to calculate the average and maximum watershed slopes. The results are 0.39% and 4.9% respectively. The calculated average slope is two times larger than the 0.19% value calculated along the stream. This means that the average surface slope perpendicular to the stream is higher than that along the stream. This was confirmed by field observations and shows that it is important to evaluate the average slope of a basin on a cellular, rather than a lumped basis.

Figure 6.3 illustrates a cross-section of the watershed surface elevation model. This cross-section shows the effect of the interpolation scheme used in deriving the elevation model. The cubic weighting used here resulted in 'S' shaped curves which are a good representation of field conditions.



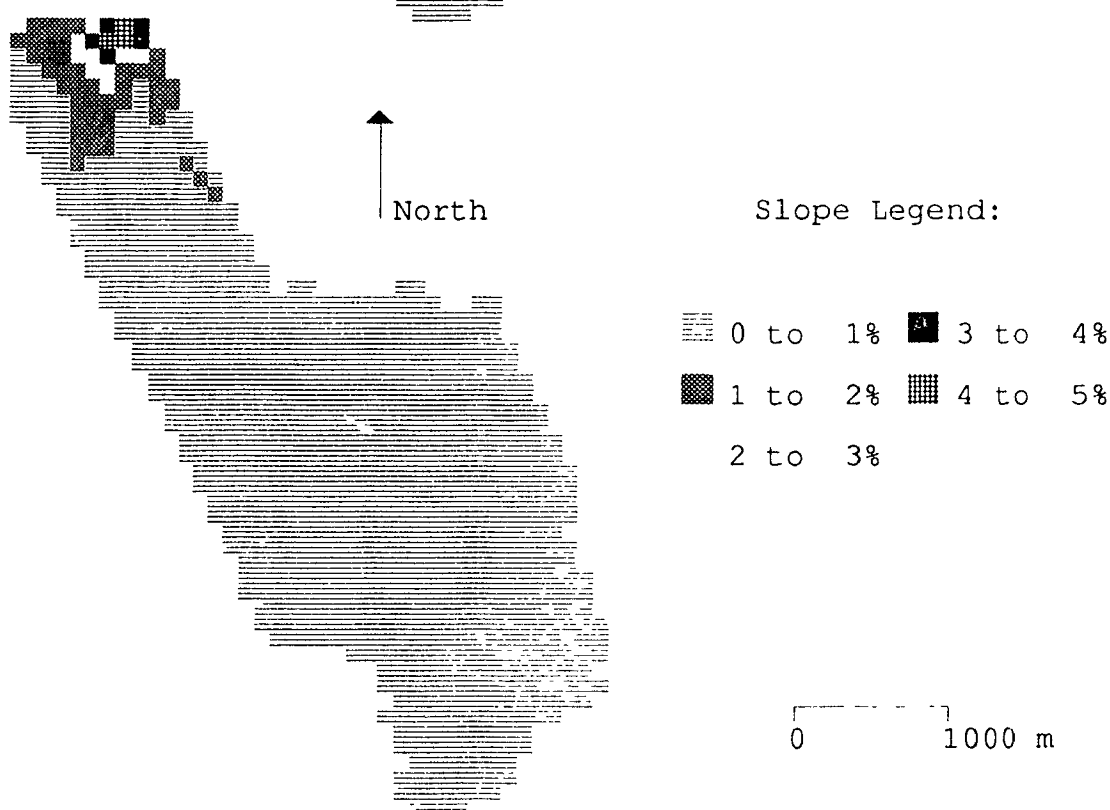


Figure 6.2: Elevation and Slope of the St-Dominique Basin

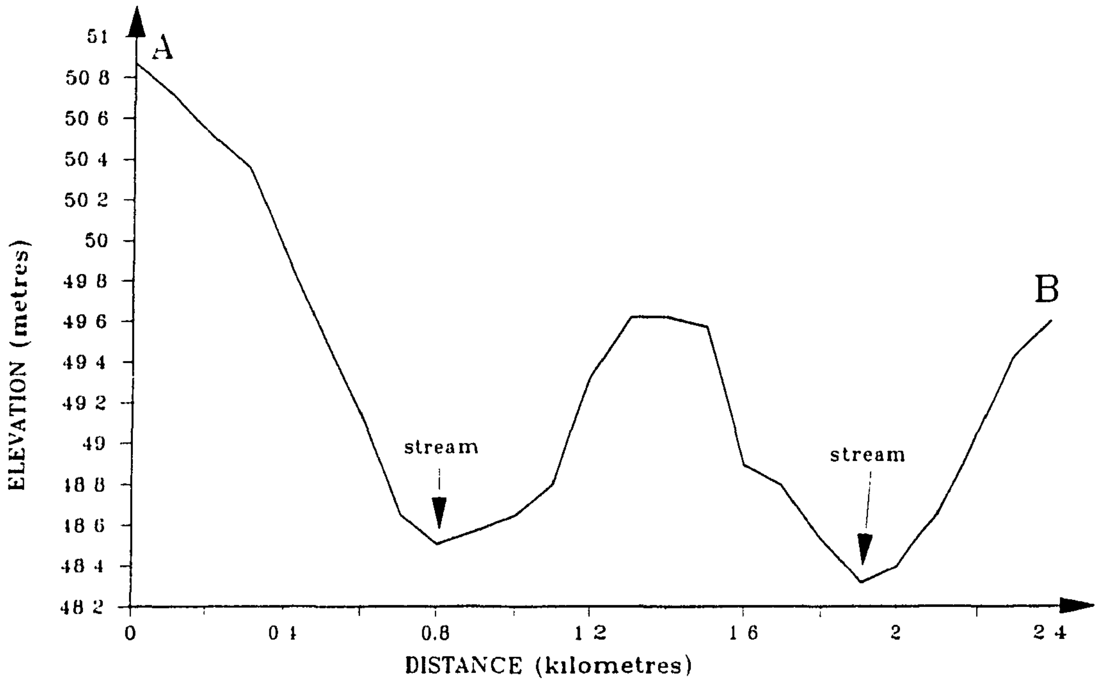


FIGURE 6.3: Cross-Section of the Digital Elevation Model

The GIS was also used to generate a table of the land use, soil type and slope combinations of the watershed (Table 6.1). Slope ranges of 1% were used. The 3 most common combinations are: i) sod-farm over St-Zotique sandy loam with a surface slope below 1% (10% of the basin); ii) corn on a St-Zotique soil and 1% slope (9.7% of the basin) and iii) tree nursery on Ste-Rosalie clay with a 1% slope (6.6% of the basin). No single combination occupies more than 10% of the St-Dominique watershed. This result demonstrates the heterogeneity of the basin and hence the importance of the distributed parameter modeling approach.

Table 6.1: Composite Analysis of the land use, soil types and slopes of the St-Dominique Basin

LAND USE	SLOPE(%)	Percentage of the Land Use, Soil Type and Slope Combination in the Basin						
		Soil Type:						
		Ro	R	Cv	Za	S	V	M
CORN	< 1	4.0	1.4	2.2	9.7	4.3	-	-
HAY	< 1	3.9	0.7	2.0	4.3	5.6	0.2	0.1
	1 TO 2	-	-	-	0.3	-	-	-
TREE NURSERY	< 1	6.6	0.7	5.1	-	1.7	-	-
GRAIN	< 1	1.0	-	1.2	-	-	-	-
SOD FARM	< 1	-	-	-	10.0	-	-	-
PASTURE	< 1	3.5	1.2	2.5	3.5	3.2	-	0.5
	1 TO 2	-	-	-	0.1	-	-	0.1
VEGETABLE	< 1	-	-	-	-	3.7	-	-
BUSH	< 1	-	-	-	4.5	-	-	2.5
	1 TO 2	-	-	-	-	-	-	0.1
WOODS	< 1	-	-	-	0.7	0.0	2.6	0.0
	1 TO 2	-	-	-	0.2	-	4.3	-
	> 2	-	-	-	-	-	1.9	-

The Rigaud watershed was analyzed using the same methods that were used for the St-Dominique watershed. The land use and soil types of the Rigaud watershed are presented in Figure 6.4. The land use map clearly shows the spatial distribution of land use within the watershed. The predominant land use is woodland. This land use occupies the eastern portion of the basin. The second most common land use is hay which is found in the western half of the basin. The soil types are shown in the lower map of the Figure. Clay soils occupy the western half of the basin. Gravelly loams are found in the eastern section.

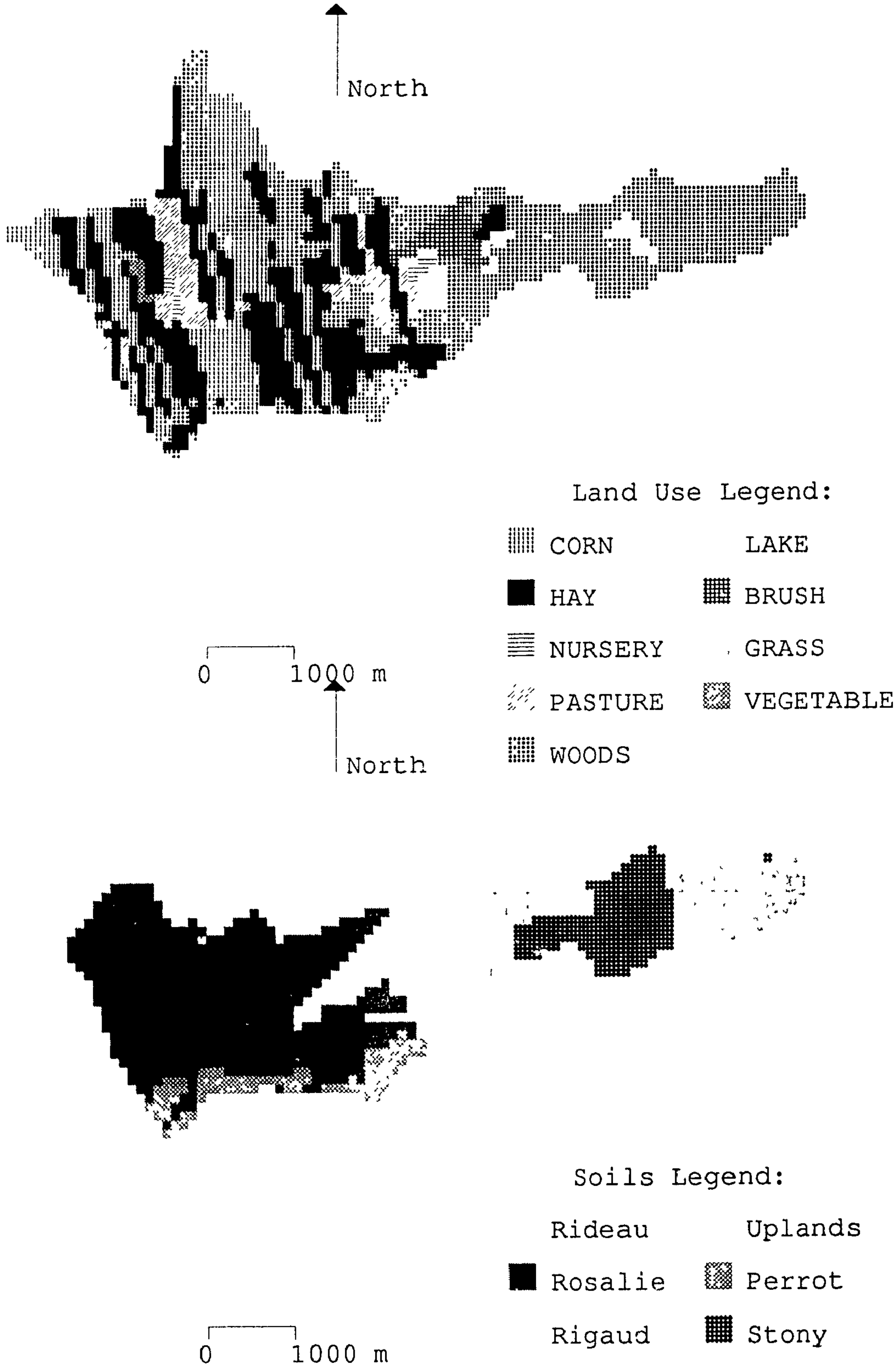


Figure 6.4: Land Use and Soils of the Rigaud Watershed

The Rigaud watershed is steeper than St-Dominique. The map of Figure 6.5 shows elevations ranging from 40 to 220 m. The largest slopes are found in the eastern half of the watershed. The average basin slope is 2.1% and the maximum 1-ha cell slope is 13%. It can be observed that the basin slope is almost twice as large as the stream slope (1.2%). This result further stresses the importance of spatially distributed analysis and modeling of watersheds.

Table 6.2 shows the land use, soil type and slope combinations of the Rigaud watershed. The three most common combinations are hay on Ste-Rosalie clay with a slope below 1% (10.1% of the basin), followed by corn with the same soil and slope (6.0% of the basin area) and woods on Rigaud gravelly sandy loam with a slope between 4 and 5% (5.3% of the basin). This demonstrates the heterogeneity of agricultural watersheds.

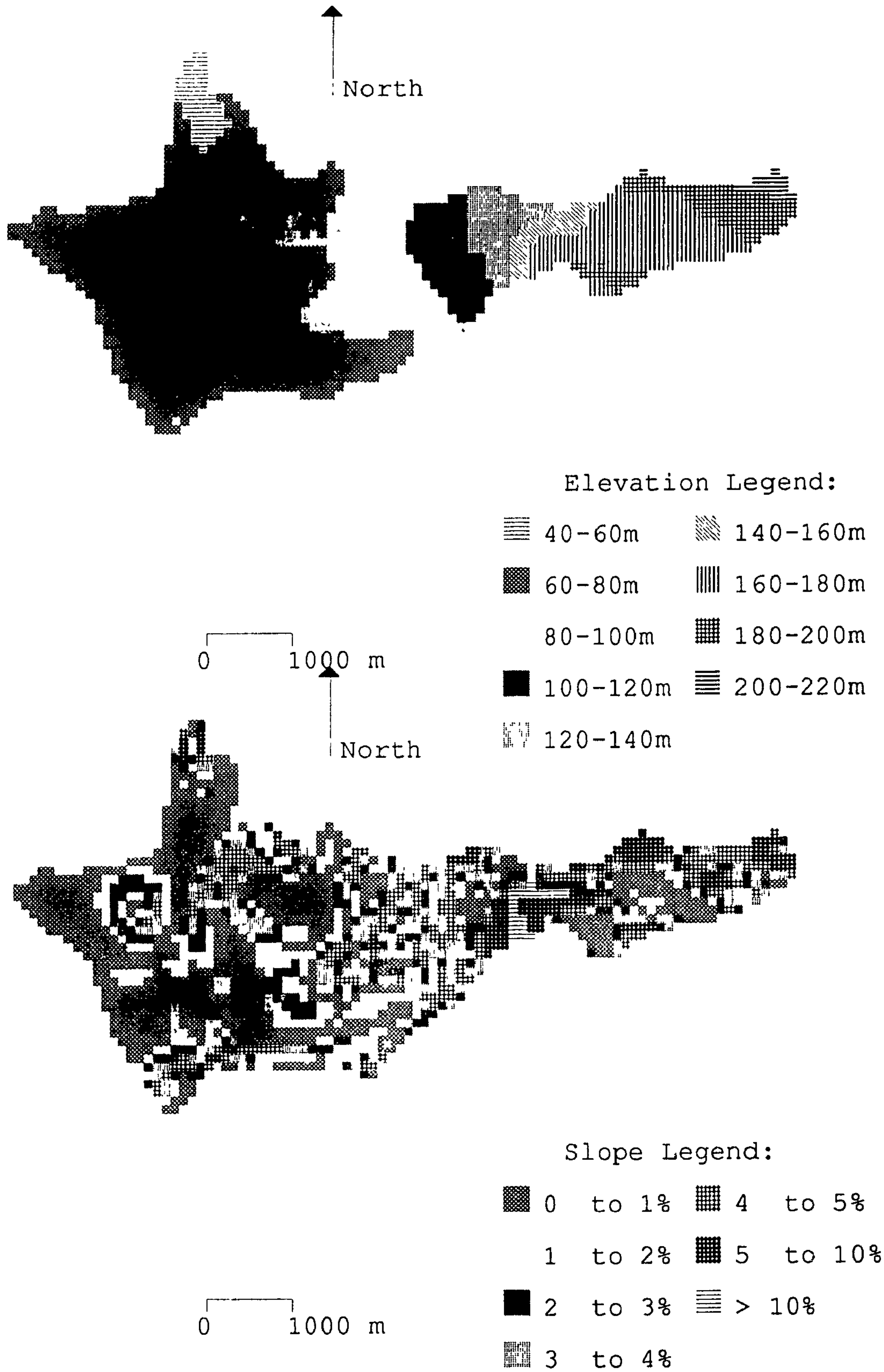


Figure 6.5: Slope and Elevation of the Rigaud Watershed

Table 6.2: Composite Analysis of the land use, soil types and slopes of the Rigaud Basin

		Percentage of the Land Use, Soil Type and Slope Combination in the Basin					
		Soil Type:					
LAND USE	SLOPE (%)	Ro	R	Rg	RS	Pg	U
CORN	< 1	6.0	4.0	0.7	-	0.1	-
	1 to 2	2.9	1.3	0.3	-	0.1	-
	2 to 5	1.5	1.2	0.5	-	0.6	-
	> 5	0.1	0.2	-	-	0.1	-
HAY	< 1	10.1	2 6	1.7	-	0.5	0.1
	1 to 2	5.1	0.4	0.8	-	0.5	0.1
	2 to 5	4.0	0.6	2.3	-	0.6	0.1
	> 5	-	-	-	-	0.1	-
TREE NURSERY	< 1	0.2	-	-	-	-	-
	1 to 2	0.1	-	0.1	-	-	-
	2 TO 5	-	-	0.2	-	-	-
	> 5	-	-	-	-	-	-
PASTURE	< 1	1.8	0.9	0.1	-	-	-
	1 to 2	1.0	0.2	0.3	-	-	-
	2 to 5	0.9	-	1.3	-	-	-
	> 5	-	0.1	-	-	-	-
WOODS	< 1	0.7	1.8	3.8	2.1	0.9	0.3
	1 to 2	0.5	0.7	3.1	0.5	0.7	0.1
	2 to 5	0.4	0.2	11.3	2.5	1.1	0.6
	> 5	-	0.2	3.6	2.8	0.1	-
LAKE	< 1	-	-	-	0.5	-	-
	1 to 2	-	-	-	0.1	-	-
	2 to 5	-	-	0.1	0.2	-	0.2
	> 5	-	-	0.1	0.1	-	-
BUSH	< 1	-	-	0.4	-	-	0.1
	1 to 2	-	-	0.4	-	-	-
	2 to 5	-	-	1.5	-	-	-
	> 5	-	-	0.1	-	-	-
GRASS	< 1	-	-	0.1	-	-	0.2
	1 to 2	-	-	0.1	-	-	0.1
	2 to 5	-	-	1.0	-	-	-
	> 5	-	-	0.1	-	-	-
VEGETABLES	< 1	0.1	-	-	-	-	-
	1 to 2	0.1	-	-	-	-	-
	2 to 5	0.2	-	-	-	-	-
	> 5	-	-	-	-	-	-

6.2. ANSWERS Validation

The hydrologic and sediment transport components of ANSWERS were analyzed. A sensitivity analysis was performed as a first step. The hydrologic portion of the model was then validated. The sediment generation and transport components were validated based on the best results from the hydrologic validation.

6.2.1. Sensitivity Analysis

The sensitivity analysis of the runoff component of ANSWERS is summarized in Table 6.3. The peak flow prediction is most influenced by the surface slope of the watershed cells. Lowering the slope of every cell by 50% reduced the peak flow by 72%. This effect is however highly non-linear, as increasing all slopes by the same amount raised the peak by only 10%. The steady state infiltration rate of the soils is the second most influential parameter. A decrease of 50% in this parameter created an increase of 48% in the predicted peak flow. This effect is also non-linear, as an increase in infiltration rate by 50% lowered the peak flow by only 18%. A third parameter of high influence on peak flow is the Manning's roughness coefficient for the land surface. The effect of this parameter on peak flow is relatively linear. An increase of 50% in surface Manning's n produced a 19% reduction in peak flow. Channel Manning's coefficient and channel width are the two other most influential parameters. Increasing any of these two parameters decreased the predicted peak flow and vice-versa. Figure 6.6 summarizes these results.

Runoff volume is also most influenced by the slope of the basin surface. This effect is highly non-linear. Decreasing the slope of each cell by 50% lowered the amount of runoff by 33%. Increasing the slope by 50% increased runoff by only 3%. The steady-state infiltration rate of the soils in the basin

TABLE 6.3: SENSITIVITY ANALYSIS ON THE RUNOFF COMPONENT OF ANSWERS

a) Peak Flow

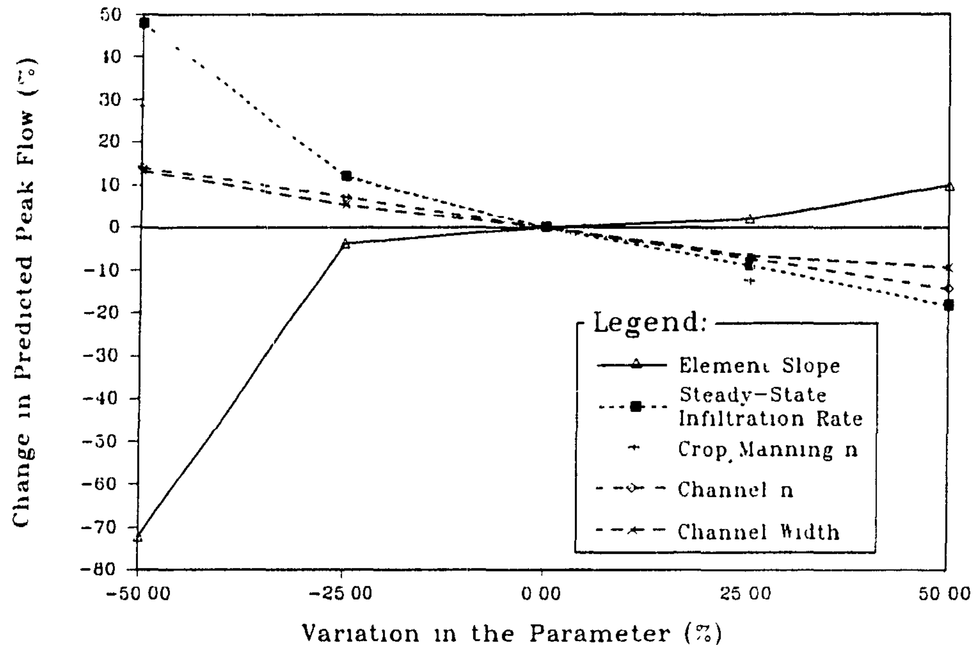
PARAMETER VARIATION (%)	VARIATION IN PREDICTED PEAK FLOW (%) DUE TO A VARIATION IN:				
	ELEMENT SLOPE	STEADY-STATE INFILTRATION	CROP ROUGHNESS COEFFICIENT	CHANNEL ROUGHNESS COEFFICIENT	CHANNEL WIDTH
-50.00	-72.03	+47.96	+28.54	+14.17	+13.32
-25.00	-3.76	+11.98	+12.24	+7.20	+5.39
0.00	0.00	0.00	0.00	0.00	0.00
+25.00	+2.01	-8.95	-12.37	-7.24	-6.59
+50.00	+10.00	-18.17	-19.28	-14.24	-9.39

b) Runoff Volume

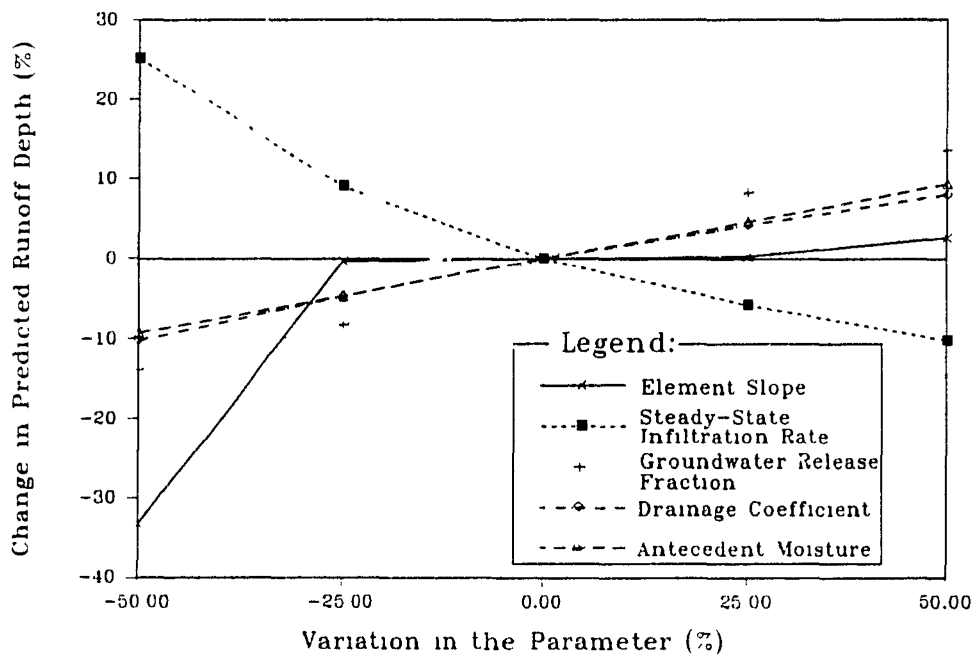
PARAMETER VARIATION (%)	VARIATION IN PREDICTED RUNOFF VOLUME (%) DUE TO A VARIATION IN:				
	ELEMENT SLOPE	STEADY-STATE INFILTRATION	GROUNDWATER RELEASE FRACTION	DESIGN DRAINAGE COEFFICIENT	ANTECEDENT SOIL MOISTURE
-50.00	-33.22	+25.20	-13.98	-10.15	-9.26
-25.00	-0.37	+9.05	-8.31	-4.67	-4.74
0.00	0.00	0.00	0.00	0.00	0.00
+25.00	+0.26	-5.80	+8.24	+4.25	+4.63
+50.00	+2.64	-10.18	+13.66	+8.02	+9.33

c) Time to Peak

PARAMETER VARIATION (%)	VARIATION IN PREDICTED TIME TO PEAK (%) DUE TO A VARIATION IN:				
	ELEMENT SLOPE	CHANNEL ROUGHNESS COEFFICIENT	CHANNEL WIDTH	CROP ROUGHNESS COEFFICIENT	STEADY-STATE INFILTRATION
-50.00	+22.22	-11.11	-5.56	-5.56	-5.56
-25.00	+0.00	-5.56	-5.56	-5.56	-5.56
0.00	0.00	0.00	0.00	0.00	0.00
+25.00	0.00	+5.56	+5.56	+5.56	0.00
+50.00	-5.56	+11.11	+5.56	+5.56	0.00



a) Sensitivity of Peak Flow Predictions



b) Sensitivity of Runoff Depth Predictions

Figure 6.6: Sensitivity Analysis of the Runoff Generation Component of ANSWERS

is the second most important factor. The effect is again non-linear. An increase of 50% in the infiltration rate created a decrease of 10% in runoff volume. A decrease of 50% in this parameter caused a 25% increase in runoff volume. The groundwater release fraction, drainage coefficient and antecedent soil moisture have a direct effect on predicted runoff volume. Increasing any of these parameters raised the volume of runoff.

Time to peak is generally less influenced by parameter variations. The largest change in time to peak was 22%, due to a 50% decrease in surface slope. A variation of 50% in the channel roughness coefficient produced a change of 11% in the time to peak. This is not a very severe effect and was therefore not plotted.

The sensitivity of the sediment generation and transport components of ANSWERS is shown in Table 6.4 and Figure 6.7. The peak sediment concentration in the runoff is most influenced by the slope of the watershed cells. The effect of this parameter is non-linear. A 50% decrease in the slope of every cell caused a decrease of 73% in the peak sediment concentration. A cell slope increase of 50% caused an 83% increase in maximum sediment concentration. Decreasing cell slope by 25%, however, caused a decrease of only 3% in peak sediment concentration. The Manning's roughness coefficient for the land surface affects the peak sediment concentration almost linearly. An increase of 50% in Manning's n caused a decrease of 21% in the peak sediment concentration. It may be recalled that the elemental slope and the surface Manning's coefficient had similar effects on peak runoff rates. Their effect on peak sediment concentration is therefore directly related to their influence on velocity and amount of surface runoff. The C, P and K parameters in the Universal Soil Loss

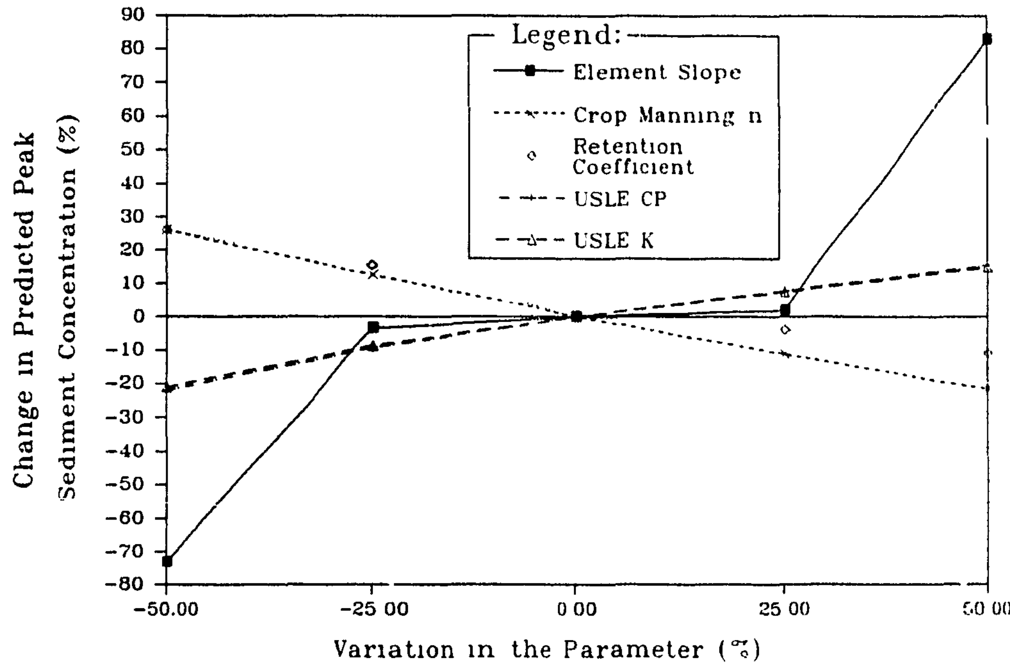
TABLE 6.4: SENSITIVITY ANALYSIS ON THE SEDIMENT COMPONENT OF ANSWERS

a) Sediment Concentration

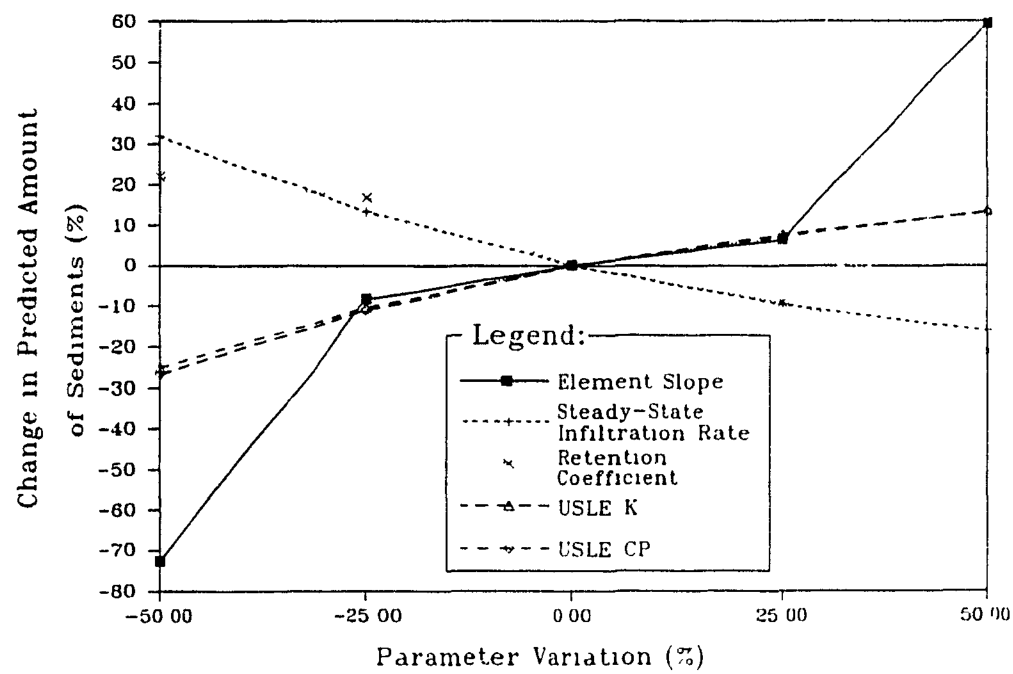
PARAMETER VARIATION (%)	VARIATION IN PEAK SEDIMENT CONCENTRATION (%) DUE TO A VARIATION IN:				
	ELEMENT SLOPE	CROP ROUGHNESS COEFFICIENT	USLE C * P	SOIL ERODIBILITY (USLE K)	RETENTION COEFFICIENT
-50.00	-73.20	+26.13	-22.16	-21.21	+25.99
-25.00	-3.39	+12.59	-9.18	-8.76	+15.54
0.00	0.00	0.00	0.00	0.00	0.00
+25.00	+1.91	-11.19	+7.73	+7.36	-3.90
+50.00	+82.92	-21.58	+15.39	+14.80	-11.05

b) Sediment Yield

PARAMETER VARIATION (%)	VARIATION IN TOTAL SEDIMENT YIELD (%) DUE TO A VARIATION IN:				
	ELEMENT SLOPE	STEADY-STATE INFILTRATION	USLE C * P	SOIL ERODIBILITY (USLE K)	RETENTION COEFFICIENT
-50.00	-72.78	+31.81	-26.68	-25.02	+21.95
-25.00	-8.34	+13.20	-11.01	-10.28	+16.72
0.00	0.00	0.00	0.00	0.00	0.00
+25.00	+6.54	-9.53	+7.63	+7.26	-9.19
+50.00	+59.36	-16.11	+13.31	+13.41	-21.33



a) Sensivity of the Peak Concentration



b) Sensivity of Total Sediment Yield

Figure 6.7: Sensitivity Analysis of the Sediment Transport Component of ANSWERS

Equation had relatively similar effects on peak sediment concentration. An increase of 50% in these parameters caused the peak sediment concentration to drop by about 22% whilst a decrease by the same amount caused an increase of 15%. The fifth most important parameter is the retention coefficient. Decreasing this parameter by 50% caused an increase of 26% in the peak sediment concentration. An increase of 50% caused a decrease of only 11% in the peak sediment concentration.

The total amount of sediment (sediment yield) carried by the runoff is also most influenced by the slope of the watershed cells. The effect is again non-linear. Second in importance is the steady-state infiltration rate. Decreasing the steady-state infiltration by 50% caused a 32% increase in the total amount of sediments removed from the basin. An increase of 50% of this parameter caused a 16% reduction in the amount of sediment. The effect is non-linear. The C,P and K factors of the Universal Soil Loss Equation have similar effects on the amount of sediments predicted by the model. Decreasing either parameter by 50% lowered the amount of sediments by about 26%. Increasing either parameter by 50% raised the sediment loss by 13%. Similarly the fifth most important parameter is the retention coefficient. Its effect on total sediment loss is relatively linear. An increase of 50% of this parameter caused a decrease of 21% in total sediment loss, and vice-versa.

Accurate prediction of runoff is crucial for sediment loss prediction. The most important parameters affecting runoff and sediment loss are slope of the watershed cells and steady-state infiltration rate of the soils. Both parameters are difficult to measure precisely. Furthermore, the steady-state infiltration rate exhibits high spatial variability. For these reasons, it is impossible to obtain extremely accurate predictions with ANSWERS.

An interesting result of the sensitivity analysis is that most parameters have a non-linear effect on the hydrologic response of the model. This is an advantage of physically based models such as ANSWERS. Simpler models like the Rational Method and the USLE, assume linear relationships between their parameters and output. This linearity is unrealistic.

We also note that most parameters influence runoff and sediment loss rather weakly. A variation of 50% in most input parameters produced a variation in the prediction which was below 50% (typically around 30%). Therefore, the inaccuracies present in the input data do not cause higher inaccuracies in the model output. This indicates that the model is robust and will not be influenced by minor errors in its input parameters.

6.2.2. Validation of the Hydrologic Component

ANSWERS was used to predict runoff hydrographs for 20 events on the St-Dominique watershed and 4 events on the Rigaud watershed (Chapter 4). These simulations were based on measured watershed properties that were presented in Chapters 4 and 5.

6.2.2.1. St-Dominique Watershed

The results of ANSWERS runoff predictions based on measured parameters are presented in Tables 6.5 to 6.7. The peak flow is generally underpredicted. The average relative error is -40.8%. This tendency to underpredict peak flow was observed earlier by Von Euw et al. (1989) and Beasley et al. (1980a). The latter associated this effect with surface crusting. Most of the events that were severely underpredicted occurred in the spring and fall. At these times soils are quite bare and prone to crusting and sealing. This could explain the underpredictions of peak flow in Table 6.5.

TABLE 6.5: PEAK FLOW PREDICTIONS FOR ST-DOMINIQUE BASED ON MEASURED PROPERTIES

Date	Peak Flow		Absolute	Relative
	Observed	ANSWERS Predicted	error	error
Yr-Mo-Da	(m^3/s)	(m^3/s)	(m^3/s)	(%)
85-09-27	0.3821	0.3592	-0.0229	-5.99
85-10-10	0.5830	0.1708	-0.4122	-70.70
85-11-13	1.2754	0.1932	-1.0822	-84.85
86-07-26	1.1269	0.4460	-0.6809	-60.42
86-08-15	0.1865	0.1377	-0.0488	-26.19
86-08-27	0.5317	0.1804	-0.3513	-66.06
86-09-30	2.4204	0.2595	-2.1609	-89.28
86-09-11	1.1922	0.2699	-0.9223	-77.36
87-05-23	0.4978	0.4924	-0.0054	-1.09
87-06-08	2.0916	0.2808	-1.8108	-86.57
87-07-14	0.6423	0.4096	-0.2327	-36.23
87-07-18	0.7069	0.8108	0.1039	14.70
87-07-24	0.3715	0.3121	-0.0594	-15.98
87-10-28	0.2655	0.1857	-0.0798	-30.07
88-04-28	1.1259	0.2026	-0.9233	-82.00
88-11-02	0.5900	0.2509	-0.3391	-57.47
88-11-06	0.2920	0.0812	-0.2108	-72.18
89-10-20	0.1512	0.4515	0.3003	198.60
89-11-14	0.9021	0.2296	-0.6725	-74.55
89-11-16	3.1355	0.2579	-2.8776	-91.77
			average:	-40.77

There are only two overpredictions of peak flow. T. July 18th, 1987 event was overpredicted by less than 15% and is therefore relatively well predicted. The peak flow of the October 20th, 1989 event was, however, overpredicted by almost 200%. This overprediction is probably due to the fact that this was the first significant hydrologic event which followed the dry summer of 1989. The soil profile was initially very dry and clay soils were cracked. These factors raised the infiltration capacity of the soils thereby decreasing surface runoff.

ANSWERS also underpredicted the runoff depth (Table 6.6). This tendency of ANSWERS had also been previously acknowledged (Dickey et al., 1979, Beasley et al., 1980a, Von Euw et al., 1989). The average relative error in this case is -32.0%. The underpredictions of runoff depth are therefore on average less severe than those of peak flow. Similarly, the worst predictions occurred during the spring and fall.

The runoff volume for the October 20th, 1989 event was severely overpredicted. The reason for this overprediction is also that this was the first significant hydrologic event after a relatively dry summer.

TABLE 6.6: RUNOFF VOLUME PREDICTIONS FOR ST-DOMINIQUE BASED ON MEASURED PROPERTIES

Date	Runoff Volume		Absolute	Relative
	Observed	ANSWERS Predicted	error	error
Yr-Mo-Da	(mm)	(mm)	(mm)	(%)
85-09-27	3.694	4.218	0.52	14.20
85-10-10	4.022	1.432	-2.59	-64.41
85-11-13	16.260	2.650	-13.61	-83.70
86-07-26	5.202	3.919	-1.28	-24.66
86-08-15	1.759	1.067	-0.69	-39.31
86-08-27	4.539	1.816	-2.72	-59.99
86-09-11	20.843	6.026	-14.82	-78.28
86-09-30	16.554	3.595	-12.96	-71.09
87-05-23	3.202	1.530	-1.67	-52.22
87-06-08	16.573	4.441	-12.13	-73.20
87-07-14	2.583	2.975	0.39	15.16
87-07-18	3.133	4.112	0.98	31.26
87-07-24	1.489	2.080	0.59	39.68
87-10-28	2.099	1.501	-0.60	-28.48
88-04-28	13.484	3.270	-10.21	-75.75
88-11-02	5.998	2.979	-3.02	-50.33
88-11-06	2.965	0.385	-2.58	-87.00
89-10-20	1.206	3.709	2.50	207.62
89-11-14	6.765	2.095	-6.67	-76.10
89-11-16	15.882	2.614	-13.27	-83.54
			average:	-32.01

Times to peak flow were better predicted than runoff depth and peak flow except for three events (Table 6.7). On June 8, 1987, November 6, 1988 and November 16, 1989, the times to peak were overpredicted by more than 100%. Each one of these events was the last one in either spring or fall, and had been preceded by at least one other event in the same season. The preceding event(s) probably caused surface sealing to occur since the soil surface was relatively bare. The surface crust lowered Manning's roughness coefficient thereby decreasing time to peak flow.

TABLE 6.7: TIME TO PEAK PREDICTIONS FOR ST-DOMINIQUE BASED ON MEASURED PROPERTIES

Date	Time to Peak		Absolute error	Relative error
Yr-Mo-Da	Observed (h)	ANSWERS Predicted (h)	(h)	(%)
85-09-27	21.00	18.90	-2.10	-10.00
85-10-10	15.00	16.80	1.80	12.00
85-11-13	16.00	24.30	8.30	51.87
86-07-26	9.00	9.00	0.00	0.00
86-08-15	14.00	13.80	-0.20	-1.43
86-08-27	11.00	13.30	2.30	20.91
86-09-30	9.00	14.40	5.40	60.00
86-09-11	36.00	39.60	3.60	10.00
87-05-23	17.00	16.20	-0.80	-4.71
87-06-08	5.00	29.60	24.60	492.00
87-07-14	10.00	10.80	0.80	8.00
87-07-18	6.00	2.00	-4.00	-66.67
87-07-24	6.00	8.75	2.75	45.83
87-10-28	19.00	22.00	3.00	15.79
88-04-28	33.00	37.20	4.20	12.73
88-11-02	21.00	25.90	4.90	23.33
88-11-06	15.00	46.20	31.20	208.00
89-10-20	24.00	25.00	1.00	4.17
89-11-14	37.00	39.60	2.60	7.03
89-11-16	5.00	10.80	5.80	116.00
			average:	50.24

Poor predictions of the volume and maximum depth of runoff could also be due to improper estimation of soil physical properties. Most of these properties were measured during the summer. Seasonal variation of parameters was therefore not estimated. The formation of a soil surface crust is one such seasonal factor. This factor tends to lower the infiltration rate of the soils in the spring and fall when the soil is relatively bare. Another important factor is faunal activity within the soil. Worms and other soil animals form macropores within the soil which may increase infiltration rate during the active summer months (Edwards et al., 1979). Root penetration also increases infiltration rate during the summer months. A fourth factor is surface cracks due to the shrinkage of swelling clay soils (Hoogmoed et al., 1980). Such surface cracks may also be observed during dry summer months. The parameters used in the infiltration equation should therefore account for the changes in soil infiltration rates during spring and fall in order to best represent field conditions and provide better runoff predictions.

Various methods can be used to account for the seasonal variations of soils parameters. Breve et al. (1989) devised a crusting factor parameter by which they multiplied both the steady-state infiltration rate and the maximum infiltration rate of the soils. Using this adjustment ANSWERS could predict runoff within a 30% difference. The overall crusting factor that they developed had a value of 0.38. Enright (1988) devised seasonal adjustment factors by which he multiplied the saturated hydraulic conductivity of the soils in the summer. Factors of 2.5 and 3 were used for clay soils and sandy loams respectively. Significantly better predictions of runoff volumes were then obtained.

Infiltration measurements were taken in the summer for Ste-Rosalie clay, Courval sandy loam and Rigaud gravelly sandy loam soils, and in the fall for Rideau clay, Soulanges very fine sandy loam and St-Zotique sandy loam soils. The infiltration parameters of the Ste-Rosalie clay, Courval sandy loam and Rigaud sandy loam should therefore have been reduced to account for surface crusting. The Rigaud gravelly sandy loam soil had such high measured infiltration rates that any adjustment was deemed useless. Of the soils measured in the fall, only Rideau clay was likely to crack in the summer. The measured infiltration rates were, however, very high for this soil and were therefore not increased. Therefore, only the Holtan's equation infiltration parameters of Ste-Rosalie clay and Courval sandy loam were seasonally adjusted.

To perform the seasonal adjustment, the measured infiltration rates were divided by the ratio of the average runoff/rainfall ratio for spring and fall conditions to the average of this ratio for summer conditions. Holtan's infiltration equation was then fitted to the adjusted data to obtain the adjusted infiltration parameters. The average runoff/rainfall ratios were calculated from the data presented in Table 3.1. An average ratio of 0.088 was obtained for the summer, and 0.250 for spring and fall. The seasonal adjustment factor was therefore 0.352. This value is very close to those presented by Breve et al.(1989) and Enright (1988). The results are presented in Table 6.8.

Table 6.8.Measured and Adjusted Holtan Infiltration Parameters

Soil Type	FC (mm/h)		A (mm/h)		P		DF (mm)	
	Measured	Adjusted	Measured	Adjusted	Measured	Adjusted	Measured	Adjusted
Ste-Rosalie	17.3	6.7	11	1	2.3	1.4	445	645
Courval	13.9	4.2	455	141	2.1	2.1	165	69

(Definition of FC, *A*, *P* and DF in Table 4.8 page 45)

All of the events were simulated using the seasonally adjusted infiltration parameters except for those that occurred in July and August. The predictions of peak flow, runoff depth and time to peak were improved. Table 6.9 presents the peak flow predictions with adjusted parameters. Note that the events that occured in either July or August are not included in this table.

TABLE 6.9: PEAK FLOW PREDICTIONS AT ST-DOMINIQUE BASED ON SEASONALLY ADJUSTED INFILTRATION PARAMETERS

Date Yr-Mo-Da	Peak Flow Observed (m^3/s)	Peak Flow ANSWERS Predicted (m^3/s)	Absolute error (m^3/s)	Relative error (%)
85-09-27	0.3821	0.7178	0.3357	87.87
85-10-10	0.5830	0.4313	-0.1517	-26.03
85-11-13	1.2754	0.4228	-0.8526	-66.85
86-09-11	1.1922	0.7299	-0.4623	-38.78
86-09-30	2.4204	2.2897	-0.1307	-5.40
87-05-23	0.4978	0.4924	-0.0054	-1.09
87-06-08	2.0916	3.4034	1.3118	62.72
87-10-28	0.2655	0.4285	0.1630	61.39
88-04-28	1.1259	0.4145	-0.7114	-63.18
88-11-02	0.5900	0.5041	-0.0859	-14.55
88-11-06	0.2920	0.3253	0.0333	11.41
89-10-20	0.1512	0.6310	0.4798	317.33
89-11-14	0.9021	0.3990	-0.5031	-55.77
89-11-16	3.1355	1.4920	-1.6435	-52.41
average (including July and August):				1.32

The underprediction is, as expected, less severe than before. The average relative error is positive but this is due to a large overprediction of the peak flow of October 20th, 1989. The coefficient of predictability was calculated for the series of predicted and observed peak flows. Its value is 1.72 when no seasonal adjustment is made and 0.60 with seasonal adjustments. This result demonstrates that the seasonal adjustment gives better predictability to ANSWERS since its CP'_A is closer to 0.

The runoff volume predictions are also improved by seasonal adjustment (Table 6.10). The average relative error is now positive. This is due to a few severe overpredictions. The events of September 27, 1985, October 28, 1987 and October 20, 1989 are all overpredicted by more than 100%. These were the first major events of the fall for those years. Probably surface sealing and other infiltration reducing processes did not affect them. The other events are better predicted. The results also show that ANSWERS tends to underpredict large volumes and overpredict small ones.

TABLE 6.10: RUNOFF VOLUME PREDICTIONS FOR ST-DOMINIQUE BASED ON SEASONALLY ADJUSTED INFILTRATION PARAMETERS

Date	Runoff Volume		Absolute	Relative
	Observed	ANSWERS Predicted	error	error
Yr-Mo-Da	(mm)	(mm)	(mm)	(%)
85-09-27	3.694	9.551	5.86	158.57
85-10-10	4.022	5.158	1.14	28.24
85-11-13	16.260	7.410	-8.85	-54.43
86-09-11	20.843	13.352	-7.49	-35.94
86-09-30	16.554	10.818	-5.74	-34.65
87-05-23	3.202	5.686	2.48	77.58
87-06-08	16.573	12.509	-4.06	-24.52
87-10-28	2.099	4.898	2.80	133.32
88-04-28	13.484	9.455	-4.03	-29.88
88-11-02	5.998	7.618	1.62	27.00
88-11-06	2.965	4.074	1.11	37.37
89-10-20	1.206	6.930	5.72	474.77
89-11-14	8.765	5.247	-3.52	-40.14
89-11-16	15.882	8.153	-7.73	-48.66
average (including July and August):				31.54

The coefficient of predictability for runoff volume was calculated. A value of 0.47 was found when seasonal adjustments were performed. This compares favourably with the previous value of 1.38, when no seasonal variation was considered.

Time to peak predictions are also better with seasonally adjusted parameters (Table 6.11). The average relative error is now -7%. The coefficient of predictability decreased from 1.00 to 0.46 when the seasonal adjustment was implemented.

TABLE 6.11: TIME TO PEAK PREDICTIONS FOR ST-DOMINIQUE BASED ON SEASONALLY ADJUSTED INFILTRATION PARAMETERS

Date Yr-Mo-Da	Time to Peak Observed (h)	 ANSWERS Predicted (h)	Absolute error (h)	Relative error (%)
85-09-27	21.000	9.800	-11.20	-53.33
85-10-10	15.000	15.000	0.00	0.00
85-11-13	16.000	23.400	7.40	46.25
86-09-30	9.000	6.300	-2.70	-30.00
86-09-11	36.000	12.000	-24.00	-66.67
87-05-23	17.000	16.200	-0.80	-4.71
87-06-08	5.000	2.400	-2.60	-52.00
87-10-28	19.000	20.500	1.50	7.89
88-04-28	33.000	37.200	4.20	12.73
88-11-02	21.000	25.200	4.20	20.00
88-11-06	15.000	12.000	-3.00	-20.00
89-10-20	24.000	24.000	0.00	0.00
89-11-14	37.000	38.400	1.40	3.78
89-11-16	5.000	4.200	-0.80	-16.00
average (including July and August):				-6.77

The general result of the validation of the hydrologic component of ANSWERS for the St-Dominique watershed is that when seasonal adjustments of the infiltration parameters are implemented, the predictions of peak flow, runoff volume and time to peak are on average good. This result is further stressed by the values of the coefficient of predictability calculated separately for each event (Table 6.12). This coefficient is lower than one for half of the events which indicates relatively good predictions.

TABLE 6.12: Coefficient of Predictability For Individual Events

Date: (yr-mo-da)	Coefficient of Predictability
85-09-27	4.7528
85-10-10	0.5342
85-11-13	0.9059
86-07-26	0.8988
86-08-15	0.6767
86-08-27	1.2386
86-09-11	0.5953
86-09-30	0.6641
87-05-23	1.6360
87-06-08	1.3136
87-07-14	0.8416
87-07-18	1.5175
87-07-24	3.1893
87-10-28	5.7123
88-04-28	0.4566
88-11-02	0.3453
88-11-06	0.9905
89-10-20	82.2694
89-11-14	1.0227
89-11-16	1.0721

The effect of the seasonal adjustment on a high intensity event is well illustrated by the results obtained for September 30, 1986 (Fig. 6.8). The peak is better estimated but the predicted hydrograph recedes too rapidly so that the volume prediction is inaccurate. This effect is probably due to the fact that ANSWERS does not simulate interflow. It was noted earlier that interflow may be substantial at St-Dominique because of the soil profile which consists mostly of shallow layers of sandy loams over impervious marine clays.

Considering the simplicity of the seasonal adjustment process, it can be stated that the results were relatively good. More complex schemes could be devised but they would require a more thorough analysis of every parameter used in the simulations. This would not only be very time consuming but would also not represent actual conditions of utilization of the model. The Decision Support System for which the model was tested is intended to be used by people with a limited knowledge of hydrology.

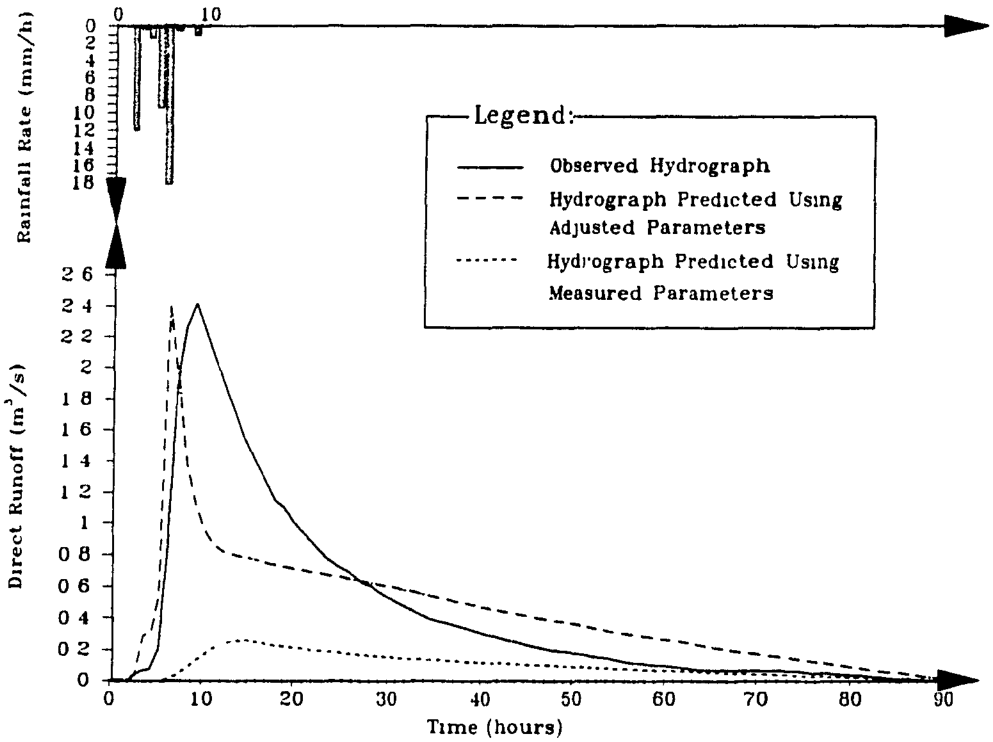


Figure 6.8: ANSWERS Prediction for the September 30, 1986 Event Using Seasonally Adjusted Parameters

6.2.2.2. Rigaud Watershed

The results of the simulations for the Rigaud watershed are presented in Table 6.13. These simulations were performed using the parameters presented in Chapters 4 and 5. The seasonal adjustment described in the preceding section was also applied. The best predictions were obtained with non-adjusted parameters for the June and October 1989 events and with seasonally adjusted parameters for the two November 1989 events. This trend is similar to that observed at St-Dominique during that particular year.

TABLE 6.13: Runoff Simulations for the Rigaud Watershed

a) Peak Flow predictions

Date (Yr-Mo-Da)	Observed Peak (m^3/s)	Predicted Without Adjustment: Peak Flow (m^3/s)	Abso. error (m^3/s)	Rela. error (%)	Predicted With Adjustment: Peak Flow (m^3/s)	Abso. error (m^3/s)	Rela. error (%)
89-06-10	0.451	0.458	0.007	1.52	1.280	0.829	183.78
89-10-20	0.506	0.656	0.149	29.51	1.635	1.128	222.84
89-11-14	1.567	0.294	-1.273	-81.25	1.523	-.044	-2.81
89-11-16	9.713	3.327	-6.386	-65.74	3.136	-6.577	-67.71
			average:	-28.99		average:	84.02
			CP'_A =	0.7092		CP'_A =	0.7560

b) Runoff Depth Predictions

Date (Yr-Mo-Da)	Observed Depth (mm)	Predicted Without Adjustment: Runoff Depth (mm)	Abso. error (mm)	Rela. error (%)	Predicted With Adjustment: Runoff Depth (mm)	Abso. error (mm)	Rela. error (%)
89-06-10	1.914	3.84	1.92	100.44	13.87	11.95	624.68
89-10-20	2.685	5.97	3.29	122.49	17.86	15.17	565.00
89-11-14	6.829	1.53	-5.30	-77.56	9.67	2.84	41.62
89-11-16	22.433	28.46	6.03	26.88	27.33	4.89	21.81
			average:	43.06		average:	313.28
			CP'_A =	0.2879		CP'_A =	1.4778

c) Time to Peak Predictions

Date (Yr-Mo-Da)	Observed Time (h)	Predicted Without Adjustment: Time to Peak (h)	Abso. error (h)	Rela. error (%)	Predicted With Adjustment: Time to Peak (h)	Abso. error (h)	Rela. error (%)
89-06-10	25.00	29.75	4.75	19.00	28.05	3.05	12.20
89-10-20	21.00	28.80	7.80	37.14	27.90	6.90	32.86
89-11-14	30.00	32.40	2.40	8.00	14.85	-15.15	-50.50
89-11-16	17.00	12.60	-4.40	-25.88	12.60	-4.40	-25.88
			average:	9.57		average:	-7.83
			CP'_A =	1.1701		CP'_A =	3.2970

Coefficients of predictability were calculated for each predicted parameter. However, it should be remembered that only four events were analyzed. The simulations with non-adjusted parameters gave the lowest values of CP'_A.

The coefficient of predictability was also calculated for each individual event. The results are presented in Table 6.14. The individual event coefficients are comparable to those obtained for the predictions of St-Dominique events that occurred in 1989.

TABLE 6.14: Coefficients of Predictability for Individual Events

Date	Coefficient of Predictability	
(Yr-Mo-Da)	Without Adjustment	With Adjustment
89-06-10	1.468	43.380
89-10-20	2.218	32.385
89-11-14	3.771	2.249
89-11-16	0.988	1.002

6.2.3. Validation of the Sediment Component

ANSWERS was used to simulate sediment concentration in the stream and sediment yield for all the runoff events that occurred during 1989 in the St-Dominique and Rigaud watersheds. All events were simulated using seasonally adjusted infiltration parameters. The results presented in Table 6.15 show that ANSWERS underpredicted the concentrations at St-Dominique.

The predicted sediment yields for the three events at St-Dominique are presented in Table 6.16. The sediment yields were all underpredicted by ANSWERS. The underprediction is most severe for the event of November 14. One explanation of these low predictions is that ANSWERS does not model re-suspension of deposited particles. This effect raises the actual sediment delivery to a stream because runoff can carry the deposited sediments without detaching them. Sediments deposited earlier during a runoff event, or during a preceding event can therefore increase the yield of the observed event.

Table 6.15: Sediment Concentration Analysis For St-Dominique

Date	Time (h)	Concentration (mg/l) Observed	Concentration (mg/l) Predicted	Relative error (%)	Flow (m^3/s) Observed	Flow (m^3/s) Predicted
89-10-20	10.00	240	222	-8	0.074	0.424
	15.50	2190	463	-79	0.168	1.185
	16.00	2140	383	-82	0.172	1.222
89-10-21	16.50	130	0	-100	0.101	1.513
89-11-14	15.75	340	4	-99	0.5	0.675
89-11-15	13.00	130	0	-100	1.185	1.245
	18.75	50	0	-100	0.934	1.141
89-11-16	12.75	830	1246	50	1.52	1.044
	16.75	950	438	-54	3.243	1.842
89-11-17	13.50	110	0	-100	0.747	1.688

Table 6.16: Predicted Sediment Yields at St-Dominique

Date (Yr-Mo-Da)	Observed (t)	Predicted (t)
89-10-20	21.77	12.59
89-11-14	21.57	0.02
89-11-16	132.11	35.02

Another reason for low predictions is the discretization of rainfall into one-hour average intensities. Dickinson et al.(1989) demonstrated that ANSWERS sediment yield predictions are very sensitive to rainfall intensity. A shorter averaging interval would therefore yield better predictions.

A third factor is the poor prediction of runoff for these three events. The sensitivity analysis revealed that a good prediction of runoff is necessary for accurate predictions of sediment yield. The measured and seasonally adjusted parameters did not result in such accurate simulations.

The sediment concentration predictions for Rigaud are presented in Table 6.17. The concentrations were always underpredicted. This is primarily due to the fact that instantaneous samples were obtained relatively late during most events. ANSWERS probably did not predict any detachment at those times because runoff velocity was too low. If the model considered re-suspension it might have predicted higher concentrations.

The sediment yields are underpredicted more severely at Rigaud than at St-Dominique (Table 6.18). Once again, the event of November 14 is the worst predicted. ANSWERS predictions are reasonable if we consider that most of the cultivated lands of the Rigaud basin are located on clay soils with low erodibility. There must be additional factors in this watershed that contribute significantly to soil loss. A one-year study of this basin did not however reveal any such factor.

Table 6.17: Sediment Concentration Analysis for Rigaud

Date	Time (h)	Concentration (mg/l) Observed	Predicted	Relative error (%)	Flow (m^3/s) Observed	Predicted
89-06-11	15.00	240	0	-100	0.12	1.70
86-06-13	16.92	270	0	-100	0.05	1.44
89-10-20	8.75	0	0	-100	0.05	0.88
	13.50	420	12	-97	0.21	1.39
	14.33	810	25	-97	0.21	1.44
	16.50	320	111	-65	0.40	1.61
	17.00	320	107	-67	0.48	1.67
89-10-21	17.00	110	0	-100	0.20	2.24
89-10-22	13.50	70	0	-100	0.12	1.91
89-11-15	11.50	330	0	-100	1.58	3.32
	15.50	270	0	-100	1.06	3.31
89-11-16	10.50	50	0	-100	0.33	4.51
89-11-17	11.50	210	0	-100	0.61	4.41

Table 6.18: Predicted Sediment Yields at Rigaud

Date (Yr-Mo-Da)	Observed (t)	Predicted (t)
89-06-10	6.680	3.394
89-10-20	12.148	2.584
89-11-14	35.435	0.331
89-11-16	119.034	6.920

Other studies also revealed the tendency of ANSWERS to underpredict sediment yield (Bingner et al., 1989, Griffin et al., 1988, Von Euw et al., 1989). Exact values of sediment yield are, however, less important than relative ones for soil conservation purposes. A model is useful as long as it can accurately predict the relative effect of management practices on soil loss. The sensitivity analysis performed on the sediment component of ANSWERS demonstrated that this model responds well to changes in management practices.

The underpredictions of sediment yield at St-Dominique and Rigaud are not as severe when we consider the approximate nature of the observed values. It must be remembered that the linear model used to interpolate between observed concentrations is only a rough approximation.

It may be concluded that ANSWERS can be used to analyze the effects of soil conservation practices at the St-Dominique and Rigaud watersheds. The obtained sediment yields should in this case be considered good on a relative basis only, as the model does not predict them accurately.

6.2.4. Summary of the Validation

The runoff and sediment components of the ANSWERS model were tested on two western Quebec watersheds. Twenty events were used to validate the runoff component at St-Dominique and four events were used at Rigaud. A seasonal adjustment of the infiltration parameters of Holtan's equation was performed based on observed rainfall-runoff relationships. It was found that ANSWERS gives reasonable estimates of peak flows, runoff volumes and times to peak. ANSWERS was found to give better predictions at St-Dominique than at Rigaud. The limited amount of data available for Rigaud was however not sufficient to verify this hypothesis on a long-term basis.

The sediment concentration and yield predictions of ANSWERS were generally better at St-Dominique than at Rigaud. The yields were always underpredicted. The model was nevertheless considered applicable for soil conservation purposes because it responds well to changes in input parameters and can therefore be used to assess the relative sediment yield due to various management practices.

6.3. Expert System Development

The 11 soil conservation practice selection rules presented in Chapter 5, were translated into PROLOG clauses and formed into a working expert system. The expert system was then tested by going through a short consultation session. For example, to the question "what conservation practices are applicable to a level corn field on Courval sandy loam ?", the system answered: conservation tillage, deep tillage and crop rotation. This demonstrated adequate functioning of the program. Further validation was provided by the watershed scale examples of the next section.

6.4. Application of the Decision Support System

The Decision Support System was used to generate soil conservation maps for the watersneds of St-Dominique and Rigaud. A 50% reduction in sediment yield and average erosion rate was targeted. A relative rather than absolute reduction was chosen because of the earlier observation that ANSWERS does not accuracely predict sediment yield. The conservation maps depicted management practices applicable at different locations within the basins.

The process started with an assessment of erosion sources driven by the intense rain storm of July 19, 1989, recorded at Harrow, Ontario (Figure 6.9). An arbitrary soil loss threshold of 1.0 t/ha was used to target erosion hot spots. This value is lower than the recommended maximum of 4.5 t/ha for renewable soils with rooting depths between 25 and 51 cm (Hall et al., 1985). A lower value is justified since ANSWERS underpredicts sediment yield.

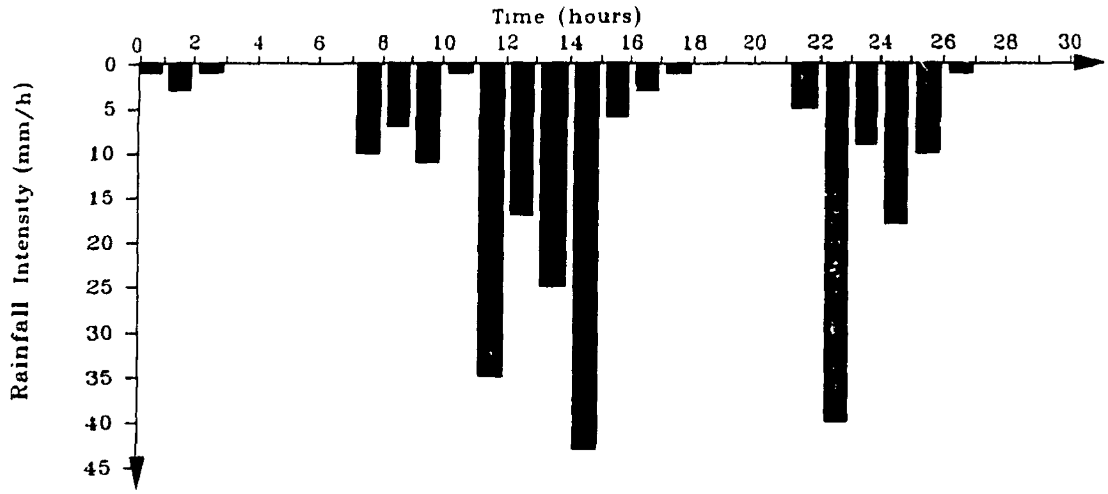


Figure 6.9. Rain Storm of July 19th, 1989

Erosion control practices were then selected by the expert system. The system selected more than one appropriate practice for each cell. The owner of each targeted plot should in theory have been contacted for making a final selection. This approach was not followed because of the theoretical nature of the study. Single practices were selected on different bases. If a filter strip was applicable to a cell then it was implemented in addition to any other selected practice. The owner of the Kramer nursery of the St-Dominique basin had expressed an interest in subsoiling. This tree nursery is located in the southern part of the basin and occupies 14% of its surface. If the considered cell was a tree nursery and deep tillage was applicable then deep tillage was chosen. In some cases the practices were homogeneous for all cells adjacent to a given cell. The study cell was therefore assigned the same practice as the neighbouring cells. In all other cases a choice was made at random between the appropriate practices.

ANSWERS was used to validate the conservation maps. The effect of conservation tillage was modeled by increasing the steady-state infiltration rate and maximum infiltration rates of the soils by 25%, and by increasing the surface roughness by 20% as suggested in the ANSWERS manual (Beasley et al., 1981). The effect of surface residues was reflected by a change in the USLE C parameter. Values of C=0.15, C=0.36 and C=0.25 were selected for corn, vegetables and tree nurseries respectively. Deep tillage was modeled as a 50% increase in the infiltration parameters. The effect of contour farming was modeled by a change in the USLE P factor. A value of P=0.55 was selected. Crop rotation was modeled by lowering the USLE C parameter of each crop to take into account the effect of a green manure. Planned grazing was assumed to lower the C value of the cell to that of a hay field. A width of 25 m was assumed for all filter strips. Terraces were assumed to have a surface slope of 1%.

6.4.1. St-Dominique Watershed

The predicted response of the St-Dominique watershed to the design storm is presented in Table 6.19. The predicted sediment yield was 314 tonnes which is higher than any of the observed values for this watershed. The total amount of eroded soil was 542 tonnes. This erosion took place in 300 of the 868 basin cells. The average soil loss for these cells was therefore 1.8 tonnes.

TABLE 6.19: Response of the St-Dominique Watershed to the Design Storm

Total Erosion	542.1	tonnes
Maximum Erosion Rate	8.956	t/ha
Average Erosion Rate	1.807	t/ha
Sediment Yield	313.7	tonnes
Maximum Concentration	3.686	g/l

The spatial distribution of erosion within the basin is presented in Figure 6.10. Most of the erosion sources were located in the southern half of the basin. This was due in part to the lower infiltration rates. A large amount of erosion came from a band 700 m wide which runs from east to west. This band corresponds to the tree nursery. The excessive erosion in this area was due to a non existent weed cover and to erodible soils. Table 6.20 summarizes the soil loss in the St-Dominique basin for various soil type-land use combinations.

TABLE 6.20: Total Erosion for Soil Type-Land Use Combinations in St-Dominique

LAND USE	EROSION (tonnes) SOIL: Cv	Ro	S	Za	TOTAL
CORN	27.174	46 708	43.280	0.151	117.313
GRAIN	0.927	7.578	--	--	8.505
HAY	1.731	0.488	2.973	--	5.192
PASTURE	8.605	7.949	19.094	--	35.648
TREE NURSERY	135.402	168.794	46.721	--	350.917
VEGETABLE	--	--	24.501	--	24.501
TOTAL	173.839	231.517	136.569	0.151	542.076

Cells with high erosion rates are large contributors to basin yield even if they are present in small quantities. Figure 6.11 illustrates this point. The number of cells with a given erosion rate decreased somewhat exponentially as the erosion rate increased. However, the contribution of these cells to total erosion did not decrease as rapidly. Fifty-one percent of the eroded cells lost more than 1 tonne of soil. These cells occupied an area of 1.5 km^2 or 17.6% of the basin surface. They however contributed 88% to the total erosion of the basin. This shows that by reducing the soil loss in a small, well targeted portion of an agricultural watershed, total erosion can be substantially reduced.

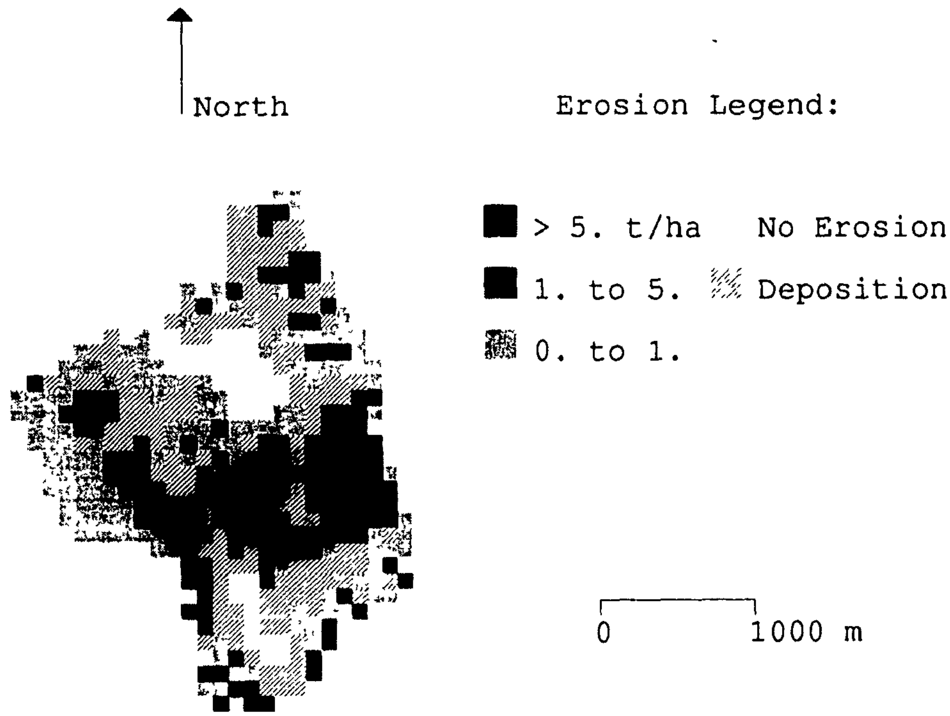


Figure 6.10: Erosion Source Map of St-Dominique

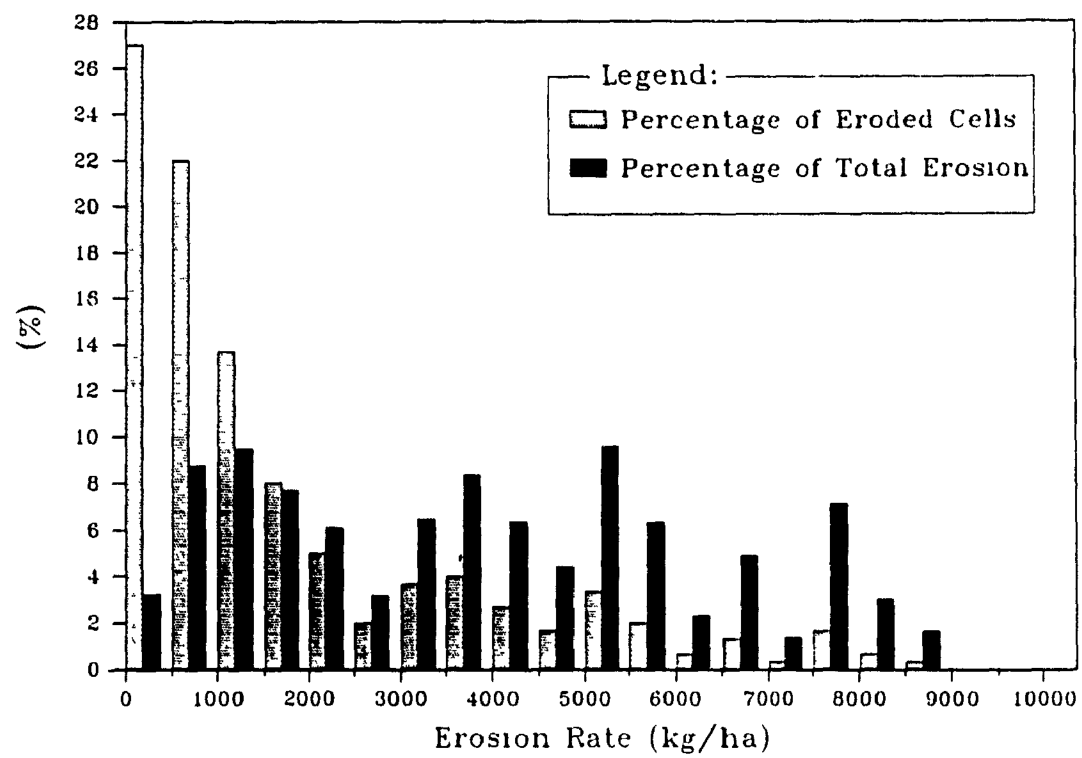


Figure 6.11: Percentage of Cells and Contribution to Total Erosion Vs Erosion Rate for the Design Storm, at St-Dominique

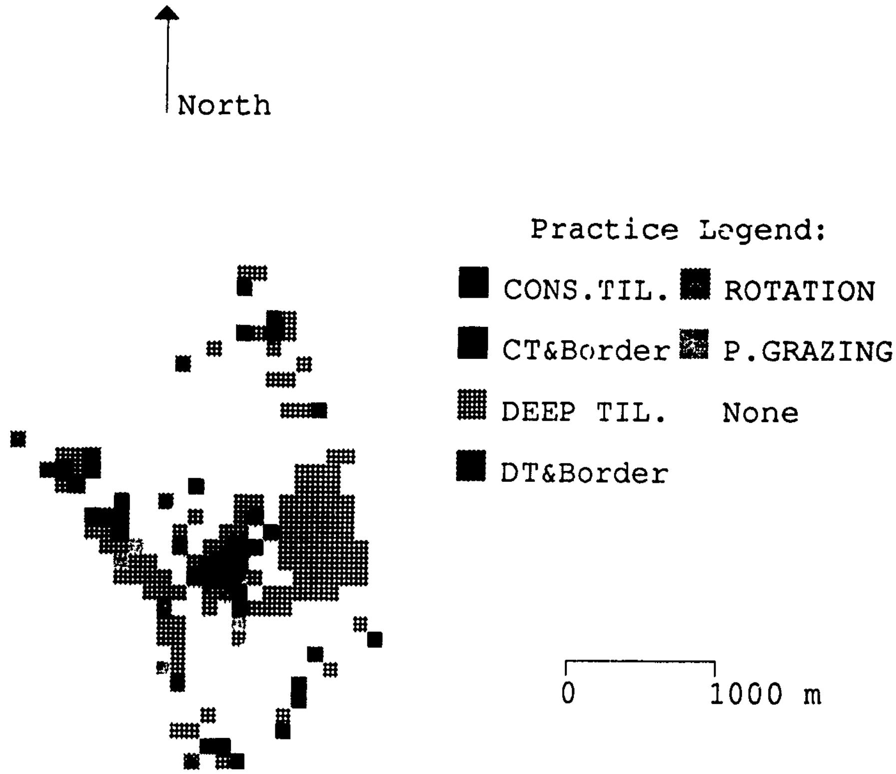


Figure 6.12: Soil Conservation Map for St-Dominique

The conservation practices selected by the expert system are presented in Figure 6.12. The system chose conservation tillage for 23 cells, deep tillage for 115 cells, crop rotation for 12 cells and planned grazing for 4 cells. Filter strips were added to 9 cells. The reasons for the predominance of deep tillage in this watershed were that most soils consist of shallow layers of sandy loam over clay subsoil and that the tree nursery was the most eroded section.

The effect of the conservation practices on the response of the St-Dominique watershed to the design storm is shown in Table 6.21. The sediment yield was 153 tonnes and the total erosion was 267 tonnes. The average erosion rate was 0.881 t/ha. The reductions were 50.7% and 51.2% for sediment yield and average erosion rate respectively. According to ANSWERS and based on our modeling assumptions we can state that our target reduction of 50% in both sediment yield and average erosion rate was achieved in the St-Dominique watershed, through the implementation of the selected conservation practices.

TABLE 6.21: Effect of Soil Conservation Practices on Erosion at St-Dominique

Total Erosion	267.1	tonnes
Maximum Erosion Rate	5.994	t/ha
Average Erosion Rate	0.881	t/ha
Sediment Yield	152.7	tonnes
Maximum Concentration	2.372	g/l

The selected soil conservation practices lowered the number of highly erodible cells substantially. Figure 6.13 presents the spatial distribution of erosion when the conservation practices are implemented. There were only two cells with more than 5 t/ha of erosion. Most of the eroded cells (71%) had rates below 1 t/ha. Figure 6.14 further shows that the contribution of cells with high erosion rates to total erosion decreased very rapidly as the erosion rate increased. This indicates that additional conservation effort should be concentrated on cells with lower erosion rates.

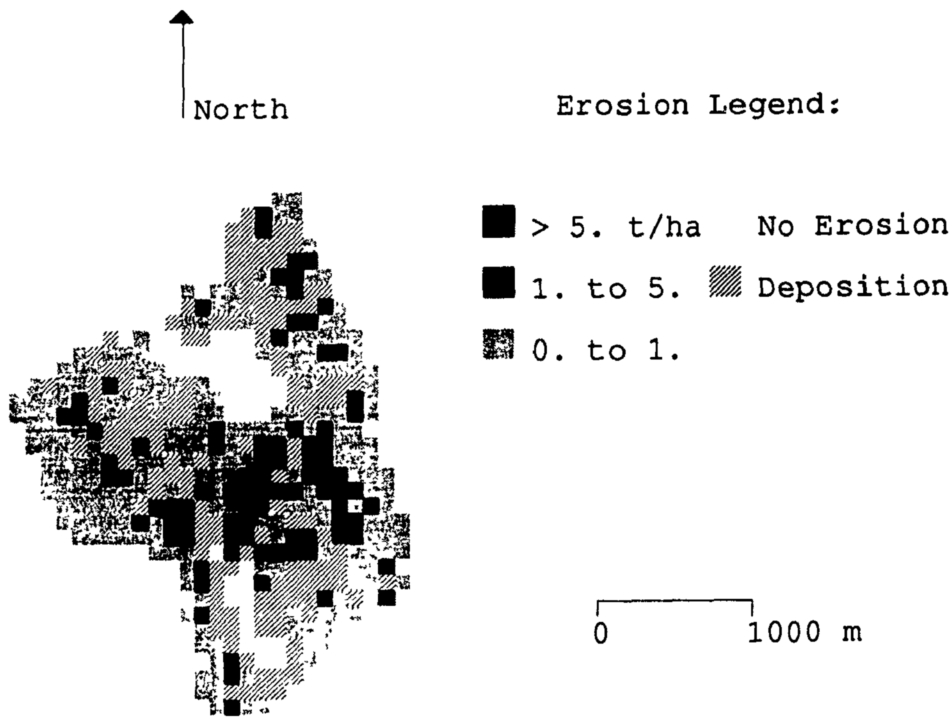


Figure 6.13: Effect of Conservation Practices at St-Dominique

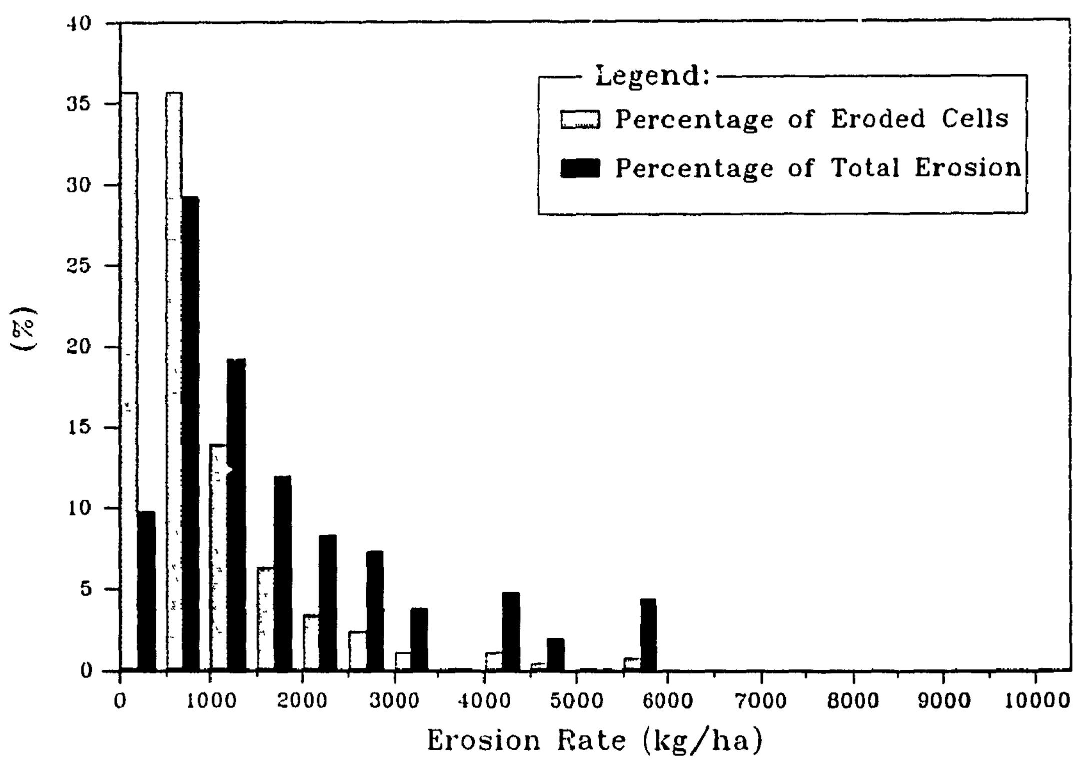


Figure 6.14: Percentage of Cells and Contribution to Total Erosion Vs Erosion Rate with Conservation Practices, at St-Dominique

6.4.2. Rigaud Watershed

The response of the Rigaud watershed to the design storm is presented in Table 6.22. The predicted sediment yield was 531 tonnes. Once again this was higher than any of the observed sediment yields for this basin. The total erosion was 822 tonnes and the average erosion rate was 2 t/ha. These values were all higher than those obtained for the St-Dominique watershed. This was probably due to the relatively steeper topography observed in Rigaud.

TABLE 6.22: Effect of Soil Conservation Practices on Erosion at Rigaud

Total Erosion	821.9	tonnes
Maximum Erosion Rate	10.289	t/ha
Average Erosion Rate	2.034	t/ha
Sediment Yield	531.2	tonnes
Maximum Concentration	2.732	g/l

Corn grown on Ste-Rosalie clay was seen to be the greatest contributor to erosion in the Rigaud basin (Table 6.23). Surface runoff erosivity was a major factor because of the greater slopes. Row crops such as corn, with low surface roughness coefficients were therefore more susceptible to erosion.

TABLE 6.23: Total Erosion for Soil Type-Land Use Combinations in Rigaud

	EROSION (tonnes)			
LAND USE SOIL:	Pg	Ro	U	TOTAL
CORN	0.018	702.952	--	702.970
GRASS	--	--	0.483	0.483
HAY	--	25.587	0.401	25.988
PASTURE	--	36.165	--	36.165
TREE NURSERY	--	28.881	--	28.881
VEGETABLE	--	27.455	--	27.455
TOTAL	0.018	821.040	0.884	821.942

The spatial distribution of erosion is shown in Figure 6.15. Most of the erosion sources were located in the south-western portion of the basin on Ste-Rosalie clay soil. This soil was observed to have a relatively low infiltration rate and was therefore prone to surface runoff generation and erosion.

The effect of cells with high erosion rates on total erosion is well demonstrated on this watershed. Figure 6.16 shows that 59% of the eroded cells lost soil at a rate lower than 1 t/ha. These cells, however, contributed only 7% to the total erosion in the basin. Most of the eroded soil came from cells which had erosion rates in excess of 5 t/ha. This indicates once again that conservation efforts on small areas of the basin can produce significant benefits. The target area for soil conservation (cells with more than 1 t/ha of soil loss) consists of 164 cells or 10% of the watershed area.

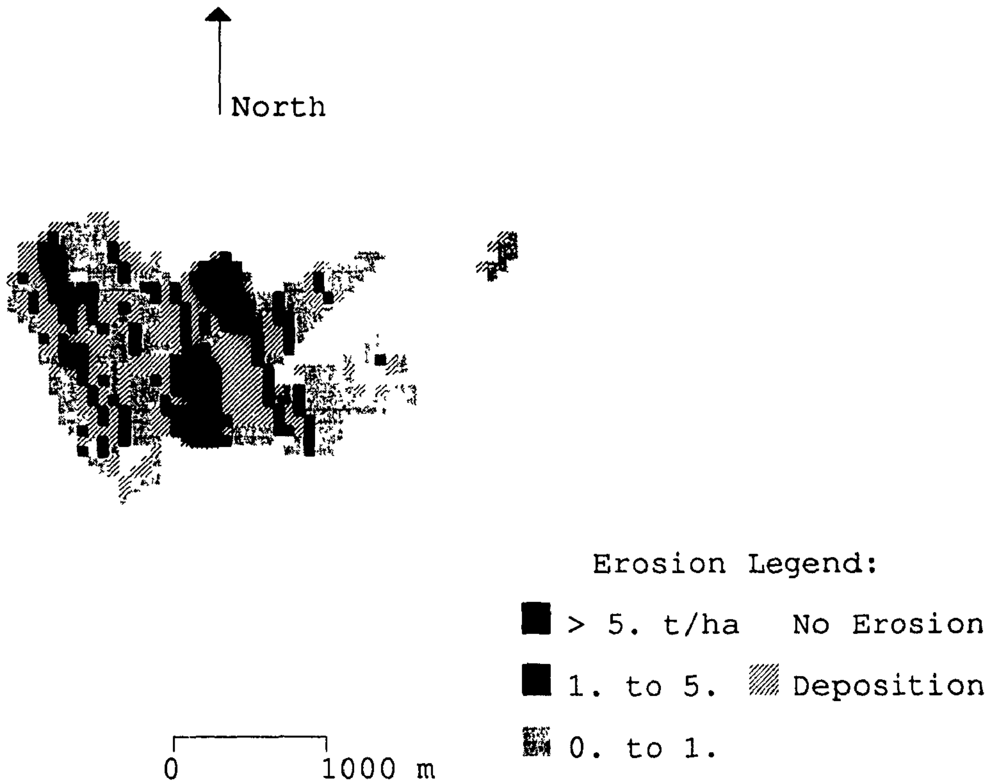


Figure 6.15: Erosion Source Map of the Rigaud Watershed

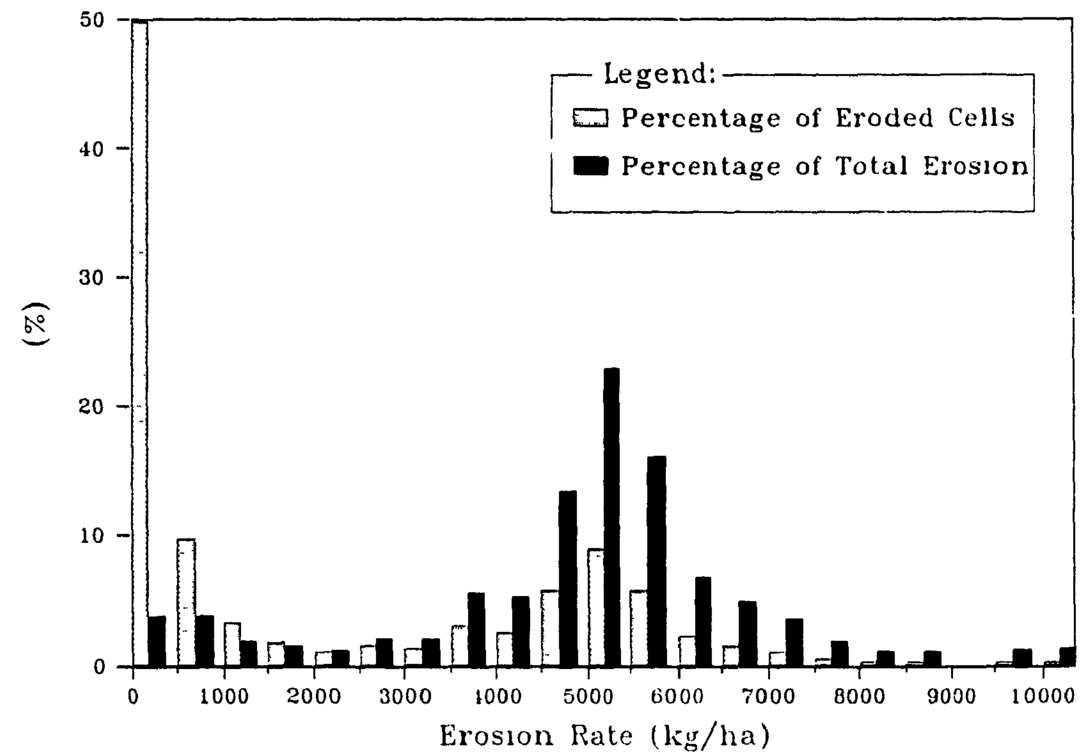


Figure 6.16: Percentage of Cells and Contribution to Total Erosion Vs Erosion Rate for the Design Storm, at Rigaud

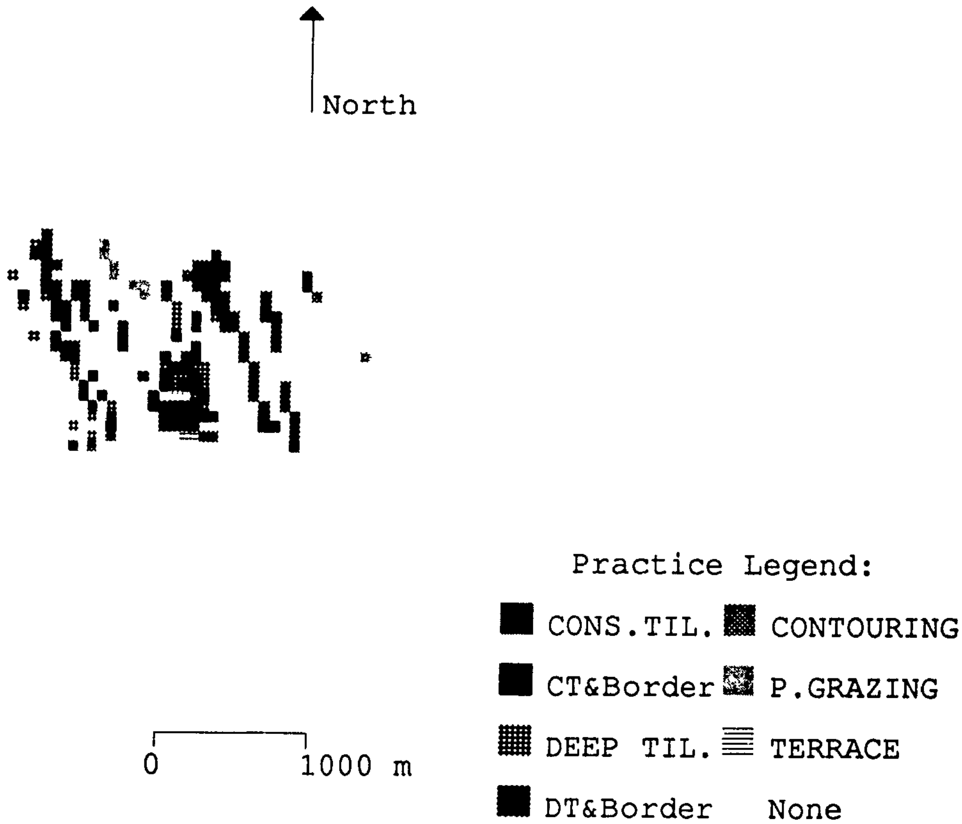


Figure 6.16: Soil Conservation Map for Rigaud

The selected conservation practices are shown in Figure 6.17. Conservation tillage was selected for 40 cells, deep tillage was chosen for 37 cells, contour farming was selected for 78 cells, planned grazing was advised for 8 cells and terraces were chosen for 2 cells. Field borders were added to 17 cells. The reason for the predominance of contour farming in this basin was its topography. The average slope of the basin is 2.1%.

The reduction of basin erosion due to the conservation practices is shown in Table 6.24. The sediment yield was 267 tonnes and the total erosion was 396 tonnes. The average erosion rate was 0.9 t/ha. The reductions in sediment yield and average erosion rate were 49.7% and 55% respectively. Therefore, the target reductions in sediment yield and average erosion rate are met by the selected soil conservation practices.

TABLE 6.24: Response of the Rigaud Watershed to the Design Storm with Soil Conservation

Total Erosion	396.4	tonnes
Maximum Erosion Rate	5.256	t/ha
Average Erosion Rate	0.915	t/ha
Sediment Yield	267.0	tonnes
Maximum Concentration	1.701	g/l

The spatial distribution of erosion with soil conservation practices is shown in Figure 6.18. There were only two cells for which the erosion rate was still above 5 t/ha. The erosion spectrum of the basin shifted towards lower erosion rates (Figure 6.19). Sixty-seven percent of the affected cells lost less than 1 tonne. These cells contributed 22% to the total erosion of the basin. Additional conservation effort should focus on cells with lower than 2.5 t/ha since they produced the largest amount of erosion.

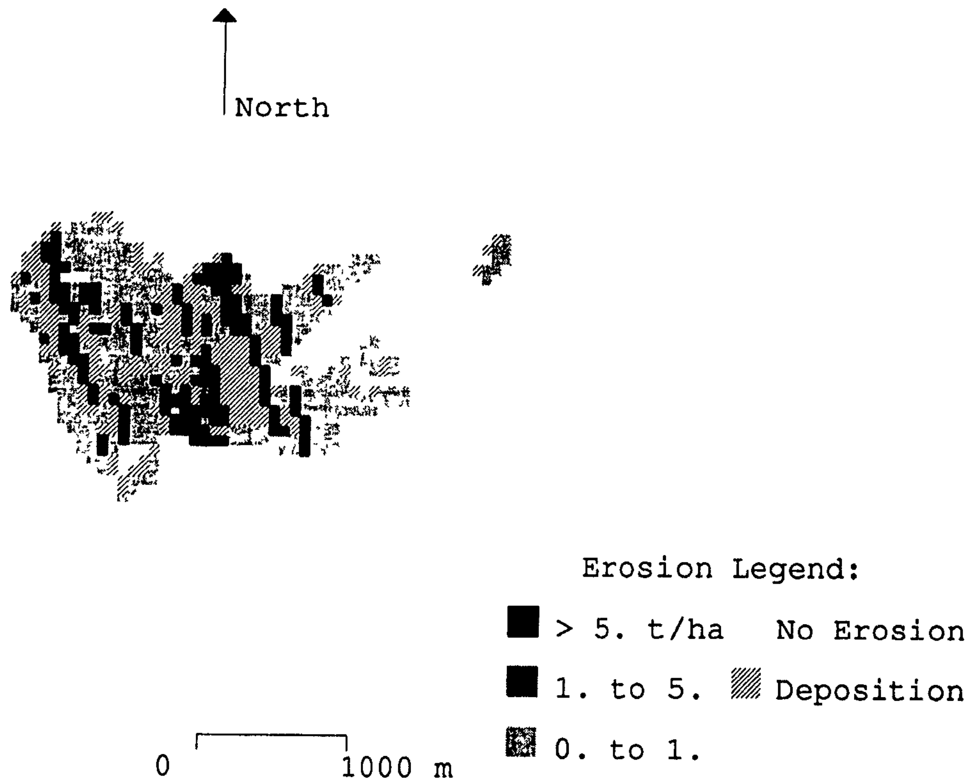


Figure 6.18: Effect of Conservation Practices at Rigaud

Figure 6.18: Effect of Conservation Practices at Rigaud

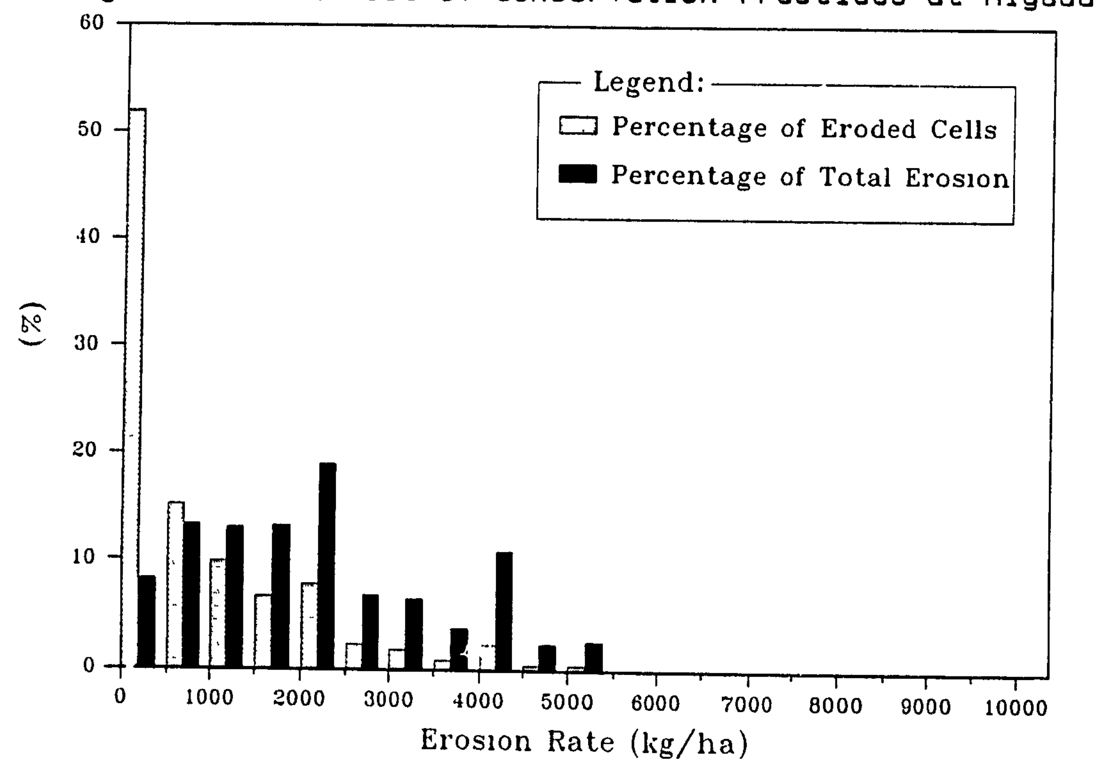


Figure 6.19: Percentage of Cells and Contribution to Total Erosion Vs Erosion Rate for With Soil Conservation, at Rigaud

7. SUMMARY AND CONCLUSIONS

Soil conservation is the key to ensuring a plentiful supply of food in a sustainable and environmentally sound way. It is, however, difficult to target erosion sources and select appropriate conservation practices in rural regions. Decision support systems are one answer to this problem.

A decision support system which integrates a geographical information system, distributed parameter hydrologic model and expert system was developed for selecting appropriate soil conservation practices on a watershed scale. The DSS was applied to the design of soil conservation maps for two rural watersheds in western Quebec.

The GIS was raster based with a cell size of one hectare. Data representing both watersheds were managed by this system. A composite analysis was performed to assess the heterogeneity of the basins. The information stored in the GIS was also used to prepare input files for simulating the response of the study watersheds to rainfall events.

A sensitivity analysis of the hydrologic model ANSWERS was performed, to assess the effects of 20 input parameters on runoff and sediment prediction.

The hydrologic component of ANSWERS was validated on 20 events that occurred in the St-Dominique watershed and 4 events that occurred in the Rigaud watershed.

The sediment detachment and transport components of ANSWERS were tested on the events that occurred in 1989 in both watersheds. More data would however be needed to obtain a reliable assessment of the applicability of these components of the model to the study region.

An expert system was developed to select appropriate soil conservation practices of eroded fields. The universe of discourse was defined and the soil conservation rules were formalized into predicate calculus clauses. The expert system was implemented in PROLOG.

The decision support system formed by the GIS, ANSWERS and the expert system was applied to the design of soil conservation plans for the two study watersheds. Sources of erosion within the St-Dominique and Rigaud basins were targeted using ANSWERS. A design storm with a return period of 25 years was used to drive the process. It was decided that conservation efforts would be focused on cells with more than one tonne of erosion. The goal of the soil conservation efforts was a reduction of 50% in sediment yield and an equal reduction in average erosion rate.

Appropriate soil conservation practices were selected by the expert system for each targeted cell in the study region. The expert system selected these practices based on eleven rules that considered topography, land use and soils of the eroded cells.

The selected soil conservation practices were validated using the ANSWERS model. The target reductions of 50% in sediment yield and average erosion rate were achieved.

Based on the results of this study, the following conclusions were drawn:

1. A decision support system which integrates a GIS,

distributed parameter hydrologic model and expert system is more powerful than any of the previous methods of designing soil conservation systems on watershed scales.

2. A decision support system can help non-expert decision makers to make effective soil conservation plans on a watershed scale.

3. Soil conservation efforts should be focused on a limited number of well targeted highly erodible cells for maximum benefit.

4. Rural basins are very heterogeneous from an hydrologic standpoint. Detailed modeling of the behaviour of these watersheds therefore necessitates a distributed parameter approach.

5. A one hectare cell size is suitable for the representation of rural basins in a GIS. A smaller cell size, however, increases the precision with which land use boundaries and streams are located.

6. The runoff generation and sediment transport components of ANSWERS are most influenced by terrain slope and the steady-state infiltration rate of the soils.

7. Sediment yield predictions are greatly influenced by runoff predictions in the ANSWERS model.

8. ANSWERS predictions of runoff parameters from measured properties are reasonable provided that a seasonal adjustment is applied to spring and fall events.

9. ANSWERS underpredicted sediment yield.

10. Soil conservation in western Quebec can be performed using ANSWERS if relative reduction ratios are used as a goal.

11. An expert system can select soil conservation practices for a large amount of eroded cells in a short amount of time and without becoming tired or bored. Expert systems are therefore key components in a soil conservation DSS which necessitates large scale applications of knowledge.

8.RECOMMENDATIONS FOR FURTHER RESEARCH

The results of this study demonstrated the need for additional research in a few specific domains:

1. The integration of the GIS, expert systems and ANSWERS into the framework of a DSS permitted soil conservation to be executed effectively on a watershed scale. Other ways in which spatial databases, artificial intelligence and modeling paradigms can be integrated should be investigated. A DSS could, for example, contain many different hydrologic models and use an expert system to select which model is the most appropriate for a given study case.

2. The DSS in this thesis used a rule based expert system to model human decision processes in soil conservation practice selection. Other knowledge representation approaches could probably be used. The applicability of frames, and semantic network based expert systems should be investigated. Research on the application of neural networks to soil conservation planning should also be performed.

3. The reasons for ANSWERS underprediction of sediment yield should be investigated. The constants in the transport and detachment equations are probably too low. Appropriate values should be determined through field experimentation in southwestern Quebec.

9. REFERENCES

Abelson, H., Sussman,G.J. and J. Sussman. 1987. Structure and Interpretation of Computer Programs. The MIT Press, Cambridge Massachussets.

Adams J.R., Logan T.J., Cahill T.H., Urban D.R. and Yaksich S.M. 1982. A Land Resource Information System (LRIS) for water quality management in the Lake Erie Basin. Journal of Soil and Water Conservation, 37(1):45-50.

Alty, J.L. and M.J. Coombs. 1986. Systemes Experts Concepts et Exemples. MASSON, Paris.

Arnold, J.G. and N.B. Sammons. 1988. Decision Support System for Selecting Inputs to a Basin Scale Model. Water Resources Bulletin, Vol.24, No.4, p.749-759.

Avery T.E. and Berlin G.L. 1985.Interpretation of Aerial Photographs. 4th ed. Burgess Publishing Co., N.Y..

Beasley D.B. and Huggins L. F. 1983. ANSWERS User's manual. United States Environmental Protection Agency Region V, Chicago, Il. USA.

Beasley, D.B., L.F. Huggins and E.J. Monke. 1980a. ANSWERS: A Model for Watershed Planning. Transactions of the ASAE. pp.938-944.

Beasley, D.B., L.F. Huggins, E.J. Monke. 1980b. Planning For Water Quality Using the ANSWERS Approach. in Hydrologic Transport Modeling Symposium. American Society of Agricultural Engineers, St-Joseph, MI. USA. pp21-30.

Beasley R.P., Gregory, J.M. and T.R. McCarty. 1984. Erosion and Sediment Pollution Control. 2nd edition. Iowa State University Press, Ames.

Bedient, P.B. and W.C. Huber. 1988. Hydrology and Floodplain Analysis. Addison-Wesley, Don Mills, Ont.

Bingner, R.L. 1989. Using Graphic Interfaces to Present the Results of Erosion Models. ASAE Paper No.89-2022. ASAE, St-Joseph, Mi. USA.

Bingner, R.L., C.E. Murphee and C.K. Mutchler. 1989. Comparison of Sediment Yield Models on Watersheds in Mississippi. Transactions of the ASAE, Vol.32(2). p529-534.

Blough, R.F., A.R. Jarret, J.M. Hamlett and M.D. Shaw. 1989. Runoff and Erosion From Slit, Conventional, and Chisel Tillage Under Simulated Rainfall. ASAE Paper No. 89-2115. ASAE, St-Joseph, MI. USA.

Borgelt, S.C. 1988. Geographic Information Systems for On-Farm Use. Paper No. 88-1606. American Society of Agricultural Engineers. St-Joseph, MI. USA.

Borland (ed.). 1988. Turbo PROLOG 2.0 User's Guide. Borland International, Scotts Valley, Ca.

Bosworth, D.A. and A.B. Foster. 1982. Approved Practices in Soil Conservation. The Interstate Printers and Publishers Inc.

Brandt, R.C., H.A. Elliot and C.A. Markel. 1989. Application of GIS for Municipal Sludge Management. ASAE Paper No.89-2655. ASAE, St-Joseph, MI. USA.

Breve, M.A., D.L. Thomas, J.M. Sheridan, D.B. Beasley and W.C. Mills. 1989. A Preliminary Evaluation of ANSWERS in the Georgia Coastal Plains. ASAE Paper No.89-2044. ASAE, St-Joseph, MI. USA.

Burrough, P.A. 1987. Principles of Geographical Information Systems for Land Resources Assessment. Clarendon Press, Oxford.

Charniak, E., McDermott, D.V. 1985. Introduction to Artificial Intelligence. Addison-Wesley Pub. Co.

Chen, W-J. 1986. "An Expert System for the Estimation of Parameter Values of a Water Quality Model". in Proceedings of the 1986 IEEE INternational Conference on Systems, Man, and Cybernetics pp.236-240.

Clarke, N.D. and T.J. Vyn. 1989. Conservation Tillage Expert System for Southwestern Ontario: Multiple Experts and Decision Techniques. ASAE Paper No.89-2015. ASAE, St-Joseph, MI. USA.

Clocksin, W.F. and C.S. Mellish. 1987. Programming in Prolog. 3rd ed. Springer Verlag, Berlin.

Cook D.J., Dickinson W.T. and Rudra R.P. 1985. GAMES User's manual. School of Engineering University of Guelph.

Coulson, R.N., Folse, L.J. and D.K. Loh. 1987. Artificial Intelligence and Natural Resource Management. Science, Vol.23 p262-267

Cunningham R. L., Petersen G. W. and Sacksteder C. J. 1984. "Microcomputer delivery of soil survey information." In Journal of Soil and Water Conservation, July-August 1984

Davis, M.W. 1988. Applied Decision Support. Prentice-Hall, Englewood Cliffs, New Jersey.

Dickey, E.C., J.K. Mitchell and J.N. Scarborough. 1979. The Application of Hydrologic Models to Small Watersheds Having Mild Topography. Water Resources Bulletin, Vol.15, No.6, p1753-1769.

Dillaha, T.A. 1989. Water Quality Impacts of Vegetative Filter Strips. ASAE Paper No.89-2043. ASAE, St-Joseph MI. USA

Dillaha, T.A., Byler R.K., Awa T.W., Jones P.N., Heatwole C.D., Mostaghimi S. and V.O. Shanholtz. 1987. Estimating Sediment Delivery Ratios using Geographic Information Systems. ASAE Paper No. 87-2106. American Society of Agricultural Engineers, St- Joseph, MI. USA.

Dillaha, T.A. and D.B. Beasley. 1983. Distributed Parameter Modeling of Sediment Movement and Particle Size Distributions. Transactions of the ASAE. pp1766-1772,1777.

Dinckinson, W.T., R.P. Rudra anc E.L. Von Euw. 1989. Sensitivity of a Non_Point_Source Model to Rainfall Data. ASAE Paper No.89-2037. ASAE, St-Joseph, MI. USA.

Edwards W.M., R.R. Van Der Ploeg and W. Ehlers. 1979. A Numerical Study of the Effects of Noncapillary-sized Pores Upon Infiltration. Soil Sci. Soc. Am. J. 43:851-856.

Elliot, Wm.J., Laflen, J.M. and K.D. Kohl. 1989. Effect of Soil Properties on Soil Erodibility. ASAE Paper No. 89-2150. ASAE St-Jospeh, MI. USA.

Engel, B.E., Beasley, D.B. and Barrett, J.R. 1988. "Estimating Soil Erosion Using Multiple Knowledge Sources". pp 297-306. in Modeling Agricultural, Forest, and Rangeland Hydrology. American Society of Agricultural Engineers. St-Joseph Michigan.

Engman, E.T. 1986. Roughness Coefficients for Routing Surface Runoff. Journal of Irrigation and Drainage Engineering, Vol.112, No.1, p39-53.

Enright, P.E. 1988. Simulation of Rainfall Excess on Flat Rural Watersheds in Quebec. Master of Science Thesis, Department of Agricultural Engineering, McGill University, Montreal, Canada.

Enright, P. E. and C.A. Madramootoo. 1989. Evaluation of a Modified Green-Ampt Infiltration Model on a Watershed Scale. ASAE Paper No. 89-2166. ASAE, St-Joseph, MI. USA.

Environment Canada, Atmospheric Environment Service. 1987. The Climate of Montreal. Ottawa.

Feezor, D.R., Hirschi, M.C. and B.J. Lesikar. 1989. Effect of Cell Size on AgNPS Prediction. ASAE Paper No. 89-2662. ASAE, St-Joseph, MI. USA.

Flores I.1981. Database architecture. Van Nostrand Reinhold Co., N.Y.

Forsyth, R. (ed.). 1984. Expert Systems, Principles and Case Studies. Chapman and Hall Computing. New York.

Foster, G.R. 1976. Sedimentation, General. in Proceedings of the National Symposium on Urban Hydrology, Hydraulics, and Sediment Control. University of Kentucky.

Gardarin G. and Gelenbe E. ed.1984. New applications of databases. London: Academic Press Inc. Ltd. N.Y.

Genesereth, M.R. and N.J. Nilsson. 1987. Logical Foundations of Artificial Intelligence. Morgan Kaufmann Publishers Inc. California.

Giannesini, F., H. Kanoui, R. Pasero and M. Van Caneghem. 1985. Prolog. InterEditions, Paris.

Gilliland M. W. and Baxter-Potter W. 1987. A Geographic Information System to predict Non-Point Source Pollution Potential. Water Resources Bulletin, 23(2):281-291.

Griffin, M.L., D.B. Beasley, J.J. Fletcher and G.R. Foster. 1988. Estimating Soil Loss on Topographically Non-Uniform Field and Farm Units. Journal of Soil and Water Conservation, 43(4):326-331.

Guy, B.T. and W.T. Dickinson. 1989. Sediment Transport Capacity of Overland Flow Under Rainfall. ASAE Paper No. 89-2048. ASAE, St-Joseph, MI. USA.

Haan, C.T., B.J. Fethi and Nofziger, D.L. 1989. Impact of Parameter Uncertainty on Infiltration. ASAE Paper No. 89-2164. ASAE, St-Joseph, MI. USA.

Hall, G.F., T.J. Logan and K.K. Young. 1985. Criteria for Determining Tolerable Erosion Rates. p.173-189. in, Soil Erosion and Crop Productivity. R.F. Follett and B.A. Stewart, eds. American Society of Agronomy, Inc. Crop Science Society of America, Inc. Soil Science Society of America.

Heatwole, C.D. 1987. Conservation Planning Using Expert Systems and Geographic Information Systems. Paper No. 87-5011. American Society of Agricultural Engineers. St-Joseph. Michigan.

Heatwole, C.D., Dillaha, T.A. and S. Mostaghimi. 1987. Integrating Water Resource Tools: Process Models, Geographic Information Systems and Expert Systems. Paper No. 87-2043. American Society of Agricultural Engineers. St-Joseph Michigan.

Hession, W.C., V.O. Shanholtz, S. Mostaghimi and T.A. Dillaha. 1987. Extensive Evaluation of the Finite Element Storm Hydrograph Model. ASAE Paper No.87-2570. ASAE, St-Joseph MI. USA.

Hoogmoed, W.B. and J.Bouma. 1980. A Simulation Model for Predicting Infiltration into a Cracked Clay Soil. Soil Sci. Soc. Am. J. 44:458-461.

Hudson, N. 1981. Soil Conservation. 2nd ed. Cornell University Press, Ithaca, N.Y.

Huggins, L.F. and J.R. Burney. 1982. Surface Runoff, Storage and Routing. in Hydrologic Modeling of Small Watersheds. American Society of Agricultural Engineers, St-Joseph, MI. USA.

Hurni, H. 1988. Principles of Soil Conservation for Cultivated Land. Soil Technology, 1:101-106.

Jasa, P.J. and E.C. Dickey. 1989. Subsoiling Effects on Erosion and Runoff. ASAE Paper No.89-2158. ASAE, St-Joseph MI. USA.

Kenimer, A.L., J.K. Mitchell and A.S. Felsot. 1989. Pesticide Losses as Affected by Tillage System and Row Direction. ASAE Paper No.89-2118. ASAE, St-Joseph MI. USA.

Ketcheson, J. 1977. Conservation tillage in eastern Canada. Journal of Soil and Water Conservation, Jan-Feb. 1977. pp.57-60.

Khuri, R.S., Shoup, W.D., Peart, R.M. and R.L. Kilmer. 1988. Expert System for Interpreting Citrus Harvest Simulation. Transactions of the ASAE, 4(3):275-280.

Kirkby, M.J. 1980. The Problem. p1-16. in, Soil Erosion. M.J. Kirkby and R.P.C. Morgan, eds. Wiley Interscience Publication, John Wiley and Sons, Toronto.

Lajoie, P. and P. Stobbe. 1951. Etude des Sols des Comtes de Soulanges et de Vaudreuil. Ministere Federal de l'Agriculture, Ottawa.

Lemmon, H. 1986. Comax: An Expert System for Cotton Crop Management. SCIENCE. 233:29-33.

Logan T.J., Urban D.R., Adams J.R. and Yaksich S.M. 1982. Erosion control potential with conservation tillage in the Lake Erie Basin: Estimates using the universal soil loss equation and the Land Resource Information System (LRIS). Journal of Soil and Water Conservation, 31(1):50-55.

Madramootoo, C.A., P. Enright and V.T.V. Nguyen. 1989. Is the Rational Method Reliable for Agricultural Watersheds? in, Channel Flow and Catchment Runoff. Proceedings of the International Conference for Centennial of Manning's Formula and Kuichling's Rational Formula. B.C. Yen ed., Department of Civil Engineering, University of Virginia.

Madramootoo, C.A. and P.E. Enright. 1988. Applicability of the SCS Equations for Runoff Prediction in the Ottawa-St.Lawrence Lowlands. Canadian Journal of Civil Engineering, 15(5):759-765.

Madramootoo, C.A., L. Laperriere and S.F. Barrington. 1988. Modeling Sediment Loss from a Quebec Watershed. In Modeling Agricultural, Forest, and Rangeland Hydrology. American Society of Agricultural Engineers, St-Joseph, MI. USA. pp264-270.

Madramootoo, C.A. 1988. Rainfall and Runoff Erosion Indices for Eastern Canada. Transactions of the ASAE,

McGregor, K.C., J.D. Greer, and G.E. Gurley. 1975. Erosion Control with No-Till Cropping Practices. Transactions of the ASAE pp.1918-1920.

McKinion, J.M. and H.E. Lemmon. 1985. Expert Systems for Agriculture. Computers and Electronics in Agriculture, 1 (1985) 31-40.

Meyer, L.D. and W.H. Wischmeier. 1969. Mathematical Simulation of the Process of Soil Erosion by Water. Transactions of the ASAE. pp754-758,762.

Microsoft Corporation (ed.). 1988. Microsoft QuickBASIC, Programming in BASIC.

Moldenhauer, W.C., W.H. Wischmeier and D.T. Parker. 1967. The Influence of Crop Management on Runoff, Erosion, and Soil Properties of a Marshall Silty Clay Loam. SOIL SCI.SOC.AMER.PROC.,VOL. 31, 1967, pp.541-546.

Monmonier M.S. 1982. Computer-assisted cartography. Prentice-Hall Inc., N.J.

Myers R.E. Microcomputer graphics for the IBM P.C.. 1984. Addison-Wesley Pub. Co., N.Y.

Needham, S. and B.Vieux. 1989. A GIS for AgNPS Parameter Input and Mapping output. ASAE Paper No.89-2673. ASAE, St-Joseph, MI. USA.

Nilsson, M. 1985. The World's Shortest Prolog Interpreter? in, Implementations of Prolog. p87-92. J.A. Campbell ed. John Wiley and Sons, Rexdale, Ont.rio.

Onstad, C.A. 1972. Soil and Water Losses as Affected by Tillage Practices. Transactions of the ASAE, 1972, pp.287-289.

Reisinger, T.W. and C.J. Davis. 1986. A Map-Based Decision Support System for Evaluating Terrain and Planning Timber Harvests. Transactions of the ASAE. Vol.29(5) p.1199-1203.

Roach, J., Virkar, R., Drake, C. and M. Weaver. 1987. An Expert System for Helping Apple Growers. Computers and electronics in Agriculture, 2 (1987) 97-108.

Robinson, V.B., Frank, A.U. and M.A. Blaze. 1986. Expert Systems and Geographic Information Systems: Review and Prospects. Paper No. 20948. American Society of Civil Engineers.

Robinson, V.B. and A.U. Frank. 1987. Expert Systems for Geographic Information Systems. Photogrammetric Engineering and Remote Sensing, Vol.53, No.10, October 1987, pp.1435-1441.

Roski S. Data structures on the IBM P.C.. Brady Communications Co., 1985

Ross, B.B., D.N. Contractor and V.O. Shanholtz. 1979. A Finite Element Model of Overland and Channel Flow for Assessing the Hydrologic Impact of Land-Use Change. Journal of Hydrology, 41(12):11-30.

Saheli, A.Pesant and R.Lagace. 1989. Evaluation of the USLE for Quebec. ASAE Paper No.89-. ASAE, St-Joseph MI. USA.

Schertz, D.L., Moldenhauer, W.C., Franzmeier, D.P. and H.R. Sinclair jr. 1985. Field Evaluation of the Effect of Soil Erosion on Crop Productivity. in Erosion and Soil Productivity. Proceedings of the National Symposium on Erosion and Soil Productivity. ASAE, St-Joseph, MI.

Schmoldt, D.L. and G.L. Martin. 1986. Expert Systems in Forestry: Utilizing Information and Expertise for Decision Making. Computers and Electronics in Agriculture, 1 (1986) 233-250.

Schwab G.O., Frevert R.K., Edminster T.W. and Barnes K.K. 1981. Soil and Water conservation engineering. 3rd ed., John Wiley and sons, N.Y.

Shanholtz V.O., Hellmund P.A., Byler R.K., Mostaghimi S., Collins E.R. and Yagow E.R. 1987. Virginia Chesapeake bay database for soil erosion estimations. ASAE Paper No.87-2109. ASAE, St-Joseph, MI. USA.

Skaggs, R.W. and R. Khaleel. 1982. Infiltration. In Hydrologic Modeling of Small Watersheds. American Society of Agricultural Engineers, St-Joseph, MI. USA.

Skaggs, R.W., L.E. Huggins, E.J. Monke and G.R. Foster. 1969. Experimental Evaluation of Infiltration Equations. Transactions of the ASAE pp822-827.

Sprague, R.H. and E.D. Carlson. 1982. Building Effective Decision Support Systems. Prentice-Hall of Canade Ltd. Toronto.

Steele, G.L. jr. 1984. COMMON LISP The Language. Digital Equipment Corporation.

Tan, Y.R. and S.F. Shih. 1989. GIS In Agricultural Landuse Study and Abandoned Well Assessment. ASAE Paper No.89-2657. ASAE, St-Joseph, MI. USA.

Townsend, C. 1987. Mastering Expert Systems with Turbo Prolog. H.W. Sams & Co., IN. USA.

Troeh, P.R., Hobbs, J.A. and R.L. Donahue. 1980. Soil and Water Conservation for Productivity and Environmental Protection. Prentice-Hall Inc., New-Jersey.

United States Department of Agriculture. 1985. National Handbook of Conservation Practices. Publication No. PB85-177137. U.S. Department of Commerce, VI. USA.

Van Caneghem, M. 1986. L'anatomie de Prolog. InterEditions, Paris.

Vieux, B.E., L.P. Herndon and R. Liston. 1989. GIS and Water Quality Modeling for Agricultural Resource Management Systems. ASAE Paper No.89-2184. ASAE, St-Joseph, MI. USA.

Vieux, B.E., V.F. Bralts and L.J. Segerlind. 1988. Hydrologic Modeling Using the Finite Element Method and Geographic Information Systems. ASAE Paper No.88-2090. ASAE, St-Joseph, MI. USA.

Von Euw, E.L., W.T. Dickinson and R.P. Rudra. 1989. Comparison of Two Non-Point-Source Pollution Models. ASAE PAper No.89-2038. ASAE, St-Joseph, MI. USA.

Whitaker, F.D., H.G. Heineman, and W.H. Wischmeier. 1973. Chemical weed controls affect runoff, erosion, and corn yields. Journal of Soil and Water Conservation, Jul.-Aug. 1973. pp.174-176.

Whittaker, A.D., Franti, T.G., Foster, G.R. and E.J. Monke. 1986. An AI Structure for Soil Erosion Modeling. Paper No. 86-5040. American Society of Agricultural Engineers. St-Joseph Michigan.

Winston, P.H. and B.K.P. Horn. 1989. LISP. 3rd ed. Addison-Wesley Pub. Co.

Wischmeier, W.H. and D.D. Smith. 1978. Predicting Rainfall Erosion Losses. Agriculture Handbook No.537. United States Department of Agriculture, Washington D.C.

Yagow E.R. and V.O. Shanholtz. 1987. Pilot implementation of a GIS approach to targeting. ASAE Paper No.87-2105. American Society of Agricultural Engineers, St. Joseph, Mich.

Yalin, Y.S. 1963. An Expression for Bed-Load Transportation. Journal of Hydraulics Division, Proceedings of the ASCE. 89(HY3):221-250.

Yoeli P. "Compilation of data for computer-assisted relief cartography." In Display and analysis of spatial data. Davis J.C. and Mc Cullagh M.K. eds., 1975

APPENDIX

RAIN STORM OF JULY 19, 1989, WHICH OCCURRED IN HARROW, ONTARIO

This intense event occurred between 12:00, July 19, 1989 and 15:00, July 20 1989. The 27 hours of rain yielded a total accumulation of 247mm. A peak rainfall intensity of 43 mm/h occurred during the 15th hour of the event. The hyetograph is summarized in Table A-1.

TABLE A-1: Hyetograph for the Intense Storm of Harrow Ontario, July 1989.

DATE	TIME	PRECIPITATION (mm)
July 19, 1989	12:00-01:00	1
	01:00-02:00	3
	02:00-03:00	1
	03:00-07:00	0
	07:00-08:00	10
	08:00-09:00	7
	09:00-10:00	11
	10:00-11:00	1
	11:00-12:00	35
July 20, 1989	00:00-01:00	17
	01:00-02:00	25
	02:00-03:00	43
	03:00-04:00	6
	04:00-05:00	3
	05:00-06:00	1
	06:00-09:00	0
	09:00-10:00	5
	10:00-11:00	40
	11:00-12:00	9
	12:00-13:00	18
	13:00-14:00	10
	14:00-15:00	1
	15:00-16:00	0
	Total:	247 mm