INFORMATION TO USERS

This manuscript has been reproduced from the microfilm master. UMI films the text directly from the original or copy submitted. Thus, some thesis and dissertation copies are in typewriter face, while others may be from any type of computer printer.

The quality of this reproduction is dependent upon the quality of the copy submitted. Broken or indistinct print, colored or poor quality illustrations and photographs, print bleedthrough, substandard margins, and improper alignment can adversely affect reproduction.

In the unlikely event that the author did not send UMI a complete manuscript and there are missing pages, these will be noted. Also, if unauthorized copyright material had to be removed, a note will indicate the deletion.

Oversize materials (e.g., maps, drawings, charts) are reproduced by sectioning the original, beginning at the upper left-hand corner and continuing from left to right in equal sections with small overlaps.

Photographs included in the original manuscript have been reproduced xerographically in this copy. Higher quality 6" x 9" black and white photographic prints are available for any photographs or illustrations appearing in this copy for an additional charge. Contact UMI directly to order.

Bell & Howell Information and Learning
300 North Zeeb Road, Ann Arbor, MI 48106-1346 USA
800-521-0600

UMI®

INTEGRATION OF A GEOGRAPHIC INFORMATION SYSTEM AND A CONTINUOUS NONPOINT SOURCE POLLUTION MODEL TO EVALUATE THE HYDROLOGIC RESPONSE OF AN AGRICULTURAL WATERSHED

By
Mohammad Hassan Mousavizadeh

A thesis submitted to the Faculty of Graduate Studies
and Research in Partial Fulfilment of the
Requirements for the degree of
Doctor of Philosophy

Agricultural and Biosystems Engineering Department
Macdonald Campus of McGill University
Montreal, Quebec, Canada
June, 1998

National Library
of Canada

Acquisitions and
Bibliographic Services

395 Wellington Street
Ottawa ON K1A 0N4
Canada

Bibliothèque nationale
du Canada

Acquisitions et
services bibliographiques

395, rue Wellington
Ottawa ON K1A 0N4
Canada

Your file Votre référence

Our file Notre référence

0-612-44524-0

Canadä

ABSTRACT

The environmental impact of agricultural activities on water quality was studied on two sub-watersheds of the L'Assomption river in Quebec, over a 3 year period. The sub-watersheds studied were the Saint Esprit (26.1 km^2) and Desrochers (17.9 km^2). Development of a methodology and associated tools for targeting conservation activities and assessing the potential impacts of conservation practices was one of the study's components. A goal of this research was the development of a tool using NPS modelling capability and GIS tools. The ANSWERS 2000 model and SPANS GIS software were selected for integration.

Using the advanced SPANS operation and EASI script language, the ANSWERS 2000 model was integrated into the latest version of SPANS GIS (Explorer ver. 7). Integration of these two software packages provided assistance in creating and handling the extensive input and output data for models, evaluating of model output, and delineating of critical areas. A sensitivity analysis of the ANSWERS model was performed on thirteen parameters to determine their effects on runoff. ANSWERS 2000 was found to be most sensitive to depth of soil horizon, silt and clay contents of soil texture, and solar radiation. Four years of runoff predictions by the model were analysed using observed data. Overall, the model was in good agreement with observed runoff in the Saint Esprit watershed, particurlarly in the years with above the average precipitation. The coefficient of performance (CP'_A) between predicted and observed runoff values was 0.5 and 1.5 for 1994 and 1995, respectively. The model predictions of total cumulative runoff were 66.6% in 1994, 54.9% in 1995, 71.7% in 1996, and 42.4% in 1997, of measured cumulative runoff values.

RÉSUMÉ

Une étude de trois ans sur l'impact de l'agriculture sur la qualité des eaux fut enterprise au Québec sur deux bassins versants tributaires de la rivière l'Assomption. Les bassins étudiés furent ceux de St. Esprit (26.1 km^2) et de Desrochers (17.9 km^2). Le développement d'une méthode et d'outils connexes pout viser les activités de conservation et d'évaluer les impactes possibles de ces activités fut un des volets de l'étude. Le but principal de ces recherches fut le développement d'un outil informatisé intégrant la capacité de modéliser la pollution SNP avec des outils de système d'information géographique (SIG). Le modèle informatisé de pollution SNP, ANSWERS 2000, et le logiciel de SIG, SPANS, furent sélectionnés pour une telle intégration.

Se servant d'opérations avancées dans SPANS et du language EASI, le modèle ANSWERS 2000 fut intégré dans la version la plus récente de SPANS EXPLORER GIS. L'intégration de ces deux logiciels nous a permis de créer un outil qui permet de manipuler plus aisément les nombreuses données d'entrée et de sortie des modèles, d'évaluer les résultats, et de circonscrire les zones critiques. Une analyse de sensibilité sur l'écoulement prédit par le modèle ANSWERS fut entreprise pour treize paramètres d'entrée. Les prédictions d'écoulement du modèle ANSWERS furent le plus influencées par l'humidité précédante du sol, la profondeur de la section de sol, le contenu en limon du sol, et l'irradiation solaire. Quatre années de données hydrologiques mesurées sur les lieux furent analysés par rapport aux prédictions du modèle pour cette même période. En général, pour le bassin versant St. Esprit, la prédiction de l'écoulement concorda relativement bien avec les mesures prises sur les lieux de St Esprit pour les années plus humides que la moyenne. Le coéfficient de performance (CP'_A) entre les valeurs prédites et mesurées fut de 0.5 et 1.5 en 1994 et 1995, respectivement. Les prédictions de l'écoulement cumulatif, furent de 66.6% en 1994, 54,9% en 1995, 71,7% en 1996 et 42,4 % en 1997 par rapport à l'écoulement cumulatif mesuré.

ACKNOWLEDGEMENTS

The author wishes to express his sincere thanks and appreciation to Dr. C.A. Madramootoo, Professor of Agricultural and Biosystems Engineeing and thesis supervisor, for his continued encouragement, guidance and constructive criticism throughout the period of his study. It was a pleasure to be a member of his creative research group. I wish to acknowledge the Government of the Islamic Republic of Iran for allowing me to undertake my studies at McGill University and for their financial support. I would like to express my gratitude to Dr. R. Hosseini, Iranian student supervisory in Canada, for his advice and help.

I would like to acknowledge Doctors G.S.V. Raghavan, V.T.V. Nguyen, R.B. Bonnell, and R. Lacroix for their participation in my doctoral comprehensive committee.

I wish to express my thanks to P. Enright, Research Assistant, for his incisive suggestions and comments and his positive nature which made working with him a pleasure. Many thanks to my friend B. Daneshvar, and Mr. B. Thomas at TYDAC Technologies in Ottawa for their invaluable GIS software related advice. I am also appreciative of the comments of Dr. S. Amin on the ANSWERS model. My gratitude to Mr. E. Thomson for accepting me as teaching assistance in the Air Photo and Imagery Interpretation course and his always pleasant discussion and help. My thanks to Dr. G. Dodds for his editing and French translation help. His friendliness and willingness to proof read my manuscript eased the writing of the thesis.

The Saint Esprit project was a joint effort, involving the farmers, the MAPAQ-DEDD in Quebec city, the local MAPAQ office, the agronomist hired by the

farmers, and other researchers from the Depatement of Agricultural Biosystems and Engineering and the Departement of Agricultural Economics. The field plan described in chapter four was executed primarily be the regional MAPAQ officers. A MAPAQ technician did all of the air photo interpretation. Two McGill students, the agronomist, a stage student working with the agronomist, and the MAPAQ technician made observations of soil degradation in the field in the summer/fall of 1994. P. Enright and F. Papineau did the data collection from the farmers. F. Papineau did data entry and provided additional elevation points from drain tile profiles. P. Lapp prepared the field plan hardcopy map. C. Dissart digitized the field plan map. J. Morek digitized the elevation point, soil texture and cadastral map. It was this work on the watershed that I was allowed to build upon.

I am grateful to my fellow graduate students, including Messrs. K. Davary, A. Rajabipour, M.R. Zareifard, A. Liaghat, Seyed J. Jebelli, S. ur Rahman, H. Ali, W. Kaluli, P. Lapp, J. Perrone, C. Cox, and F. Delombaerde for their help in a number of ways.

Many thanks to the members of the administrative staff of the Department of Agricultural and Biosystems Engineering. I also extend my thanks to Macdonald Campus computer center staff, especially S. Broughton, for their computer-related advice.

I wish to extend my deepest thanks to my wife Ensieh for her patience and prayerful support for all difficult times that we had, and to our sons Hamed, Mohammad, and Hassan, for whom all this is for. My thanks is owed to my dearest sister Zahra for all of her support since my childhood. Finally and most of all, I am thankful to God for the entire blessing and success that He bestowed us in our life.

CONTRIBUTIONS TO KNOWLEDGE

The following contributions to knowledge were achieved from this study:

1- An integration of ANSWERS 2000 and SPANS GIS was successfully undertaken. A problem frequently encountered when using complex NPS pollution distributed parameter models such as ANSWERS had been their inability to efficiently handle, manipulate, and manage large volumes of spatially variable input and output data. This software integration provided a tool to spatially organize and effectively manage large input and output data sets.

2- A methodology within SPANS GIS was developed to create spatial data layers for agricultural watershed delineation. Applying GIS tools for agricultural watershed management is a new area, and was investigated in this study. This study demonstrated the capability of using SPANS (one of the strongest GIS software packages on the market) for watershed management. The GIS techniques allowed for a deeper understanding of the influence of agricultural practices on water quality.

3- The ANSWERS 2000 model was modified in order to run on an IBM compatible PC. The model was validated for the Saint Esprit watershed. ANSWERS 2000 is the only physically based, distributed parameter, watershed scale model that simulates hydrologic events *continuously.*

4- A database was organized based on the previous application of the

ANSWERS model. This database serves in the selection of input parameters for the model. Most of the NPS pollution models need a large amount of input data to obtain acceptable results. Data acquisition and entry are probably the most expensive part of using NPS models such as ANSWERS.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF BOXES

LIST OF FIGURES

LIST OF TERMS AND ABBREVIATIONS

AGNPS	AGricultural Non-Point Source
ANSWERS	Areal Nonpoint Source Watershed Environment Response Simulation
BMP	Best Management Practice
CCREM	Canadian Council of Resource and Environmental Ministers
CP'A	coefficient of performance
C	celsius
cm	centimetres
d	day
ET	evapotranspiriation
ha	hectare
FESHM	Finite Element Storm Hydrology Model
GIS	Geographic Information Systems
GPS	Global Positioning Systems
GRASS	Geographical Resources Analysis Support System
h	hour
km	kilometre
L	litre
Ly	langely
m	metre
mg	milligram
mm	millimetre
N	nitrogen
NA	not available
NPS	Non-Point Source
OS	operating system
P	phosphorous

PC	**Personal Computers**
SCS	**Soil Conservation Service**
SPANS	**SPatial ANalysis System**
t	**time**
USEPA	**United States Environmental Protection Agency**
%	**percent**

CHAPTER 1

INTRODUCTION

1.1 Background and statement of the problem

The intensification of agricultural production and the associated increased applications of agrochemicals has caused water pollution to become a serious threat to the environment, and consequently, to humans and animals. Sources of water pollution are either point or nonpoint. Nonpoint source (NPS) pollution has been recognized as an important environmental problem with negative effects on agricultural productivity, and soil and water quality (USEPA, 1993). Sediment, nutrients, and pesticides are the main NPS pollutants from agricultural watersheds (Blankenship, 1994; Lal and Stewart, 1994). Control of pollutants from agricultural watersheds presently focusses on these parameters. A major objective of pollution control is to protect water quality from adverse effects of agriculture by limiting pollutant levels in the waters that receive runoff from nonpoint sources (Mannion, 1995). A conceptual basis for efficiently attaining this objective views the watershed as a hydrologic system of interconnected components overlaid with agricultural and other activities on the land (Laroche et al., 1995).

There are about 3.7 million hectares of farmland in Quebec, mostly along the St. Lawrence river and its tributaries (CCREM, 1994). Close to 600,000 hectares of this area are subsurface drained, much of which are intensively cropped to cereals and grains. The potential exists to drain at least twice this area in the future (Madramootoo, 1990). Significant quantities of agrochemicals, especially fertilizer, are used in corn production. In Quebec, the consumption of fertilizers is reported to be constant at about 260,000 tonnes (Statistics Canada, 1992). Studies by the Quebec Ministry of the Environment have shown that most of the rivers draining agricultural lands have elevated nitrate, phosphorous and pesticide concentrations (Simoneau, 1996). In the L'Assomption, Yamaska and Chaudiere River watersheds, elevated concentrations of sediments, nutrients and pesticides are found in the areas where agricultural activity is most intensive (Berryman and Giroux, 1994). The Ministry of Agriculture of Quebec (MAPAQ) stated that 85% of agricultural pollution resulted from non point sources (Gagné, 1995).

A combination of methodologies collectively known as best management practices (BMP) is expected to control and reduce pollutants (Bailey and Waddell, 1979). BMPs are alternative combinations of land use, soil and/or water conservation practices, and management techniques. The application of BMPs on agricultural watersheds will result in the opportunity for a reasonable economic return within acceptable environmental standards (Gregersen et al., 1987). The United States Congress has recognized BMPs as the standard for controlling NPS pollution (CAST, 1992, cited in Muchovej and Rechcigl, 1994).

The concentrations of water pollutants produced by agricultural nonpoint sources are difficult to quantify since pollutant loads are costly to measure. Modelling and monitoring are two general methods of estimating BMP effectiveness (Beasley et al., 1982). Compared to monitoring, modelling is an inexpensive and quick technical tool to quantify results in time and space, but it lacks the credibility of actual measured data. However, monitoring cannot be applied to every site because of the time and cost involved (D'Elia et al., 1989). Models can evaluate alternate management practices for controlling soil erosion, sediment transport, and loss of agrochemicals. They provide a basis for guiding management and regulatory decision-making processes. They can also be used to help plan where, when, and what to monitor, thus making monitoring more effective and less costly.

A major problem facing modellers has been the inability to efficiently handle, manipulate, and manage large volumes of model input parameters. Recent developments in Geographic Information Systems (GIS) provide the opportunity and tools to spatially organize and effectively manage data for modelling. GIS also has tools to analyze and visualize model outputs.

To reduce the environmental impact of agricultural activities on water quality, a three year study of agricultural NPS pollution was initiated on two sub-watersheds of the L'Assomption river in Quebec. The sub-watersheds studied were the Saint Esprit (26.1 km^2) and Desrochers (17.9 km^2). Development of a methodology and associated tools for targeting conservation activities and assessing the potential impacts of conservation practices was one of the study's components. Integration of a NPS model with a GIS can provide assistance in creating a tool to handle the extensive input and output data for models, delineation of critical areas, and assessment of the long term effectiveness of BMPs for NPS pollutant mitigation. Development of such a tool using modelling ability and GIS tools was the goal of this research.

1.2 Objectives

The broad objective of this research was to link a GIS, Spatial Analysis System (SPANS), and a continuous hydrologic model, Areal Nonpoint Source Watershed Environment Response Simulation (ANSWERS 2000). This integration would serve to map the agricultural activities on the watershed, analyse the measured water quality parameters, and provide input data for hydrologic and water quality models. The specific objectives of this research were to:

1- Create a spatial database in SPANS. This database is to accommodate both public domain and site specific information.

2- Develop appropriate methods for creating new information layers (maps) such as reclassified soil and land use.

3- Reorganize the ANSWERS 2000 source code into a better structure, debug it, and make it executable on a personal computer.

4- Validate ANSWERS 2000 for use on the Saint Esprit watershed. Compare predicted runoff with observed data and modify ANSWERS 2000 as needed.

5- Integrate the ANSWERS 2000 model and the SPANS GIS to make a tool with sufficient flexibility that:

- modifying, updating and/or creating new input data for the model can be routinely organized,

- the user interaction and time requirement to prepare the related ANSWERS 2000 input data from a SPANS spatial database is minimized,

- ANSWERS 2000 output can be visualized and analyzed in SPANS. Maps produced from subsequent simulations can be compared by SPANS modelling overlay.

1.3 Thesis organization

This thesis is comprised of nine chapters. Chapter 1 introduces the background and states the problems dealt with in this work. Chapter 2 is a review of the literature on three aspects of the project. Chapter 3 describes the study area and the Saint Esprit project. Chapter 4 discusses the development of a spatial database for the Saint Esprit watershed. Chapter 5 describes the use of the database in different applications. Chapter 6 outlines the integration of the ANSWERS 2000 model with the SPANS GIS software. Chapter 7 presents an evaluation of the hydrologic components of the ANSWERS 2000 model, using the integrated tool. Chapter 8 summarizes and draws conclusions from the findings of this study. Finally, Chapter 9 proposes recommendations for future research. A CD ROM is included on the cover of the thesis. The following chapters will refer to material on this CD ROM. There exist five directories on the CD ROM, containing:

i. ANSWERS: all files related to the model.
ii. Climate data: all files related to climatic data for the Saint Esprit watershed.
iii. GIS: the digitized format of the different information layers of the Saint Esprit watershed and the final database in SPANS format.
iv. ANSWERS and SPANS integration: all the files for installation of the ANSWERS-SPANS integrated tool.
v. Thesis: the text of this thesis in different chapters

1.4 Scope

The development and testing of the integrated software was undertaken on 2 watersheds north of Montreal, Canada. The complete SPANS database in this study includes layers of information for the upper Ruisseau Saint Esprit watershed in Quebec. Information available for the Desrochers watershed, which is adjacent to Saint Esprit watershed, is also included within the database.

The ANSWERS 2000 model is made up of 3 components: hydrology, sediment, and nutrient. This thesis only evaluated the first of these components.

CHAPTER 2

LITERATURE REVIEW

This literature review adresses three main topics: nonpoint source pollution models, geographic information systems, and integrated NPS models and GIS.

2.1 Nonpoint source pollution models

2.1.1 Model definition and history

A model can be defined as an imitation of the real world for the purpose of understanding a phenomena. During the past two decades there has been an increase in the development and application of hydrologic and NPS models to quantify pollution, and assess management practices.

Novotny (1986) divided the history of NPS models into four periods:
The first period (1900-1950): the precomputer age or the age of empirical hydrology. During this period, many mathematical models with no consideration of such issues as the environmental aspects of water quality were developed. These included the Green Ampt (1911) model of infiltration, followed by those of Horton (1939) and Philip (1954).

The second period: the transition of the 1950s. Hydrologic data collection accelerated during this period but the analysis was slow and costly. Small basin studies of hydrologic processes began during this period.

The third period: the early years of computer use during the 1960's. Computer models began to be developed during this period. The Soil

Conservation Service (SCS) curve number model for determining runoff (Mockus, 1964), the Universal Soil Loss Equation (Wischmeier and Smith, 1965), and the Stanford Watershed Model (Crawford and Linsley, 1962) are examples of this period.

The current period: the mid 1970s to present. With the rapid development of inexpensive microcomputers, a new generation of models was developed. ACTMO (Frere et al., 1975), NPS (Donigian et al., 1977), CREAMS (Kinsel, 1980), ANSWERS (Beasley et al., 1980) are the models developed since 1970. Novotny (1986) indicated that the success of these early models was limited. From the latter half of the 1980's, new model development has slowed and the focus has been on adapting existing models to personal and work station computers. Tim (1995) described how new technologies like GIS, User Interface (UI), Expert System (ES), scientific visualization (Animation and Virtual Reality), software engineering (Object-Oriented Programming), and Remote Data Acquisition (Remote Sensing) will influence hydrologic and water quality modelling research.

2.1.2 Types of models

Depending on the definition of a model and the need of a particular discipline, several criteria have been used to classify models. Mathematical models can be grouped into empirical and theoretical (Woolhiser and Brakensiek, 1982). Empirical models omit the physical law that relates to the system processes. They are often referred to as cause and effect models. Theoretical models can be further subdivided into deterministic and indeterministic (Chow, 1972).

Nonpoint source models are usually classified into screening and hydrologic assessment types (Novotny, 1986). Screening models are based on a simple value or function that expresses pollution generation per unit area and unit time of each typical land use. They are used to identify critical areas that contribute the most to the total loading of pollutants. Hydrological assessment models can be further subdivided into lumped and distributed models, depending on the handling of space. Lumped and distributed models can be subsequently classified as event-base and continuous, depending on the time scale. More discussion about different types of models is available in Woolhiser and Brakensiek (1982), Chow (1972), Clark (1973), Frere (1982), and Novotny (1986).

2.1.3 Model selection

Several factors should be taken into account for selecting a model. These factors include the definition of the problem to be solved, model assumptions and limitations, previous model validation, data availability, and precision of the output desired. This research needed an NPS pollution model which could meet the following requirements:

* Potential for integration with GIS. It means the model should be of a distributed parameter type.

* Facility to provide information relevant to the effects of soil and water conservation BMP on reducing water resources pollution. The facility must include different components for computing surface and subsurface water quantity and nonpoint source pollution from nutrient, pesticides, and sediment.

* Operate at the watershed scale and handle frozen soil conditions.

There are several hydrologic and NPS computer models available from various agencies and individuals (Ghadiri and Rose, 1992; Novotny and Olem, 1993; DeVries and Hromadka, 1993). Table 2.1 presents some of these models. They differ in their modelling concepts, and the processes and parameters to be considered.

They may be classified as field or watershed scale, lumped or distributed parameters, event-base or continuous models. These models can be used to identify NPS pollution problems and environmental impacts of alternate agricultural management practices. They simulate physical, chemical, and biological processes in agricultural watersheds. These models vary from simple screening models to very detailed and complex research tools. A few of these models have only hydrologic components (e.g., HYDROTEL). Some have hydrologic and sediment transport components (e.g., ANSWERS), whereas others (e.g., CREAMS) have hydrologic, sediment, nutrient and pesticide components. Different aspects of the models in Table 2.1 are reviewed in Appendix A. Appendix A shows that the abilities of the models are different. However, none of them supports all the above model selection requirements. Table 2.2 gives a comparison of three models which best address the above criteria. The Finite Element Storm Hydrograph Model (FESHM), Agricultural Nonpoint Source (AGNPS), and Areal Nonpoint Source Watershed Environment Response Simulation (ANSWERS) are three distributed parameter watershed models available for NPS modelling. All

Table 2.1 Hydrologic and NPS models

Model Name	Reference
1- ACTMO, Agricultural Chemical Transport MOdel	Frere et al., 1975
2- AGNPS, AGricultural Non-Point Source	Young et al., 1985
3- ANSWERS, Areal Nonpoint Source Watershed Environment Response Simulation	Beasley et al., 1980
4- ANSWERS 2000	Bouraoui, 1994
5- ARM, Agricultural Runoff Management	Donigian et al., 1977
6- CREAMS, Chemical, Runoff and Erosion from Agricultural Management Systems	Kinsel, 1980
7- EPIC, Erosion Productivity Impact Calculator	Williams, 1983
8- FESHM, Finite Element Storm Hydrograph Model	Ross et al., 1979
9- GAMES, The University of Guelph model for evaluating effect of Agriculture Management Systems on Erosion and Sedimentation	Cook et al., 1985
10- GLEAMS, Groundwater Loading Effects of Agricultural Management Systems	Leonard et al., 1986
11- HSPF, Hydrologic Simulation Program Fortran	Johanson et al., 1984
12- HYDROTEL,	Fortin et al., 1991
13- LEACHM, Leaching Estimation and CHemistry Model	Wagenet et al., 1989
14- PERFECT, Productivity, Erosion, and Runoff Function to Evaluate Conservation Technique	Littleboy et al., 1989
15- PESTFADE, PESTicide FADE and Dynamics in the Environment	Clemente et al. 1993
16- PRZM, Pesticide Root Zone Model	Carsel et al., 1984
17- SWRRB, Simulation for Water Resources in Rural Basins	Arnold et al., 1988
18- TOPMODEL, TOPography based hydrological MODEL	Beven and Kirby, 1979
19- WEPP, Water Erosion Prediction Project	Lane & Nearing, 1989

three models have the potential for integration with GIS. FESHM has not

Table 2.2 Model overview

Model aspects / Model name			AGNPS	ANSWERS 2000	FESHM
Model Criteria	Scale	Field	N	N	N
		Watershed	Y	Y	Y
	Simulation period	Event	Y	N	Y
		Continuous	N	Y	N
	Aerial distribution of parameter	Distributed	Y	Y	Y
		Lumped	N	N	N
	GIS Integration Potential		Y	Y	Y
Hydrologic Parameter	Water Quantity	Surface	Y	Y	Y
		Subsurface	N	N	N
	Snowcover variation and melt		N	N	N
	Soil moisture		?	Y	?
Nonpoint Source Pollution	N		Y	Y	N
	P		Y	Y	N
	K		N	N	N
	Pesticides		N	N	N
	Sediment		Y	Y	N

Y=yes N=no ?=no information found

been widely validated (Heatwole et al., 1982; Hession et al. 1987; Hession et al. 1994), while AGNPS (Young et al., 1987; Panuska and Moore, 1988; Young et al., 1989; Summer et al., 1990; Bingner et al., 1992; Mitchell et al., 1993; Wu et al., 1993; Arakere and Molnau, 1994; Park and Kim, 1995) and ANSWERS (Park et al., 1982; Griffin et al., 1988; Breve et al., 1989; De Roo et al., 1989; Razavian, 1990; Connolly et al., 1991; Montas and Madramootoo, 1991; Rewerts, 1992; Ritter, 1992) have been validated under different conditions and used successfully for BMP assessment. FESHM does not simulate nutrient transport. AGNPS is probably the most widely used distributed parameter NPS model. The latest version of

AGNPS is event-oriented. It uses the SCS curve number to calculate rainfall excess, which limits its application for Quebec conditions (Madramootoo and Enright, 1988). The SCS curve method's limitation are based on the use of soil infiltration, soil moisture, and rainfall coefficient classes, rather than a physically based description of these parameters. It uses four hydrologic soil groups, and three antecedent soil moisture conditions. However, a physically based model like ANSWERS 2000 uses an empirical equation (Green-Ampt, 1911) to calculate soil infiltration and soil moisture. The sediment subroutine of AGNPS is based on the empirical Modified Universal Soil Loss Equation.

2.1.4 The ANSWERS 2000 model

ANSWERS 2000 (Bouraoui, 1994) is the latest version of the ANSWERS model (Huggins and Monke, 1966; Beasley et al., 1980; Dillaha and Beasley, 1983; Storm et al. 1988). It was developed to simulate the effectiveness of selected BMPs on runoff, sediment, and nutrient losses from agricultural watersheds. It is a physically based, distributed parameter, continuous simulation, watershed scale model.

The ANSWERS model is based on the hypothesis that: "at every point within a watershed, relationships exist between water flow rates and those hydrologic parameters which govern them. These water flow rates can be utilized in conjunction with appropriate component relationships as the basis for modeling other transport related phenomenon such as soil erosion and chemical movement within that watershed" (Beasley and Huggins, 1991).

The model consists of three interfaced components; hydrology, sediment and nutrient (transformation and transport). Based on the model hypothesis the hydrology component is the most important.

Mathematically, each element's hydraulic response is computed, as a function of time, by an explicit, backward difference solution of the continuity equation:

$$I - Q = \frac{dS}{dt} \qquad 2.1$$

where:

I = inflow rate to an element from rainfall and adjacent elements,

Q = outflow rate,

S = volume of water stored in an element,

t = time.

The model combines the continuity equation with a stage-discharge relationship. Manning's equation is used as the stage-discharge equation for both overland and channel flow routing.

After rainfall begins, some precipitation is intercepted by the vegetative canopy, until the interception storage potential is satisfied. As rainfall proceeds, infiltration decreases until it equals the rainfall rate. At this point water begins to accumulate on the surface in micro-depressions. Once the capacity of the micro-depressions is exceeded, runoff begins. The accumulated water in excess of surface retention capacity and surface detention, produces surface runoff. When rainfall ceases, the water in surface detention begins to dissipate until surface runoff ceases altogether. However, infiltration continues until all the depressional water has infiltrated. Infiltration is modeled using Holtan's (1961) infiltration equation:

$$FMAX = FC + A\left(\frac{PIV}{TP}\right)^{p} \qquad 2.2$$

where:

FMAX= infiltration capacity with the land surface inundated (cm/h),

FC = steady state infiltration capacity (cm/h),

A = maximum infiltration capacity in excess of FC (cm/h),

TP = total porosity within the control depth (cm),

PIV = air remaining in the control depth before saturation (cm), and

p = empirical coefficient.

Water in the soil moisture control zone in excess of field capacity drains from the control zone in accordance with the Huggins and Monke (1966) equation:

$$DR = FC\left[1 - \frac{PIV}{GWC}\right]^{3} \qquad 2.3$$

where:

DR = drainage rate of water from the control zone (cm/h), and

GWC = gravitational water capacity of the control zone (cm).

Between rainfall events, the model maintains a water balance. Evapotranspiration is computed and if soil moisture exceeds field capacity, the model also computes percolation. Evapotranspiration is computed using Ritchie's method (1972):

$$E = \frac{0.0504 H\Delta}{0.68 + \Delta} \qquad 2.4$$

where:

E = potential evapotranspiration (cm),

H = net solar radiation (Ly), and

Δ = slope of the saturation vapor pressure curve at the mean air temperature.

Percolation varies from zero when soil moisture is close to field capacity, to a maximum rate when the soil profile is saturated.

ANSWERS 2000 uses the expanded sediment transport model based on the Yalin (1963) equation that simulates different detachment and transport of the various particle size classes. Soil detachment, transport, and deposition are modeled as a function of the precipitation and the runoff process. The model simulates nitrate, dissolved and sediment-bound ammonium, sediment-bound total Kjeldahl nitrogen (TKN), and dissolved and sediment-bound P losses in surface runoff. The nutrient transformation model was adapted from the GLEAMS and EPIC models. Detailed description of the equation and methods discussed above are available in Bouraoui (1994) and the ANSWERS User's Manual (Beasley and Huggins, 1991).

2.1.5 ANSWERS 2000 validation

Validation of ANSWERS has been conducted at various stages of model development (Beasley et al., 1980; Shichani 1982; Storm et al., 1988, Bouraoui, 1994). ANSWERS 2000 was validated using two watersheds in Watkinsville, Georgia and one watershed in Virginia. Overall, the model appeared to perform well in predicting runoff, sediment, nutrient, dissolved ammonium, sediment-bound total Kjeldahl nitrogen, and dissolved labile phosphorous, with some inaccuracy noted in the prediction of sediment-bound ammonium (Bouraoui, 1994; Wolfe et al. 1995). Zahradka et al. (1994) described that output values produced by the ANSWERS 2000 are most sensitive to the input parameters of total porosity, depth of the A horizon, clay content, saturated and effective hydraulic conductivity, and field capacity. The preliminary study by Yoon and Rawls (1995) showed that ANSWERS 2000 could be applied to a mixed land use watershed with acceptable results.

2.2 Geographic Information Systems

2.2.1 Introduction

Geologists and geoscientists have been using computers for manipulation of spatial data since the 1960s. During the 1980s, advances in computer hardware, particularly processing speed and data storage, catalyzed the development of software for handling spatial data. The emerging capabilities for graphical display played an important role in this development. One of the significant products of this period of rapid technological change was Geographic Information Systems (Bonham-Carter, 1994). GIS is a helpful tool in every field requiring the management and analysis of spatially distributed data (Laurini and Thompson, 1992). It has been defined in various ways. A simple definition is that a GIS is a computer system for managing spatial data (Star and Estes, 1990). It is a system for capturing, storing, integrating, analyzing, and displaying data that are spatially referenced. The primary purpose of such systems is to be able to read geographical data from one or many digital maps or statistical sources and selectively measure, combine, compare and analyze those data to produce information for the decision making process (Tomlinson and Toomey, 1995). GIS combines elements of database management, mapping, image processing and statistical analysis (Aronoff, 1991).

GIS technology is now used by different public and private organizations throughout the world, for a wide variety of applications (Burrough, 1986; Maguire et al., 1991; Sample, 1994; Heatwole, 1995). The field has been growing at a rate of about 25 to 40% per annum. If trends continue, more than one million people will be using GIS technology by the year 2000 (Johnson et al., 1992). At the same time the techniques have become important in the areas of: *water resources planning* (Ferreira and Faber, 1994; Negahban et al., 1994; Srinivasan et al., 1995); *soil and water contamination* (Ghidey et al., 1994; Cho et al., 1995; Searing et al., 1995); *nitrogen managemen* (Gorres et al., 1994; Zhang et al., 1994); *erosion control* (Mellerowicz et al., 1993; Batty, 1994); *and environmental monitoring and analysis* (Hudak et al., 1993; Ston et al., 1994).

With the analytical power of GIS, it is possible to merge information assembled using traditional field-data collection methods with other information sources, such as remote sensing and global positioning systems (GPS) technology (Muhr et al., 1994). These technologies allow farmers to manage a field on a "site-specific" basis instead of using "field average" methods (Oiu et al., 1995). Farmers will be able to manage fields in accordance with the variability in yield potential, soil properties, and a host of other agronomic factors. Runyon (1994) described the process used to integrate soil information, GIS and GPS, and aerial photography to provide an effective approach for managing agrochemicals. He reported that this approach helped the farmer to provide nutrients at a uniformly optimum level. He mentioned that the expense of the data collection and analysis was offset by the reduced chemical costs.

2.2.2 GIS software

The number of GIS software packages has rapidly increased since 1990. These packages have different levels of functionalities. Among these software; ARC/INFO (ESRI, 1992), GRASS (USACERL Army, 1988), IDRISI (Eastman, 1995), and SPANS (TYDAC Technologies Inc., 1992) are the most popular and widely used.

ARC/INFO is designed by Environmental Systems Research Institute (ESRI). It is a vector based GIS and is composed of two primary components. ARC is used to store coordinate data and perform all the operations on that type of data. INFO is a relational database management system used to store and perform operations on the attributes.

GRASS (Geographical Resources Analysis Support System) is a raster based public domain software developed and supported by the United States Army Construction Engineering Research Laboratory (USACERL). GRASS provides the source code to the user. This is advantageous because additions and modifications can be made by the user to fit specific needs. Version 4.0 of GRASS was completed in July 1991 and is being distributed with source code; reference, tutorial and programmer documentation; and an extensive sample data set. Version 4.1 of GRASS was completed and released in May 1993 and is available on the Internet.

IDRISI is a low-cost, geographic information and image processing software system developed by the Graduate School of Geography at Clark University. Since its introduction in 1987, IDRISI has grown to become the most distributed raster-based microcomputer GIS and image processing system on the market. During its early development, partial support was provided by the United Nations Environment Programme Global Resource Information Database (UNEPGRID), the United Nations Institute for Training and Research (UNITER), and the United States Agency for International Development (USAID). Today, all support comes through software sales. The latest version of IDRISI was developed for the Windows operating system. The software is not expensive, as it is supported and sold on a non-profit basis.

SPANS is a collection of GIS software tools. It is a modular system. The basic software modules, SPANS/GIS, includes a set of GIS tools for building databases, constructing analytical models and the visualisation and querying of data. Additional modules for digitizing, desktop mapping, image processing, and data translation are also available. SPANS provides a modelling language within the system which allows users to combine multiple layers of spatial data and other entities using a range of spatial and non-spatial operations (TYDAC Technologies Inc., 1992:Modelling Handbook of SPANS manuals). The modelling ability is a useful tool to create desired maps from existing maps, targeting sources of pollution, determining critical areas, and evaluating the effectiveness of BMPs.

2.2.3 SPANS applications in water resources

SPANS is used in different countries throughout the world. Most SPANS customers are involved with management and study of natural resources, including water resources, forestry, agriculture, geology, and oceans. A smaller but growing number are users in the business sector who perform economic analyses (Tomlinson and Toomey, 1995). Landreville (1990) used SPANS to determine physiographic parameters for hydrologic modelling in southeastern Quebec. Applying the SPANS modelling module, Stempvoort et al. (1993) produced maps by comparing and merging with other GIS-referenced information. They used the maps to determine the areas where, along the Saskatchewan-Alberta boundary, groundwater contamination would most likely occur. Bajjali and Daneshfar (1995) used SPANS to determine the suitability of groundwater resources for drinking purposes in North Jordan by using a fuzzy logic model inside SPANS. This was achieved by creating several maps showing distribution of different chemical and isotopic data in the study area. The geology of the study area was also digitized, transformed and used as a basemap to display these different parameters. Gasser (1995) used SPANS with an intensive soil experiment designed to evaluate two common methods of soil sampling, in order to generate variable rate phosphorus maps for precision farming. He describes how they used SPANS/GIS in their evaluation of the methods. A methodology was developed by Luo (1995) for the use of SPANS in the analysis of erosion risk in Snowdonia National Park, U.K. at various degrees of detail, taking into account different options with respect to the availability of input data. Based on this method, a user can select the optional analysis approaches which can be applied in his particular case. Forty years of daily meteorological and river discharge data were analyzed (Telmer, 1995) using SPANS to calculate the water loss due to evaporation and evapotranspiration for the entire Ottawa River basin. This includes both open water and terrestrial areas. Ghallab et al. (1994) used SPANS to develop salinity hazard maps by creating various soil salinity parameter maps and interrelationships between soil and groundwater properties in two provinces of Egypt.

2.3 Integrated NPS models and GIS

Increasingly over the past 10 years, GIS is being used for agricultural watershed delineation and integration with NPS pollution distributed models. According to Maidment (1993), hydrologic/water quality modelling in combination with GIS can be ranked as (1) hydrologic assessment, a weighted and summarized index of the influence of hydrologic factors that pertain to some situation; (2) hydrologic parameter determination, using GIS to poll a layer or combination of layers to extract or derive input for models; (3) hydrologic modelling within GIS; and (4) linking GIS and hydrologic models. The following discussion presents the efforts of integration of NPS models with GIS. These works are examples of one or more of the classification steps listed above.

Since 1985 the Information Support Systems Laboratory at Virginia Tech has developed a large scale (4.8 million hectare) GIS database of the Chesapeake Bay drainage basin (Tim et al., 1991, Yagow and Shanholtz, 1992). Their primary goals have been to develop procedures for identifying and prioritizing agricultural land areas needing improved management for NPS pollution control and evaluating the effectiveness of BMP.

Hodge et al. (1988) described the linkage of the ARMSED watershed model with GRASS. The linkage output included total runoff, runoff for sub-watersheds, hydrograph data, and sediment yield for storm events.

De Roo et al. (1989) developed methods to use ANSWERS with the MAP Analysis Package (MAP)GIS. MAPGIS was used for storage, transformation, retrieval, and display of digital data. The authors point out that with GIS techniques, modification of inputs (for example, simulating different land use or conservation measures) are possible in a short time. Feezor et al. (1989) developed a method to interface ARC/INFO output with AGNPS input data files. Needham and Vieux (1989) employed a series of ARC/INFO commands to generate input files for AGNPS.

Delimand and Wolfe (1990) used the GRASS GIS analysis tools to assess the effect of dairy farms on the NPS pollution potential of surface waters. Using input maps based on soils, elevation, dairy location and streams, they were able to make classifications such as "dairies located on soils unfit for land disposal of agricultural wastes", as well as assess the distance of the dairies to the stream network, and the volume of runoff from the study area. Using GRASS, Haliday and Wolfe (1991) employed the DRASTIC methodology to combine map layers and determine the availability of nitrogen fertilizers, and its influence on groundwater contamination. Hamlett et al. (1990) integrated a NPS model and a GIS to rank the agricultural pollution potential of a watershed in Pennsylvania. They developed a screening model which combines runoff, sediment production, land use, and animal loading indices into a single index. Stuebe and Johnston (1990) used GRASS to compare manual and GIS methods of rainfall runoff estimations using the SCS runoff curve method. They reported that the GIS method was a satisfactory alternative to the manual method for watersheds lacking relatively flat terrain. Zhang et al. (1990) interfaced a one-dimensional solute transport model with ARC/INFO to form an agricultural chemical impact evaluation and management system.

Moeller (1991) successfully used GIS to derive aerially-weighted hydrologic parameters for input to the HEC-1 hydrologic model for a large basin. Scott et al. (1991) utilized GRASS tools to analyze the relationship between nitrate-N concentration in wells, springs, and various landscape parameters in a watershed. Utilizing GRASS, Srinivasan and Engel (1991) estimated SCS curve numbers using soil, land use and management-practice layers for each cell. They implemented the SCS curve numbers on GRASS to estimate runoff for each cell and also for the whole watershed. They reported that their techniques could be integrated with AGNPS and could be used as input for lumped parameter models like SWRRB, CREAMS, EPIC, and GLEAMS.

Kiker et al. (1992) linked the CREAM-WT model with ARC/INFO to show the effects of phosphorous control practices. Montas and Madramootoo (1992) developed a decision support system for the planning of soil conservation systems for an agricultural watershed in southwestern Quebec. The system integrated a simple GIS, ANSWERS, and an expert system. Srinivasan (1992) developed a Spatial Decision Support System (SDSS) for assessing agricultural NPS pollution by linking the AGNPS model with GRASS. The SDSS creates 22 AGNPS inputs for each cell of a watershed from eight GRASS input layers (soil, elevation, land use, management practice, fertilizer or nutrient inputs, type of machinery used for land preparation, channel slope, and slope length factor). He reported that the tool allowed the use of AGNPS with a significant savings of time, labour, and expertise over traditional AGNPS usage methods, and felt that the tool could serve as an effective and efficient management tool to control NPS pollution.

Corwin et al. (1993) coupled a one dimensional solute transport model to ARC/INFO. In their approach, simulation modelling of water and salt movement and GIS techniques were used to integrate and summarize the large scale behaviour of spatially-variable soils. This provided management guidance on issues related to salt loading to the groundwater. They reported that the approach could be used to predict solute loading for various irrigation scenarios. SCS initiated the Hydrologic Unit Water Quality (HUWQ) project to provide tools to assess the effects of agricultural activities on water resources at the hydrologic unit level. A model interface was designed (Drungil et al., 1993) to link AGNPS, SWRRBWQ, EPIC and GLEAMS to GRASS. The interface facilitates the input data assembly and simplifies interpretation of model output. Richards et al. (1993) integrated a three dimensional, finite difference, groundwater flow model (MODFLOW) to a GIS. They used GIS as the primary tool in the development of the model grid, performance of the modelling procedure, and model analysis.

Arakere and Molnau (1994) developed an interface between IDRISI and AGNPS to assess the performance of AGNPS on a small watershed. IDRISI was used to create a database containing input data useful for AGNPS. Chen et al. (1994) developed a UNIX-based Windows to integrate a phosphorus transport model with GRASS. The integrated GRASS-modelling system prioritized potential phosphorus loading from fields or cells in a watershed and could evaluate the effects of alternate management practices on phosphorus yield. Fraisse et al. (1994) integrated ARC/INFO and GLEAMS for alternative dairy waste management analysis. Al-Abed and Whiteley (1995) wrote a simple macro program to create an interface between the HSPF model and ARC/INFO, to model irrigation water quality parameters. They plan to use ARC/INFO to generate an input data file for the HSPF model.

2.4 Summary and Conclusions

This study required an NPS pollution model, meeting certain criteria. Several NPS models were considered. FESHM, AGNPS, and ANSWERS 2000 were three distributed parameter watershed scale models available for NPS modelling. ANSWERS 2000 is the only *continuous simulation* model. As well, it does not rely on the SCS curve number method to simulate runoff. It simulates runoff, erosion, transport of dissolved and sediment-bound nutrients, and transformation of nitrogen and phosphorus for unguaged watershed. ANSWERS 2000 was selected as the NPS model for this study. A GIS software which would work on an IBM compatible PC was also needed for the research. It needed to support a raster data structure to allow for the exchange of data and links with the NPS model. It also needed to have strong *modelling capabilities* to tabulate baseline statistics and interpret different measured water quality data on the watershed. SPANS GIS met these requirements and was selected as the GIS platform.

NPS models such as ANSWERS 2000 are complex. They need a very detailed input data, which is impractical to handle and manipulate in the traditional way, by hand. They can be effectively managed in a GIS platform. GIS also provides tools to analyze and visualize NPS model outputs. Integration of a NPS model and a GIS could provide a tool to use GIS techniques for NPS modelling. Such a tool was not previously developed for agricultural watersheds in Quebec.

CHAPTER 3

SAINT ESPRIT PROJECT

3.1 Site description

In January 1994, a three year study on the impacts of agricultural production and conservation practices on water quality was initiated on two sub-watersheds of the *L'Assomption* river in Quebec. The *L'Assomption* river basin had been identified by the Quebec Ministry of the Environment as a watershed where a significant portion of the pollutant load came from agricultural sources (Simoneau and Grimard, 1989). The two selected sub-watersheds were the *Ruisseau Saint Esprit* and the *Cours d'eau Desrochers*, hereafter referred to as the Saint Esprit and Desrochers watersheds (Figure 3.1). The basins are located between 45°55′00″ and 46°00′00″ north latitudes and 73°41′32″ and 73°36′00″ west longitudes. There are no industries nor village within either watershed. The area's climate is temperate. Average annual precipitation, potential evapotranspiration, and temperature are 1087 mm, 572 mm, and 5.2 °C, respectively (MEF, 1995). To a great extent, most of the activities in the watersheds are agricultural. The total human population of the Saint Esprit watershed is approximately 700 (Enright et al., 1998).

3.2 The project objectives

The *Gestion de l'eau par basin versant de la partie supérieur du ruisseau St-Esprit* [watershed scale management of the waters of the upper reaches of the Saint Esprit Creek] project was funded by the Canada-Quebec

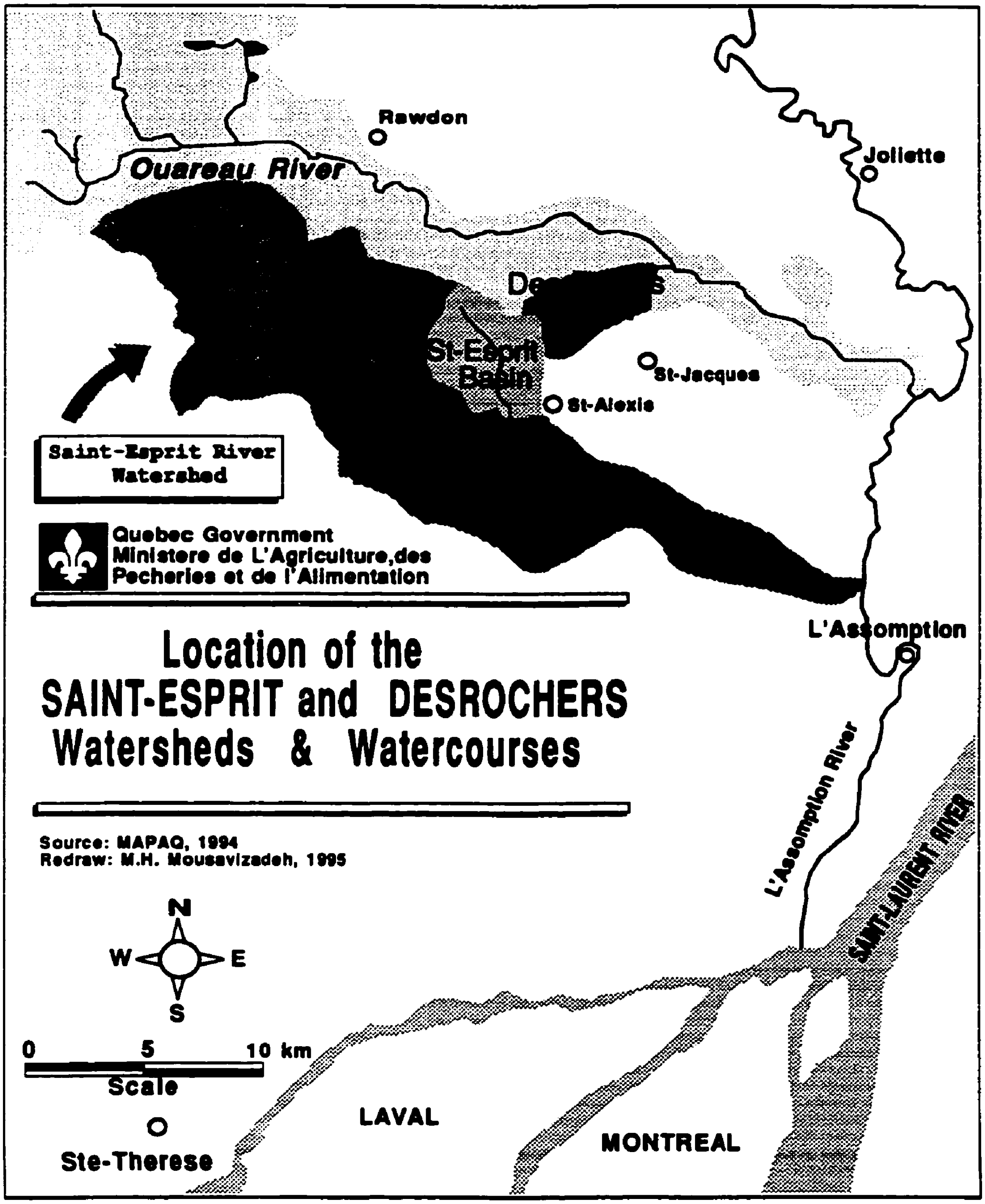


Figure 3.1 St.-Esprit and Desrochers watershed locations

subsidiary agreement on environmental sustainability in Agriculture – Drainage Basin Management Program; a joint effort of Agriculture Canada and the "Ministère de l'Agriculture, des Pêcheries et de l'Alimentation du Québec" (MAPAQ). The global objective of the agreement, which is part of the Green Plan, was to reduce the impacts of agricultural activities on water quality. The Drainage Basin Management Program was one component of the agreement. The objectives of the Drainage Basin Management Program were to:

1. support the actions of the watershed farming community to improve integrated water management and environmental quality;
2. develop technological expertise in integrated water management within individual agricultural drainage basins;
3. accumulate knowledge on agricultural technology and the processes that cause contamination of surface waters;
4. develop an intervention strategy applicable on other small watersheds in Quebec with similar environmental problems.

The project had to take place on a small watershed with intensive agricultural activities where the water quality was significantly degraded. The actions to be taken to achieve the goals were:

1. define the environmental problems related to agriculture on the watershed, and develop an environmental plan of action for each farmer participating to the project;
2. implement activities and promote conservation practices that would

correct the environmental problems identified on the basin;

3. ensure that an agronomist would do a follow-up of all soil and water conservation activities taking place on the basin and support the farmers in the implementation of their environmental plan;
4. promote environmentally sound agricultural practices;
5. evaluate the economic impacts of each activity at the farm and watershed scale;
6. monitor intensively the water quality on two adjacent watersheds and develop tools that would permit the identification of the most efficient conservation practices for reducing the environmental impacts of agricultural production (Enright, 1995).

McGill University was the scientific partner in the project. Several research teams from the Department of Agricultural and Biosystems Engineering (Enright et al., 1995; Lapp, 1996; Enright et al. 1997; Perrone et al., 1997, Papineau and Enright, 1997a and 1997b, Enright et al., 1998) and the Department of Agricultural Economics (Dissart, 1998) were involved in the project. Four tasks were assigned to McGill University. They were:

1. define and characterize the environmental problems related to agricultural activities on the watershed, and based on the initial findings, suggest remedial actions;
2. monitor discharge and water quality at the outlet of the two watersheds and analyze the data as a function of the agricultural activities;
3. develop a methodology and associated tools for targeting conservation

activities and assessing the potential impacts of conservation practices;

4. assess the economic impacts of the soil and water conservation projects implemented at the farm and watershed scales.

The work in this thesis was undertaken as part of the third task above.

3.3 Instrumentation

The stream gauging station at the outlet of the watersheds and a meteorological station on the Saint Esprit basin were installed by staff and students of the Department of Agricultural and Biosystems Engineering. The instrumentation for the gauging station was housed in a small building (1.8 m × 2.4 m) adjacent to a culvert (Figure 3.2). The building was supplied with AC power and heating. The stream gauging stations were equipped with: a tipping bucket rain gauge, water and air temperature sensors, a water level sensor installed on the stream bed bottom, an ultrasonic water level sensor mounted over the culvert (Figure 3.3), a datalogger located in the building to record and store data from all instruments, and a backup system consisting of a Flowlog datalogger. An automatic water sampler was also installed within each gauging station (Figure 3.4). The meteorological station was equipped with: sensors for air and soil temperature, solar radiation, wind speed and direction, snow accumulation, a tipping bucket rain gauge, and a datalogger (Figure 3.5).

3.4 Data collection

To accumulate knowledge on agricultural technology and the processes that

Figure 3.2 Saint Esprit gauging station

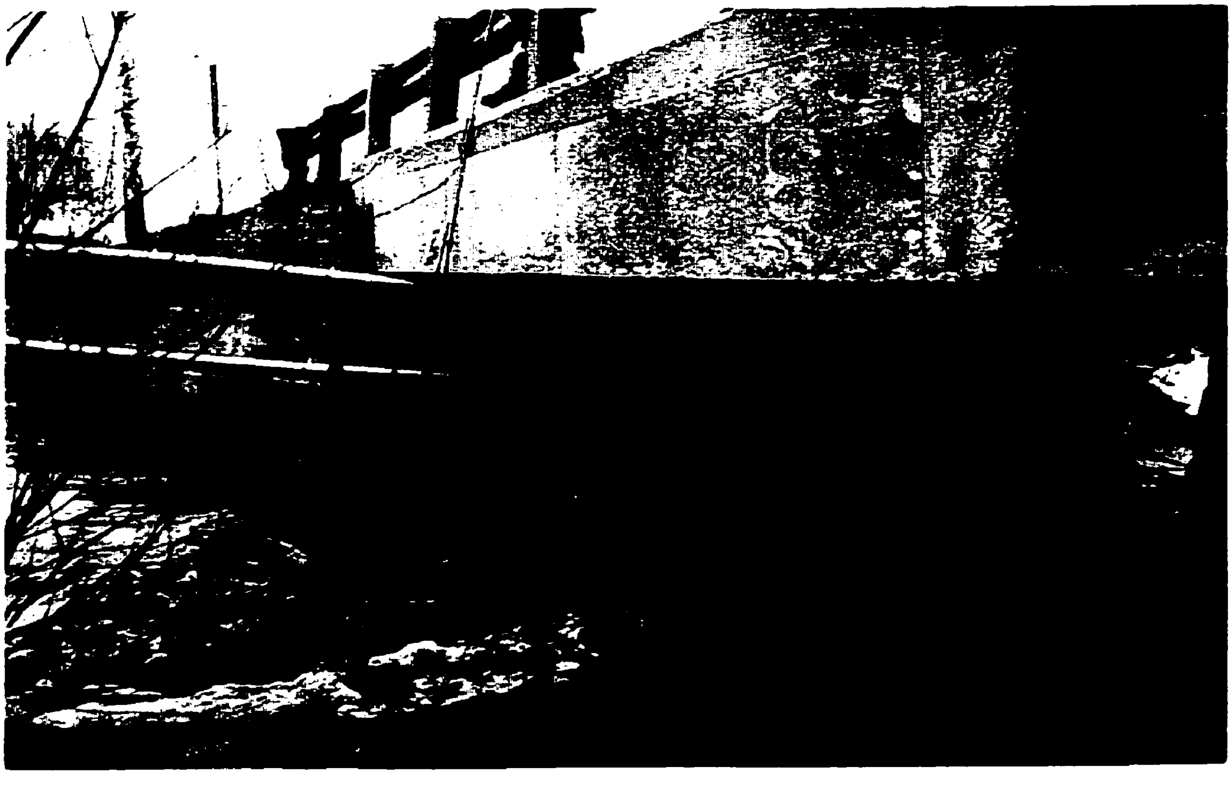


Figure 3.3 Ultrasonic level sensor over the Saint Esprit outlet culvert

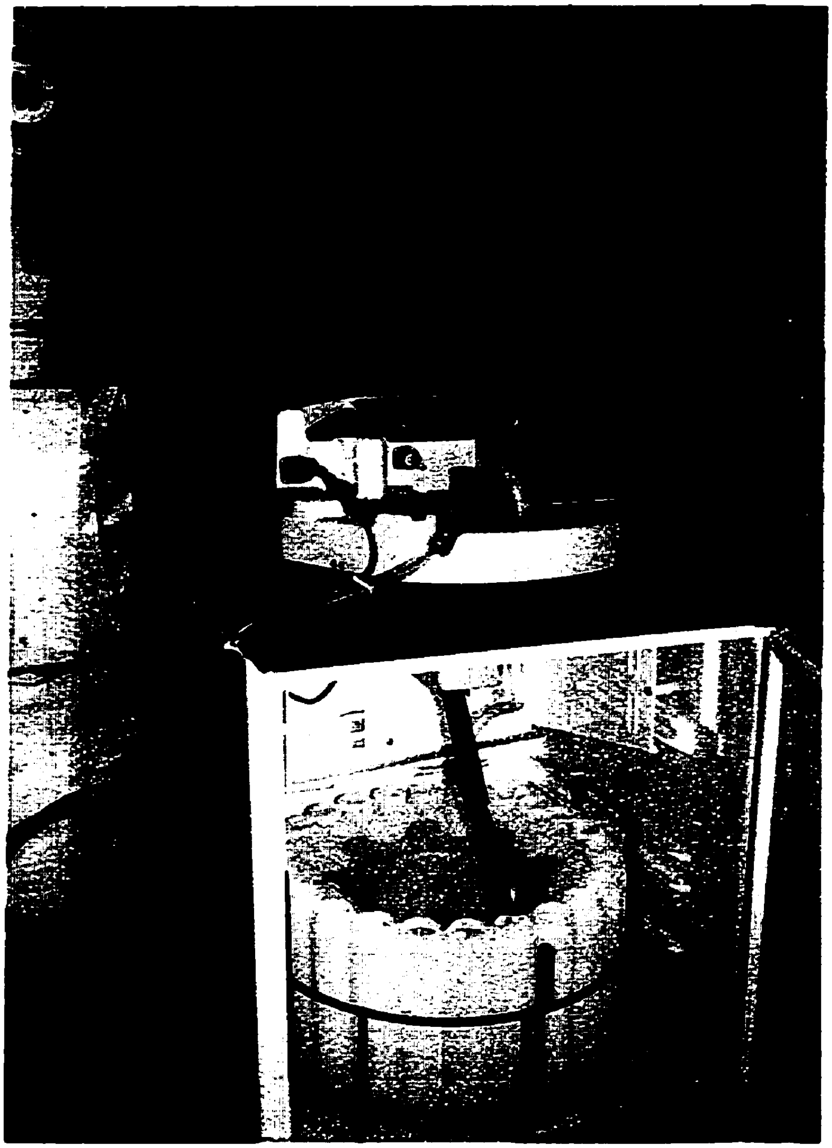


Figure 3.4 Water sampler and datalogger in the Saint Esprit gauging station

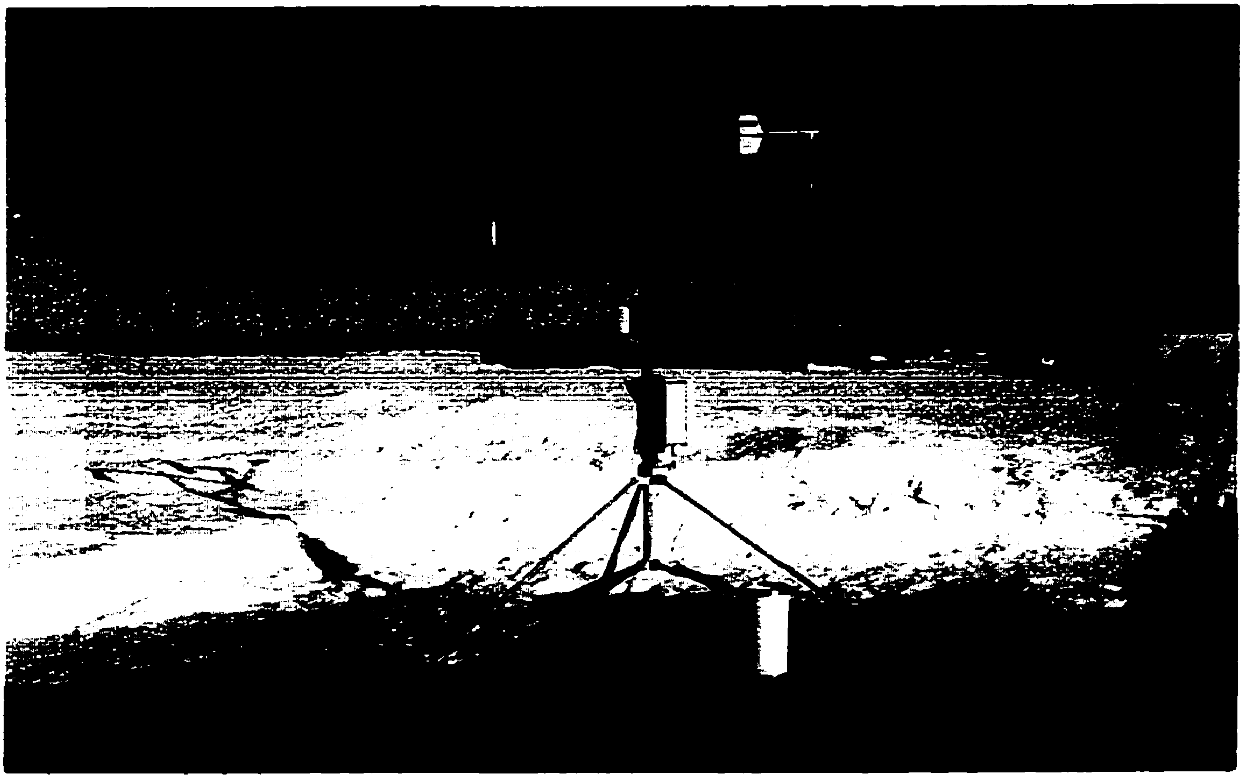


Figure 3.5 Saint Esprit meteorological station

cause contamination of surface waters, a wide range of data was collected (Papineau and Enright, 1997b). The data consist of:

- water quality monitoring
- climatic parameter measurement
- soil sampling
- field activities such as management practices, crop yield data, fertilizer, manure, and pesticide application, etc.

Box 3.1 shows chemical and physical parameters that were analyzed in water samples.

Box 3.1 Chemical and physical parameters measured

Category	Parameters	
Nutrients:		
	- nitrates (NO^{-}_{3}-N)	- ammonia (NH^{+}_{4}-N)
	- total phosphorous (P)	- orthophosphate (PO^{-2}_{4}-P)
	- total Kjeldahl nitrogen (TKN)	
	- potassium (K)	
Pesticides:	- atrazine	- deisopropyl atrazine
	- deethyl atrazine	- metolachlor
	- metribuzin	- cyanazine
	- carbofuran	- chlorthalonil
	- dactal	- linuron
Biological parameters:		
	- fecal coliforms	
	- total coliform bacteria	
	- fecal streptococcus bacteria	
	-biological oxygen demand (BOD_5)	
Physical parameters:		
	- suspended sediment	
	- dissolved oxygen	
	- pH	

Discharge, rainfall, air temperature, and water temperature were measured at each gauging station. The following climatic data were measured at the meteorological station:

- air temperature
- wind speed and direction
- precipitation intensity
- soil temperature at three depth
- relative humidity
- snow depth - solar radiation

A complete description of the project organization and sampling methodology can be found in Enright et al. (1995). Also, a detailed discussion of the seasonal variations of some of the 1994 measured water parameters is presented in Lapp et al. (1995). Papineau and Enright (1997a and 1997b) reported a detailed discussion of collected data, precipitation, nutrient, sediment concentrations, pesticides, and biological parameters. A detailed analysis of the project execution and results can be found in the final report (Enright et al., 1998).

CHAPTER 4

DEVELOPMENT OF THE SAINT ESPRIT SPATIAL DATABASE

4.1 Introduction

The development of the Saint Esprit spatial database was one of the objectives of this study. It was deemed necessary to:

i. tabulate baseline statistics for the intervention and control basins,
ii. establish a clear portrait of the agricultural activities on the watersheds,
iii. interpret the measured water quality results at the outlet of each watershed,
iv. prepare the input data to run hydrologic and water quality models.

The database was developed within SPANS GIS. Based on the literature review, SPANS GIS met the research requirements and was selected as the GIS software. In 1994, the first year of the study, version 5.2 of SPANS running under OS/2 version 2.1 was used. Through the years, it was upgraded to versions 5.3, 5.4 (running under OS/2 Warp), and in February 1997 version 6.0 (the Explorer) which ran under OS/2 Warp and Windows 95 was released. The last version of SPANS Explorer (version 7.0) was released in November 1997. The Saint Esprit spatial database was also continuously updated to take advantage of the lastest software improvements.

Collection of the spatial data was conducted at two scales. In the initial phases of the project, general data, most of it public domain, was collected for both watersheds. In the second phase, field level management data were collected on a field-by-field basis for the Saint Esprit basin.

In 1994, when the development of the database was initiated, none of the maps of interest were available in digital form. To establish the database the following public domain hardcopy maps were used:

Saint Esprit 1:20000 map number 31H 13-200-0202, published by *the Service de la cartographie, Ministère de l'énergie et des ressources du Québec* in 1993, and *Hydraulique agricole* 1:20000 map number 31 H/13 N.E., published by *the Ministère de l'agriculture du Québec,* were used to extract the watershed boundaries, streams, roads (Figure 4.1), and elevation information (Figure 4.2).

L'Assomption-Montcalm Counties Soils (1:63360) map published by the Research Branch, Canada Department of Agriculture, Ottawa in 1962. This map was used to extract natural drainage conditions, soil texture, and soil series information (Figure 4.3).

Ca*dastral* 1:20000 map number 31 H/13 N.E. published by *the Ministère de l'agriculture du Québec* in June 1975. This map (Figure 4.4) was used to develop the first landuse map for both the Saint Esprit and Desrochers

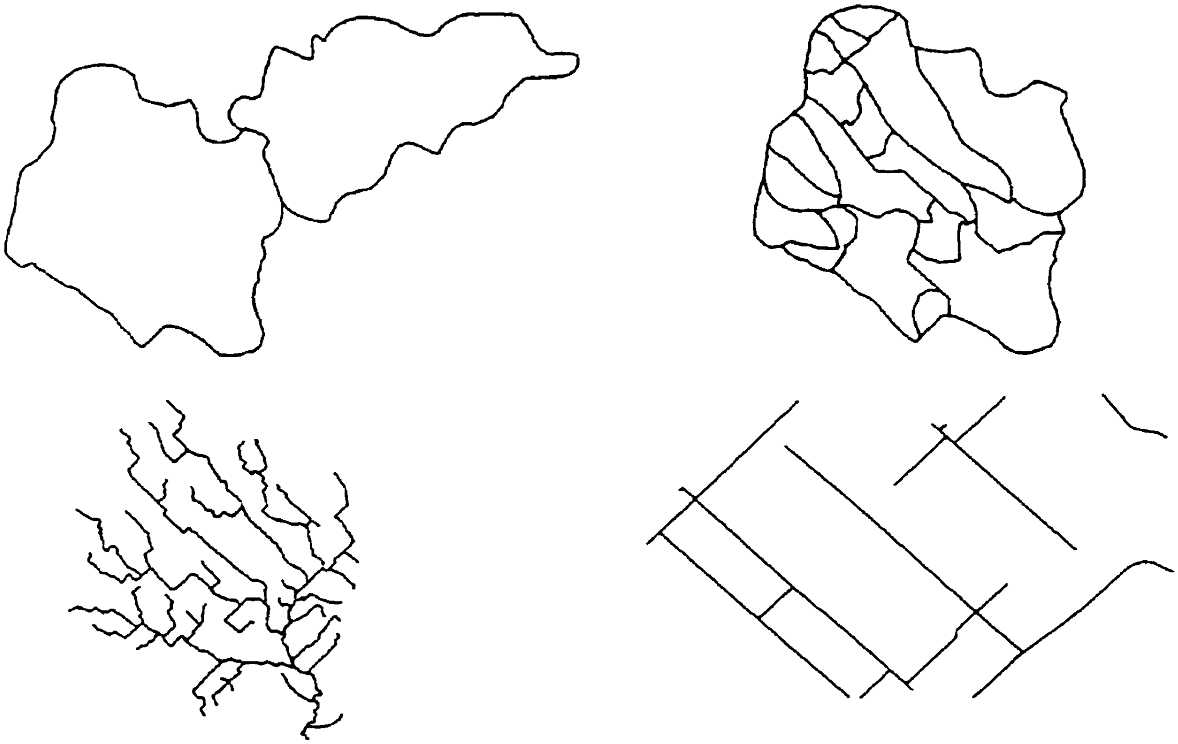


Figure 4.1 Digitized watershed boundaries, stream, and road data

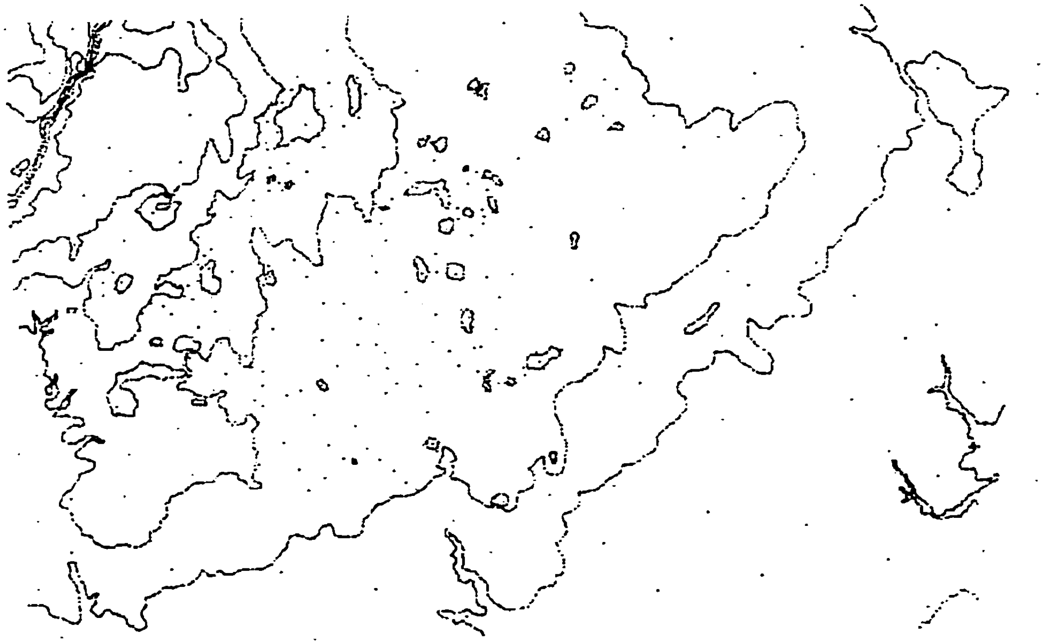


Figure 4.2 Digitized elevation data for both watersheds

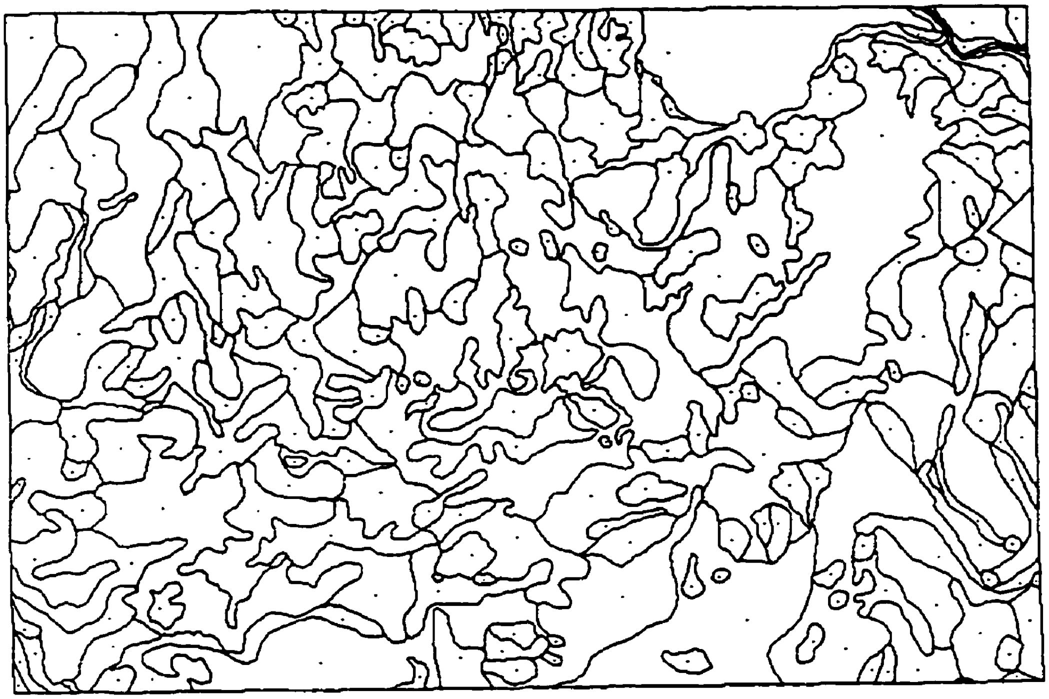


Figure 4.3 Digitized soil texture and series information for both watersheds

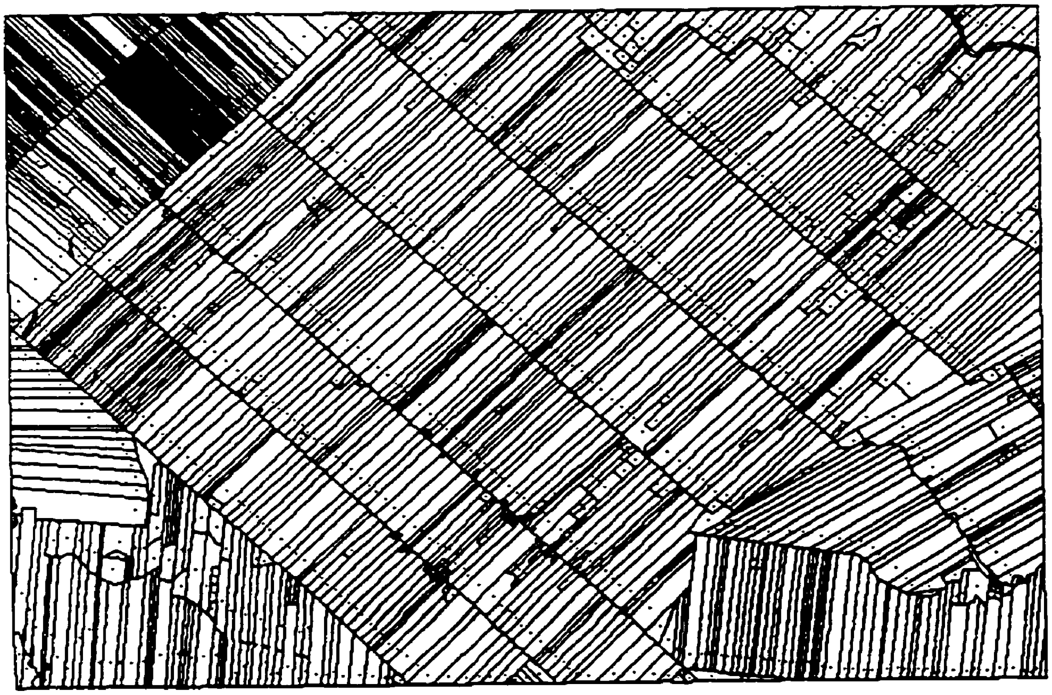


Figure 4.4 Digitized cadastral data for both watersheds

in 1994 (Figure 4.5) and landuse map for Desrochers in 1995 and 1996 (Figure 4.6). It was also used to develop a field map of individual farms (Figure 4.7).

The first step was to transfer the information from hardcopy maps to proper format files for use in SPANS GIS. SPANS TYDIG was selected to digitize these maps and make the necessary files for further work in SPANS GIS. The second step was to select and apply the SPANS GIS tools to build the database. Each of these steps is explained in detail in the TYDIG and SPANS GIS procedures below.

4.2 TYDIG procedures

SPANS TYDIG is a digitizing and editing system designed for manipulation of cartographic data and its related attributes. It provides a number of tools to create digital files from hard copy maps. The most important of these are related not only to the initial data capture but also to subsequent editing of the digital file. One of the main advantages of TYDIG compared to other digitizing and editing systems, such as AutoCad, was its ability to assign attributes to different entities.

For developing the database, three kinds of spatial entities had to be digitized. They were points, lines, and areas. TYDIG offers different methods to digitize these entities. Elevation (Figure 4.2), weather and stream gauging stations were digitized as points. The watershed

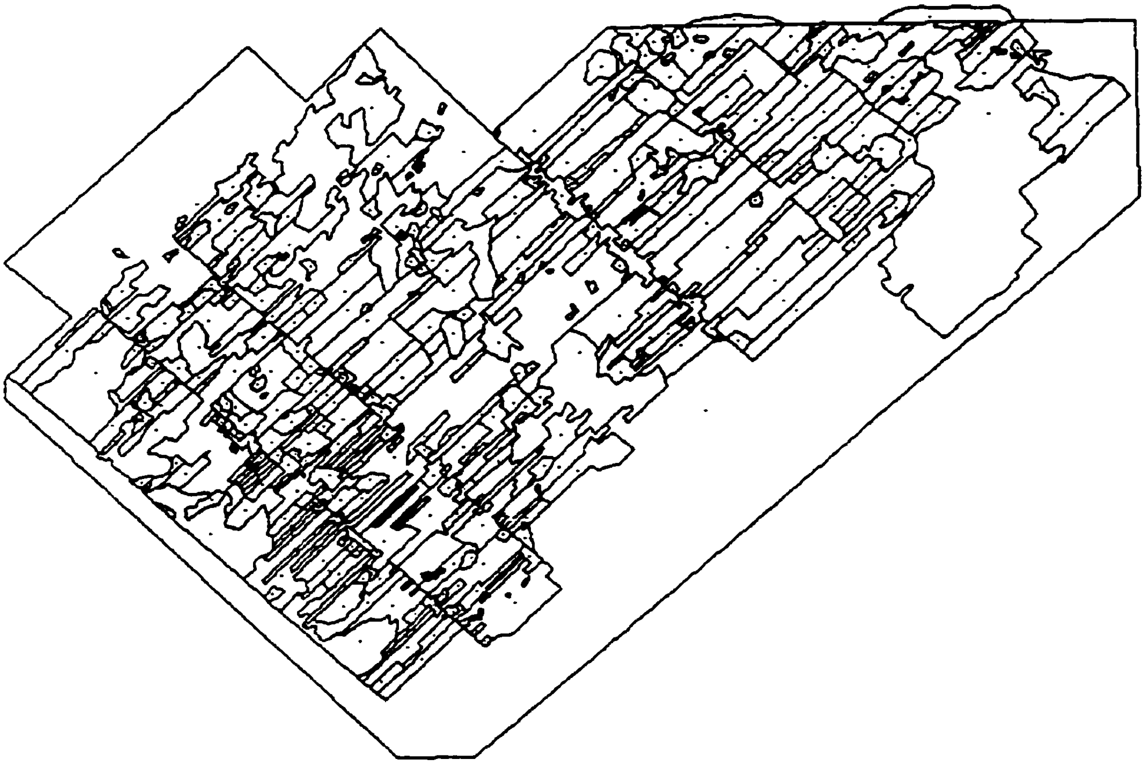


Figure 4.5 Digitized 1994 Landuse data for both watersheds

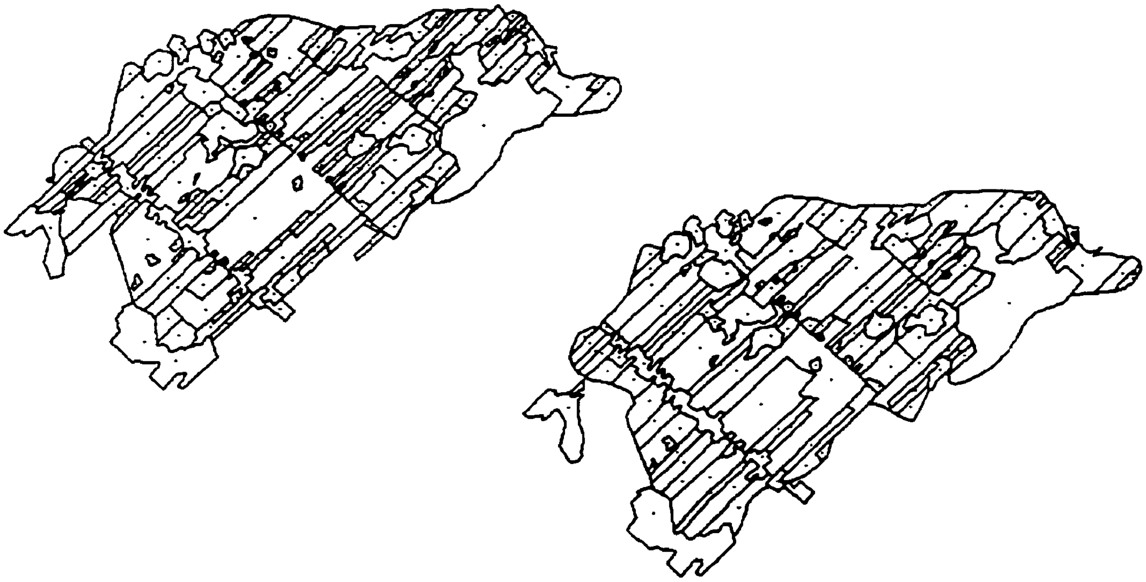


Figure 4.6 Digitized 1995 and 1996 Landuse data for the Desrochers watershed

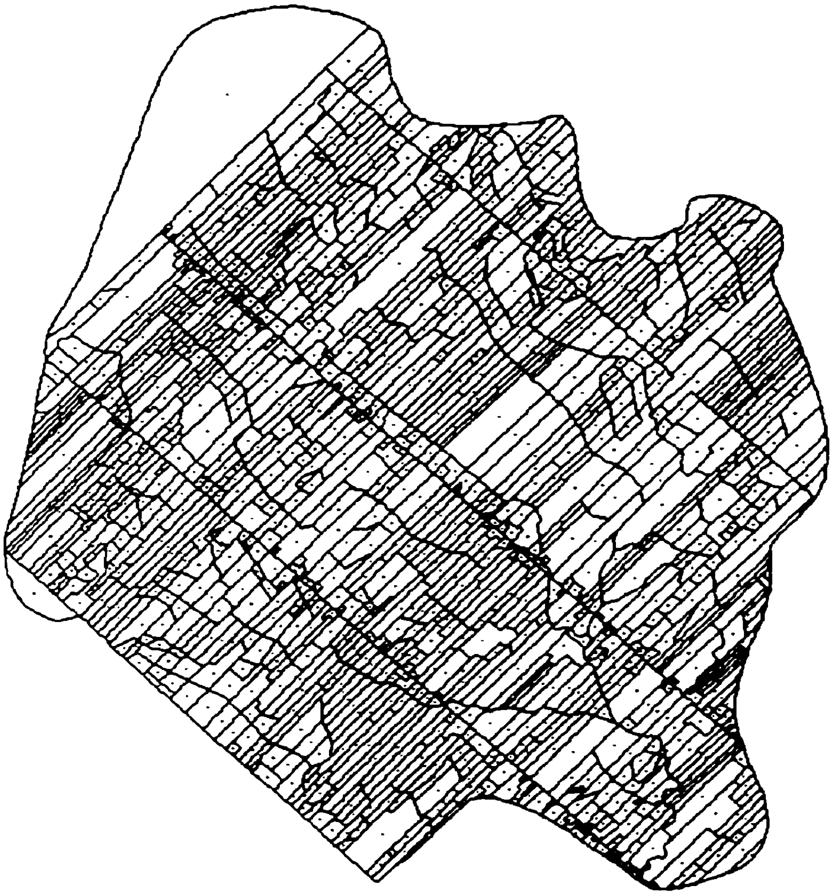


Figure 4.7 Digitized field data for the Saint Esprit watershed

boundries, streams, and roads (Figure 4.1) were digitized as arcs. The arc-nodepolygon method was selected to digitize different areas on soil, cadastral, and landuse maps for both watersheds in 1994, landuse for Desrochers in 1995 and 1996, and farm field maps (Figures 4.3, 4.4, 4.5, 4.6, 4.7 respectively). Arc-node polygons are formed from arcs intersecting at nodes. This system stores the vertices of arcs defining the polygon, rather than a closed set of x,y pairs. Polygon attributes were assigned to a special point digitized inside each of the polygons. Digitizing each layer of the above information was performed by:

1. selecting a project name (whether new or existing), and recording the appropriate data for the layer being digitized,
2. calibrating the digitizing tablet,
3. digitizing ground control points,
4. digitizing the entities,
5. assigning attributes, and
6. exporting data to SPANS GIS. At the end of the fifth step once digitizing was completed and attributes assigned, five types of file were created.

A brief description of each type of file and its contents is given below:

1. *layername.hdr* A header file containing the information entered during the Project Setup, Project Description Entry and Ground Control Point Entry screens. This data were recorded for reference only.

2. *layername.crd* A coordinate file to store x,y coordinate pairs of digitized points and vertices.

3. *layername.fmt* A format file to hold key project information, including ground control points.

4. *layername.dir* A directory file containing a list of all the digitized entities (lines and points) , along with any attribute codes, and the information about their spatial relationships to each other (i.e. their topology).

5. *layername.hst* A history file which recorded all operations that took place in the project.

TYDIG has three options for exporting the digitized layers to SPANS GIS. They are: exporting without topology, with arc/node topology, and with left/right topology. Of these, exporting without topology gave the best results. This step also created a file pair with extensions of ".vec" and ".veh" and a file with extension of ".oft" for each layer. The ".vec/.veh" file pair is the ASCII format for vector archiving and data interchange. The ".veh" (header) file describes the global parameters of the ".vec" (data) file, as well as the data itself. The ".vec" file consists of one or more data sections which are described by the corresponding header records in the ".veh" file. The data sections of the ".vec" file may contain data for nodes, points, arcs or areas. Each section consists of records that occur on a separate line. Only the ".vec/.veh" file pair was exported to SPANS GIS.

4.2.1 Common digitizing errors

In principle, digitizing is easy. In practice, a number of difficulties are encountered and a number of errors can be introduced into the digital files. Digitizing the nodes and line segments making up the raw vector data of the maps requires concentration and a steady hand. If either is lacking, errors can result which may only show up later in SPANS GIS procedures, when building topology, for example. Dangles, non-intersecting or crossing lines (also known as spaghetti), and knots were the most common digitizing errors that occurred. Sometimes finding and correcting the errors took the same amount of time as the digitizing itself. To avoid this problem, especially with maps containing a significant numbers of polygons, i.e. farm field data (Figure 4.7), each polygon was assigned a unique identity number to facilitate error checking and data correction.

4.3 SPANS GIS procedures

All the layers necessary to build the Saint Esprit spatial database were successfully digitized with TYDIG. The appropriate ".vec/.veh" file pairs were imported into SPANS GIS to create the different data layers. They were then copied to the corresponding SPANS GIS sub-directory to create the Saint Esprit study area.

4.3.1 Study area setup and basemap creation

In SPANS GIS, a study area is a directory that contains a complete set of files pertaining to a specific geographic area. Defining the Saint Esprit study area involved three steps:

1. Identifing the directory that holds all imported ".vec/.veh" file pairs.
2. Establishing the projection: A projection is a mathematical formula which is used to reduce the amount of distortion appearing when the three dimensional, curved surface of the earth is projected onto a flat, two dimensional surface. Universal Transverse Mercator (UTM), zone 18, was selected.
3. Setting the extents of the study area: The extents define the physical limits of the area. The digitized ".vec/.veh" file pairs of the cadastral map were used.

These setup steps were required only once. Once the Saint Esprit study had been defined, all other operations were done in the same study area. The following SPANS GIS functions were used, in respective order for the steps:

"File \ New Study area \ Create" and *"File \ New Study area \ Open"*
"File \ New Study area \ Establish projection \ Interactively"
"File \ New Study area \ Set extents \ From vector".

Many SPANS functions require a basemap. A basemap is a quadtree map which represents the boundaries of the area. The basemap of the Saint Esprit watershed (Figure 4.8) was created after defining the study area.

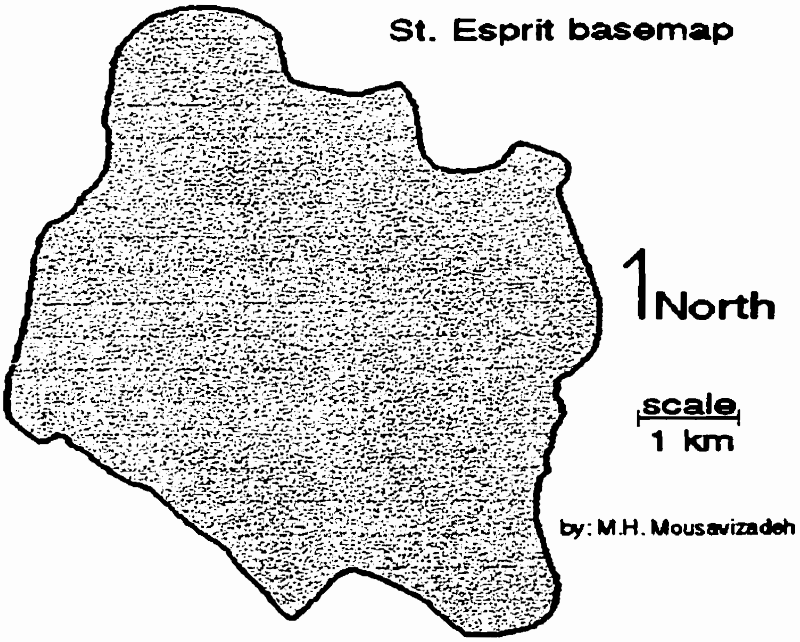


Figure 4.8 Saint Esprit basemap

4.3.2 Development of spatial data layers

The Saint Esprit spatial data layers were grouped into three categories. The first group contained all of the point and line layers. They were weather and gauging stations, watershed boundaries, streams, and access roads. All of the area layers such as soil texture, soil series, subwatershed areas, and farm ownership were listed in the second group. Contour, slope and aspect layers which needed to be created from elevation points, were assigned to the third group.

Some of the SPANS GIS functions were recognized as the best tools to use for developing the data layers. They will be mentioned within each group below. The first group of data layers (Figure 4.9) was created as a vector using the "*Transform \Import \ Vectors*" function.

Assigning a topology to different areas, i.e. in soil and farm data, inside TYDIG was tedious and prone to errors. The following technique was found to be the best method:

i. digitizing the area as vectors without topology;
ii. digitizing a point within each area, assigning the polygon attribute to a level or feature associated with the point;
iii. assigning the point attributes back to the polygons using the following SPANS GIS functions:
   "Transform \Import \ Vectors"

"Transform \Data types \ Vectors to Polygons"
"Transform \Data types \Polygons to map"
"Transform \Import \Points".

The same technique was used to create the data layers in the second group. Once these steps had been completed, the following functions were used to build soil texture (Figure 4.10), soil series (Figure 4.11), subwatershed (Figure 4.12), and farm (Figure 4.13) maps:

"Edit \Library \Legend \Create"
"Model \Points \Append class"
"Model \Reclassification \Build map \From table"
"Edit \Library \Map information"
"Visualize \Entities \Maps".

Contour (Figure 14), slope (Figure 15), and aspect (Figure 16) maps were in the third group. They should be made from digitized elevation points (Figure 4.2). Three surface interpolation methods are available in SPANS GIS. They are Contouring, Potential Mapping and Point Aggregation:

1. *Contouring*: The Contouring method uses a triangulated irregular network (TIN) algorithm. The TIN algorithm works on the basis of a distribution of points. All points are connected to their nearest points to form a TIN. Each triangle in the network forms a plane (Figure 4.14) with

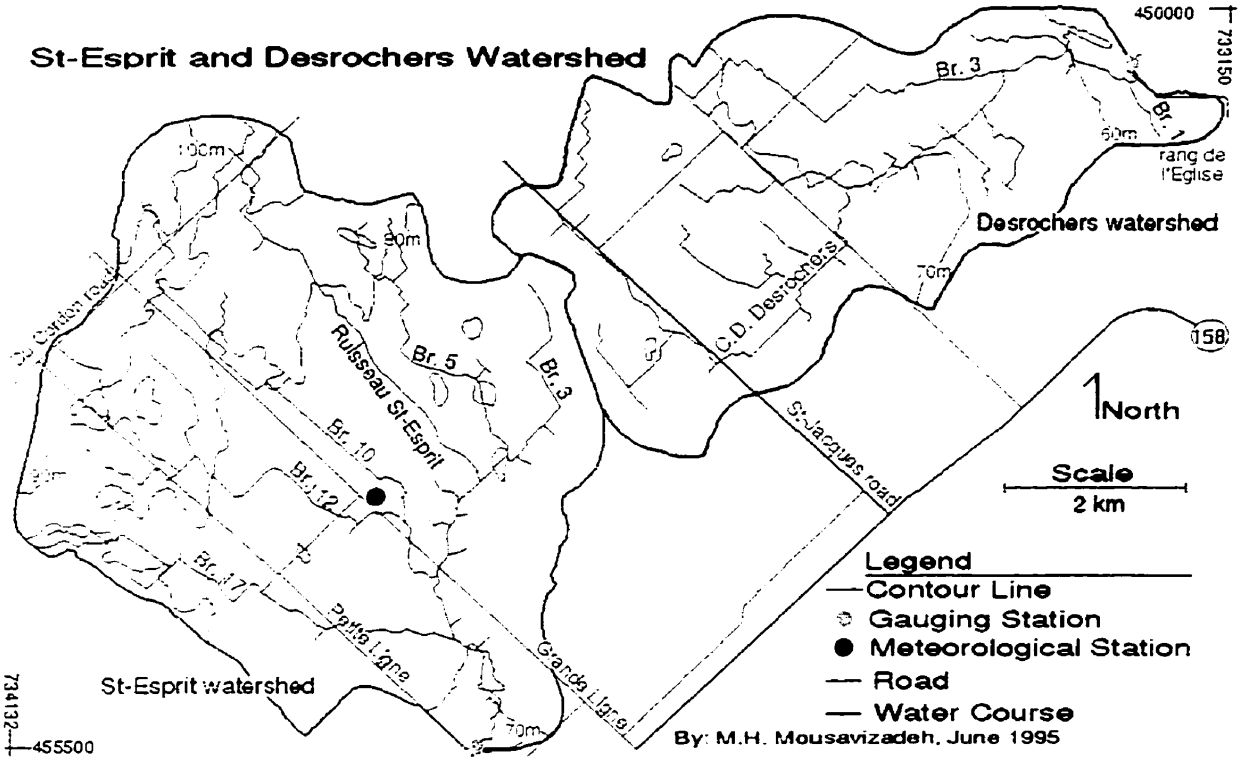
the value at each point represented by the height of the plane at the point. The surface is thus constrained to pass through the data points.

2. *Potential Mapping*: Potential mapping applies a moving weighted average function to the point data to derive a surface for the attribute of the point being mapped. A circular sampling window is moved over the data points, and at each position of the window the contained points are weighted.

3. *Point Aggregation*: This method generates a map by aggregating points based on spatial criteria. The map is comprised of variable sized cells. The size of each cell is determined by a criterion based on the number of points occurring within each cell.

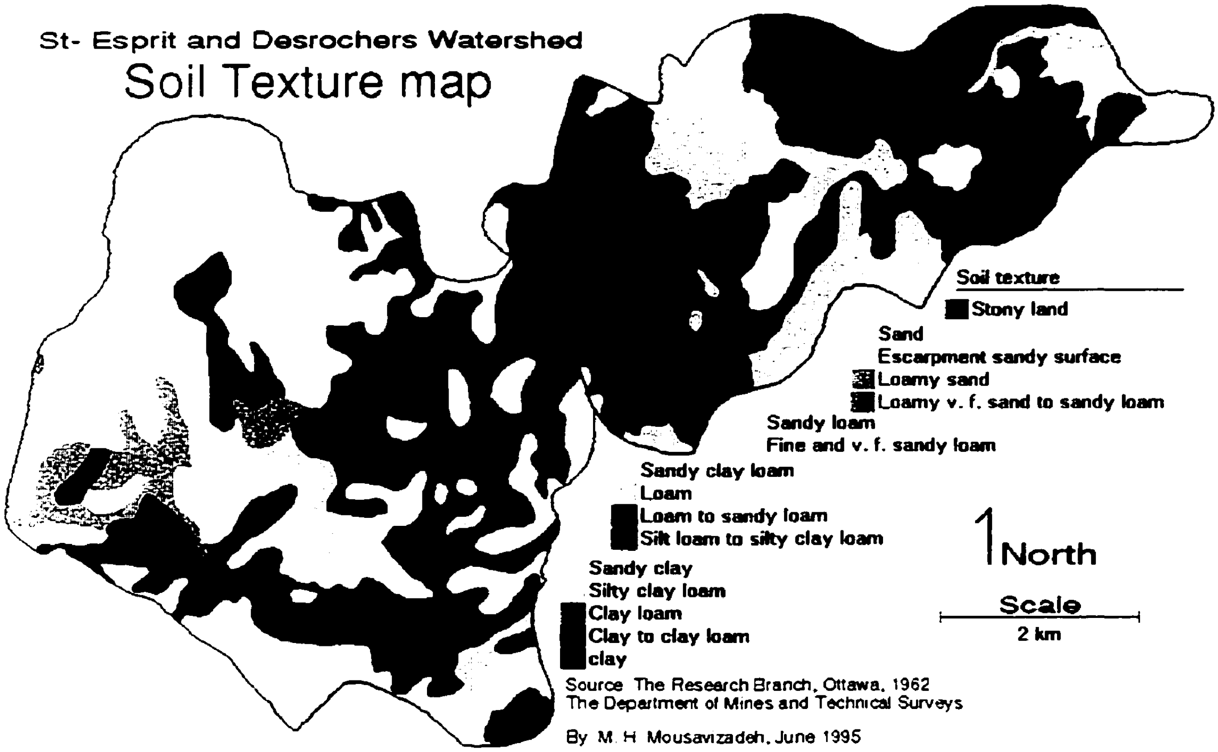
The Contouring method was found to be the most appropriate for elevation point data that represents a continuous phenomena. This method generated reasonable contour, slope and aspect maps (Figures 4.14, 4.15, and 4.16). The following SPANS GIS functions were used:

"Transform \ Import \ Vectors"
"Transform \ Import \ Points"
"Edit \ Library \ Classification"
"Edit \ Library \ Legend \ From Classification"
"Transform \ Data type \ Points to map \ Contouring "



By: M.H. Mousavizadeh, June 1995

Figure 4.9 General view of both basins



Source The Research Branch, Ottawa, 1962
The Department of Mines and Technical Surveys

By M. H. Mousavizadeh, June 1995

Figure 4.10 Soil texture map

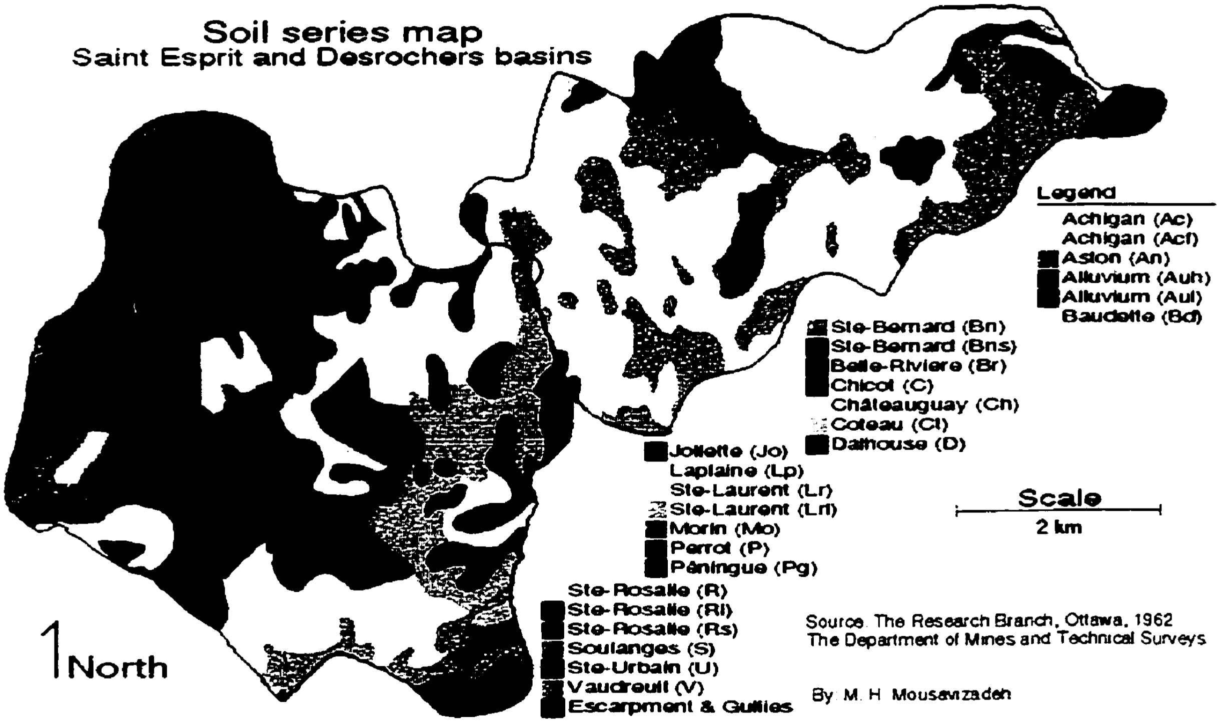


Figure 4.11 Soil series map

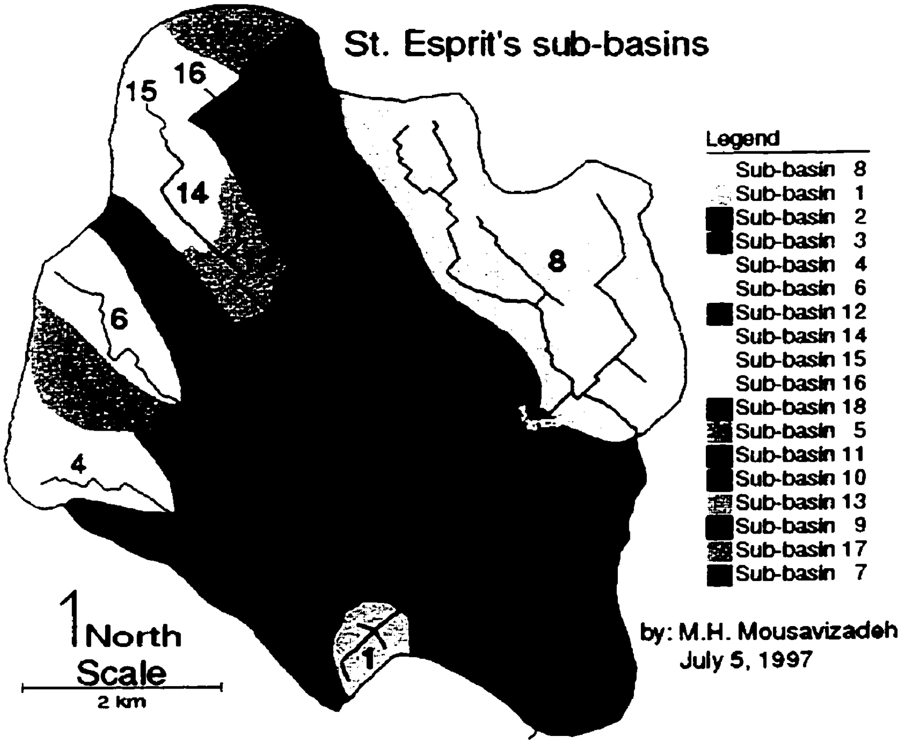


Figure 4.12 Saint Esprit subwatershed map

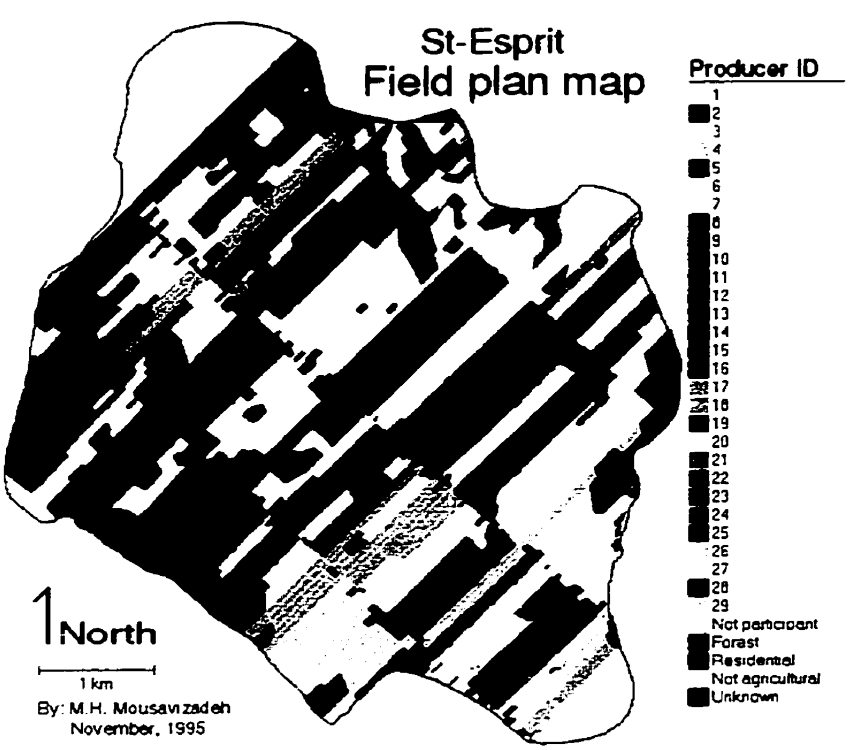


Figure 4.13 Field map

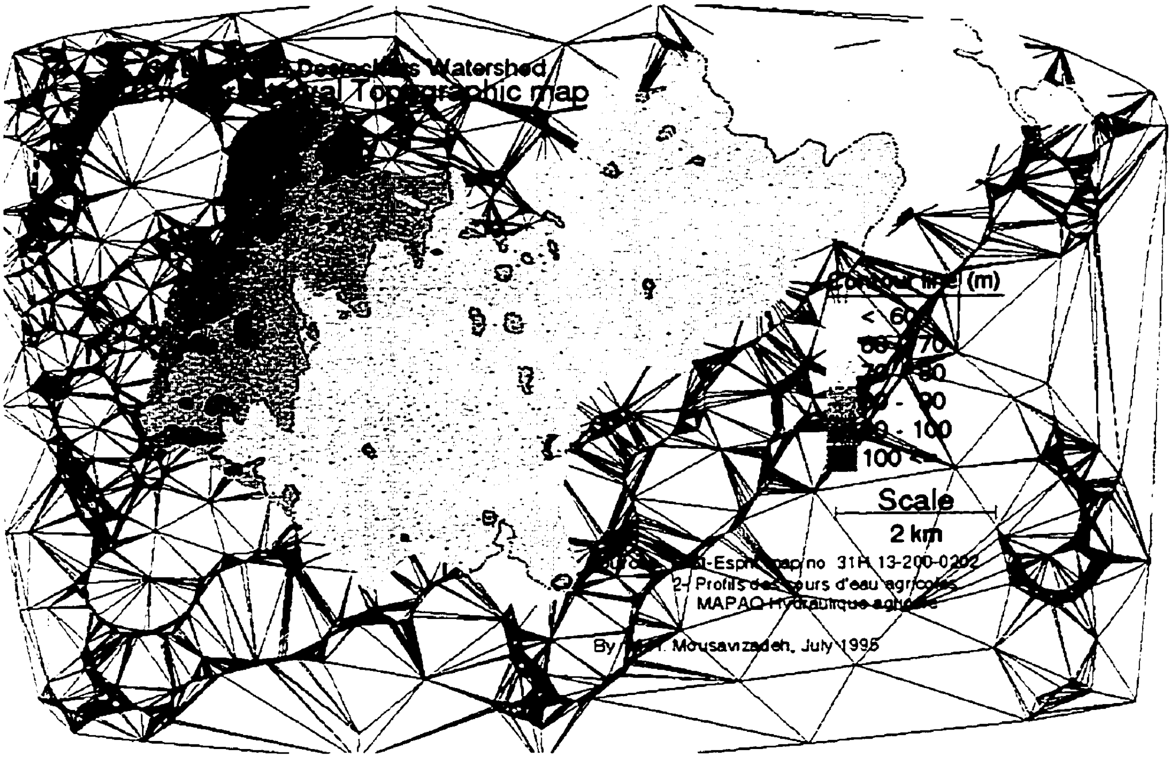


Figure 4.14 Contour map

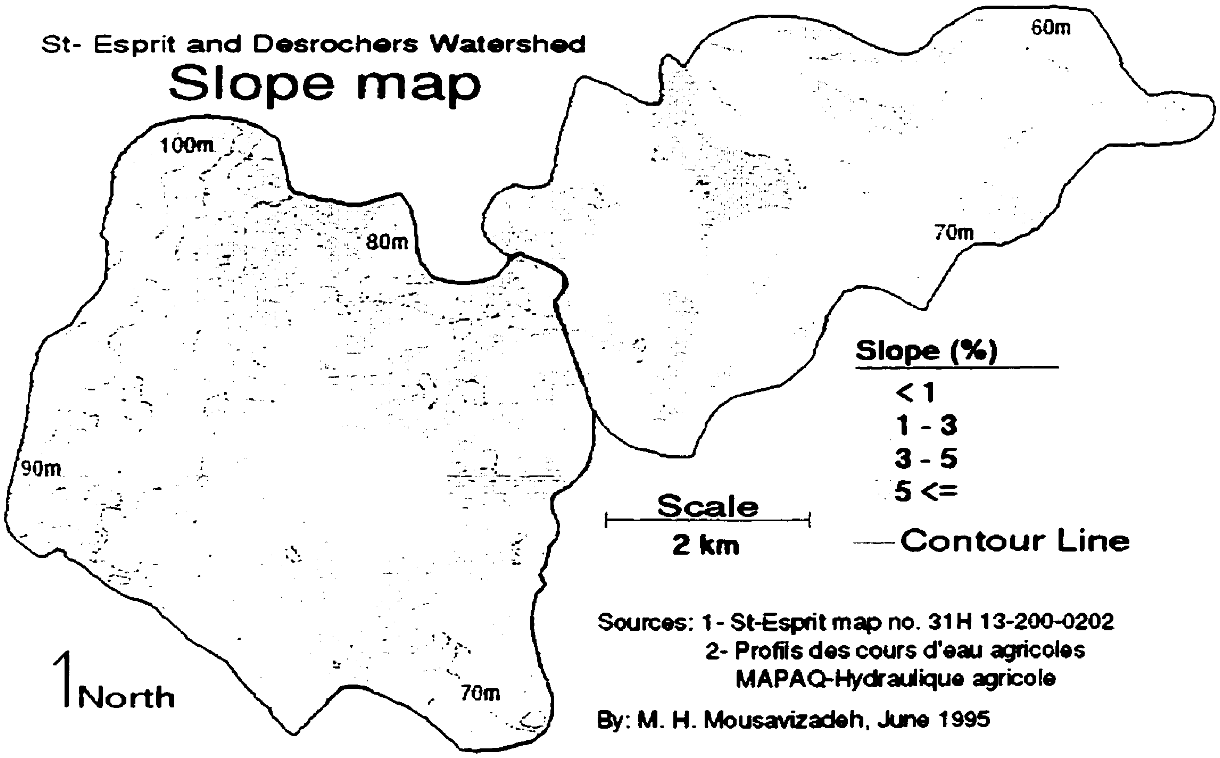


Figure 4.15 Slope map

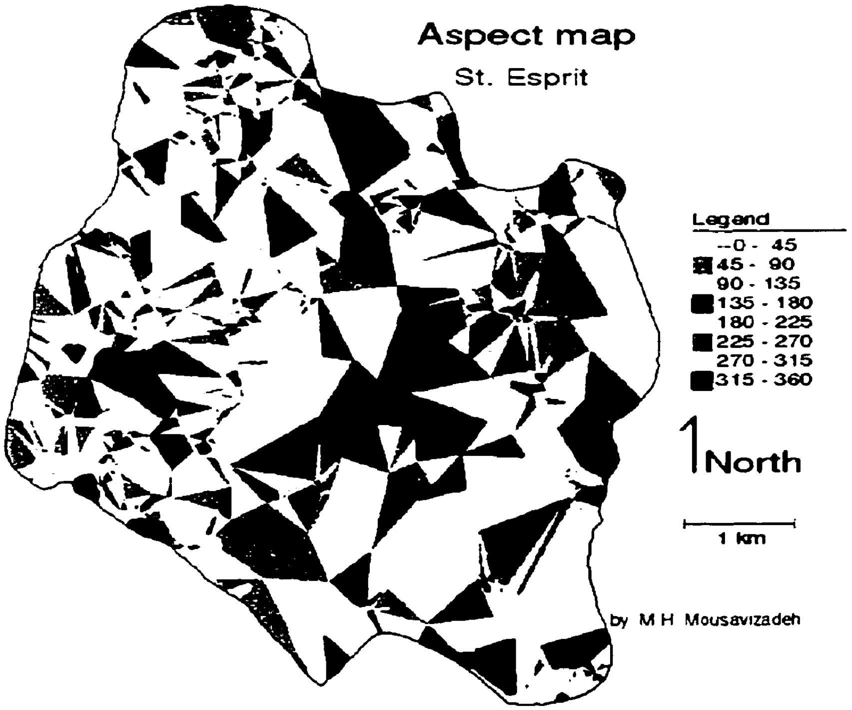


Figure 4.16 Aspect map

The elevation data (Figure 4.2) was digitized from the national topographic map. Topographic information on the national topographic maps is limited, with the contour interval being 10 m. On the Saint Esprit basin, a relatively small watershed, this provided only a minimum level of detail. We investigated the possibility of having a new map developed for the area with a contour interval of 2 m, but it was prohibitively expensive. Additional elevation data were obtained from the watercourse profiles. The combination of the watercourse profile and the national topographic map data provided a reasonably accurate picture of topography. It was used to develop acceptable contour, slope, and aspect maps.

4.3.3 Development of a methodology to create new data layers

The collection of the spatial data was conducted at two scales. In the initial phases, general data were collected. They were converted to SPANS GIS format as described in section 4.3.2. In the second phase, field level management data were collected on a farm-by-farm basis on the basin. The amount of data collected was huge. It included: availability of field data; landuse in 1994, 1995, and 1996; a detailed portrait of fertilizer, manure and herbicide application practices in 1994, 1995, and 1996; phosphorous and soil organic matter information from 1994 soil fertility analysis; and subsurface drainage information. It was practically impossible to digitize this huge amount of data. To manage and use this data the **field attribute database** was created. Air photos, at a scale of

1:15000 were obtained for each farm. These photos were enlarged to 1:5000 and a farm plan was developed for each farm, to identify each field. Based on these photos, the cadastral map and land ownership information, the fields were located, identified, digitized, and constructed in SPANS GIS format. Once the field map (Figure 4.13) was created, a file containing the field label, location, and an ID number was exported from SPANS GIS, and imported into a spreadsheet. All data collected at the farm level were coded and entered into the spreadsheet database by their farm ID identifier. The result was a large table that contained a wide range of spatial information. Table 4.1 shows only a few rows and columns of this information. The whole table is available on the Saint Esprit spatial database on the attached CD ROM. An advanced SPANS "***PNTBA***" utility was used to convert the information table to a SPANS ASCII table file (".tba"). The "*Transform\Import\Points*" function was used to import the table file ".tba" as a binary table file ".tbb" into SPANS GIS. Then the "*Points\Append class*" and "*Model\Reclassification\Build map\From table*" SPANS GIS functions were used to create the following maps from imported ".tbb" files:

landuse maps for 1994, 1995, and 1996 (Figure 4.17),

the data availability field data map (Figure 4.18) which shows participating verses non-participating farms,

the subsurface drainage map (Figure 4.19),

the soil phosphorous fertility map (Figure 4.20),

and fertilizer application maps (Figure 4.21 and 4.22).

Table 4.1 The field attribute database

```
" Mohammad H. Mousavizadeh - July 6, 1997   " 45.9557 -73.6869  123 " 30 1 30 1 FOREST"        2000 31 2 2
" ***************************************** " 45.9573 -73.6842  129 " 11 1 11 1 FARMER #1    "   300 11 1 2
"This is README for data.pnt file. It       " 45.9307 -73.6312 3780 " 30 2 30 2 RESIDENTIAL." 2500 32 2 2
"describes each column in the file. For each" 45.9315 -73.6324 3781 " 30 2 30 2 RESIDENTIAL." 2500 32 2 2
"column's legend description refer to       " 45.9312 -73.6326 3782 " 30 2 30 2 RESIDENTIAL"  2500 32 2 2
"the attachment at the end of this file.    " 45.9318 -73.6337 3783 " 30 2 30 2 RESIDENTIAL"  2500 32 2 2
"                                           " 45.9320 -73.6333 3784 " 30 2 30 2 RESIDENTIAL"  2500 32 2 2
"The origin of this file is field.pnt. After" 45.9329 -73.6346 3785 " 30 2 30 2 RESIDENTIAL"  2500 32 2 2
"the filed map is digitized it has been used" 45.9327 -73.6348 3786 " 30 2 30 2 RESIDENTIAL"  2500 32 2 2
"to develop other maps based on the field   " 45.9329 -73.6352 3787 " 30 2 30 2 RESIDENTIAL"  2500 32 2 2
"information from different resources.      " 45.9340 -73.6367 3788 " 30 2 30 2 RESIDENTIAL"  2500 32 2 2
"                                           " 45.9336 -73.6348 3789 " 30 2 30 2 RESIDENTIAL"  2500 32 2 2
"col. 1 is this column (readme)             " 45.9344 -73.6375 3790 " 30 2 30 2 RESIDENTIAL"  2500 32 2 2
"                                           " 45.9348 -73.6371 3791 " 30 2 30 2 RESIDENTIAL"  2500 32 2 2
"col. 2 is latitude                         " 45.9347 -73.6379 3792 " 30 2 30 2 RESIDENTIAL"  2500 32 2 2
"                                           " 45.9354 -73.6389 3793 " 30 2 30 2 RESIDENTIAL"  2500 32 2 2
"col. 3 is longitude                        " 45.9364 -73.6408 3794 " 30 2 30 2 RESIDENTIAL"  2500 32 2 2
"                                           " 45.9376 -73.6426 3795 " 30 2 30 2 RESIDENTIAL"  2500 32 2 2
"col. 4 is SPANS code                       " 45.9382 -73.6431 3796 " 30 2 30 2 RESIDENTIAL"  2500 32 2 2
"                                           " 45.9407 -73.6472 3797 " 30 2 30 2 RESIDENTIAL"  2500 32 2 2
"col. 5 and 6 are Paul Lapp's code for each " 45.9414 -73.6482 3798 " 30 2 30 2 RESIDENTIAL"  2500 32 2 2
"    farm                                   " 45.9420 -73.6492 3799 " 30 2 30 2 RESIDENTIAL"  2500 32 2 2
"                                           " 45.9426 -73.6498 3800 " 30 2 30 2 RESIDENTIAL"  2500 32 2 2
"col. 7 and 8 are modified Paul code by     " 45.9441 -73.6510 3801 " 30 2 30 2 RESIDENTIAL"  2500 32 2 2
"    Mohammad                               " 45.9440 -73.6520 3802 " 30 2 30 2 RESIDENTIAL"  2500 32 2 2
"                                           " 45.9457 -73.6542 3803 " 30 2 30 2 RESIDENTIAL"  2500 32 2 2
"col. 9 is farm ownership                   " 45.9477 -73.6559 3804 " 30 2 30 2 RESIDENTIAL"  2500 32 2 2
"                                           " 45.9484 -73.6572 3805 " 30 2 30 2 RESIDENTIAL"  2500 32 2 2
"col. 10 is Mohammad's code for each farm   " 45.9482 -73.6594 3806 " 30 2 30 2 RESIDENTIAL"  2500 32 2 2
"    (for legend discription see Attac. 1)  " 45.9488 -73.6608 3807 " 30 2 30 2 RESIDENTIAL"  2500 32 2 2
"                                           " 45.9501 -73.6607 3808 " 30 2 30 2 RESIDENTIAL"  2500 32 2 2
"col. 11 is Land Ownership (Attach. 2)      " 45.9503 -73.6599 3809 " 30 2 30 2 RESIDENTIAL"  2500 32 2 2
"                                           " 45.9512 -73.6602 3810 " 30 2 30 2 RESIDENTIAL"  2500 32 2 2
"col. 12 is availability of Field Plan      " 45.9518 -73.6622 3811 " 30 2 30 2 RESIDENTIAL"  2500 32 2 2
"    1=yes, 2=no                            " 45.9523 -73.6630 3812 " 30 2 30 2 RESIDENTIAL"  2500 32 2 2
```

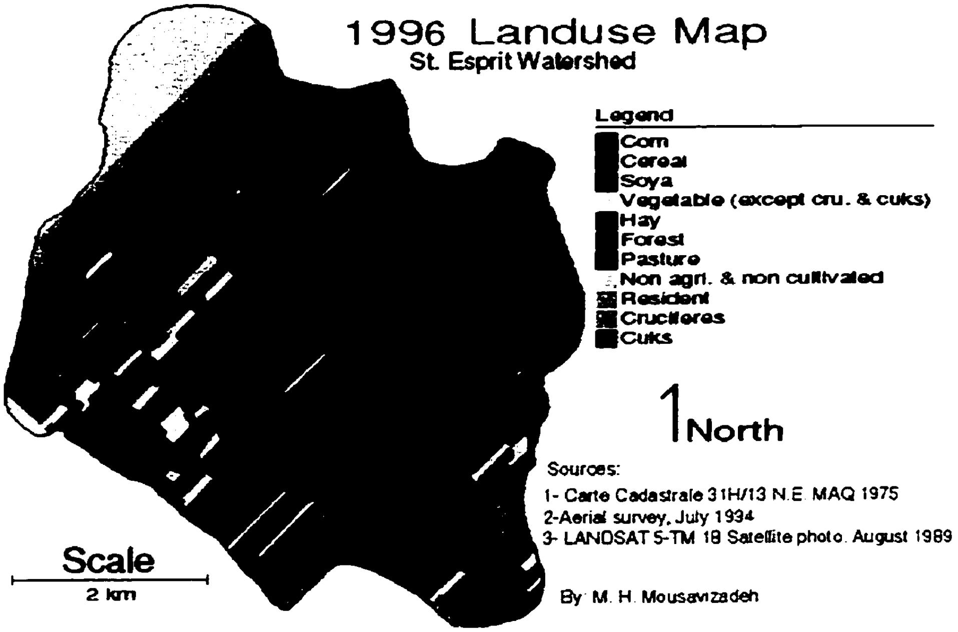


Figure 4.17 1996 Landuse map

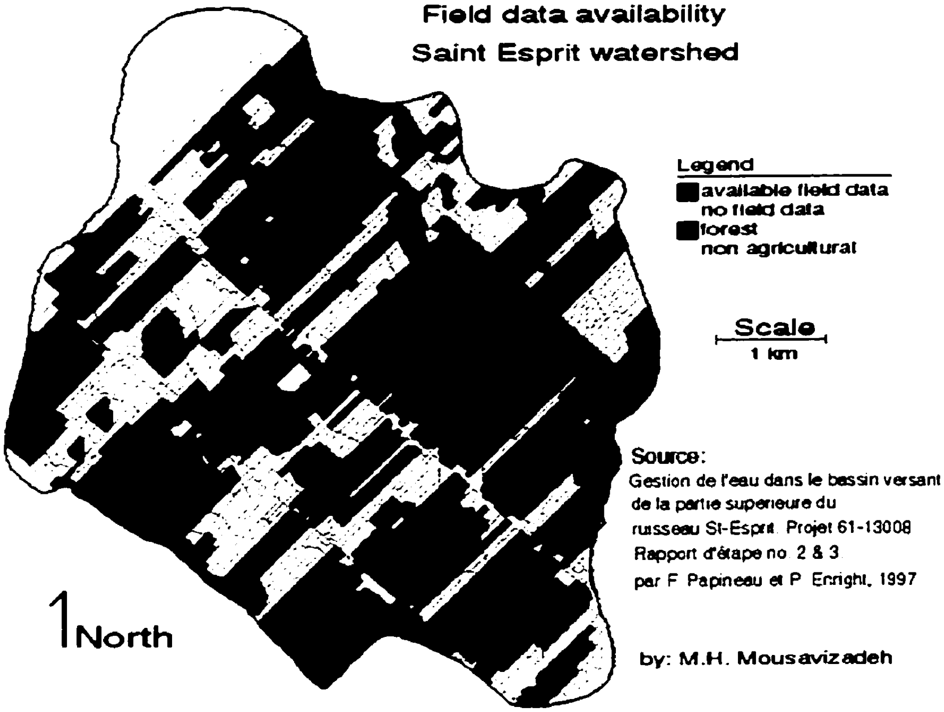


Figure 4.18 Data availability map (schematic of fields that have data available from participating farmers)

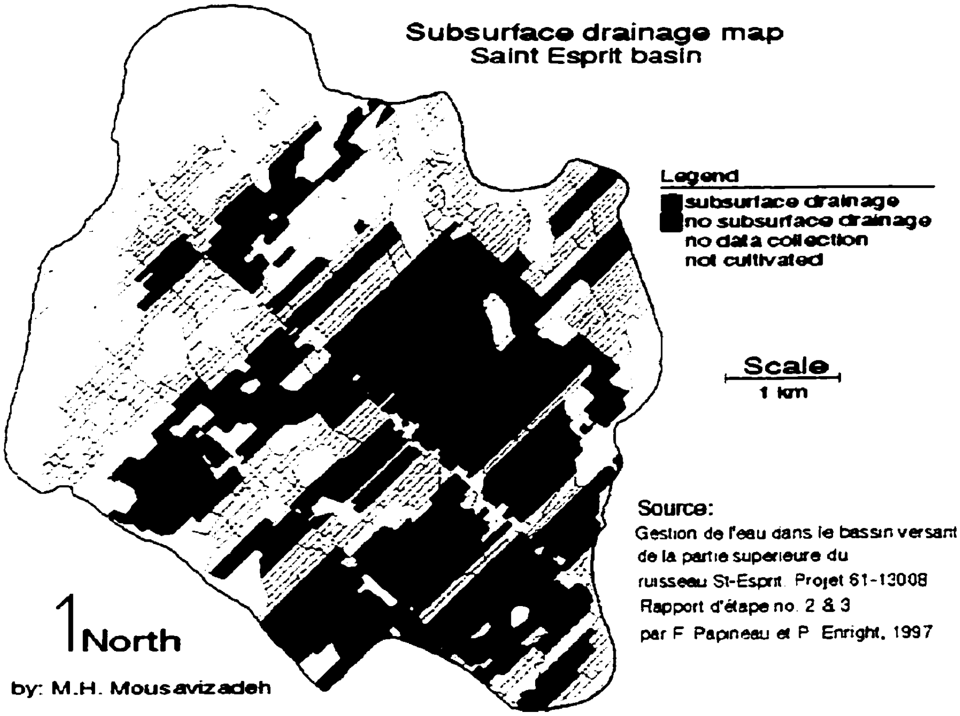


Figure 4.19 Subsurface drainage map

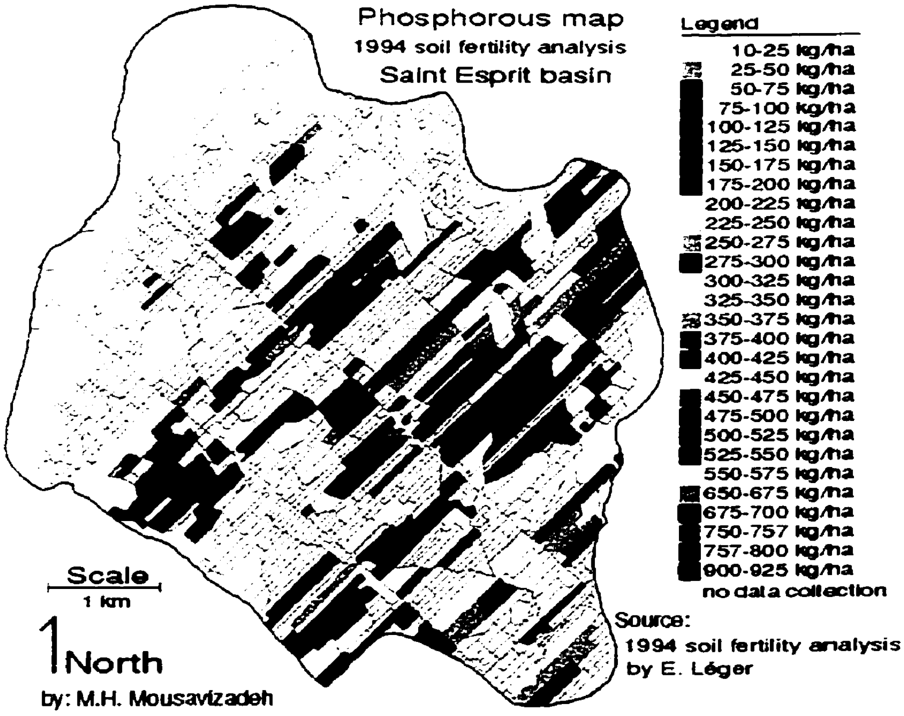
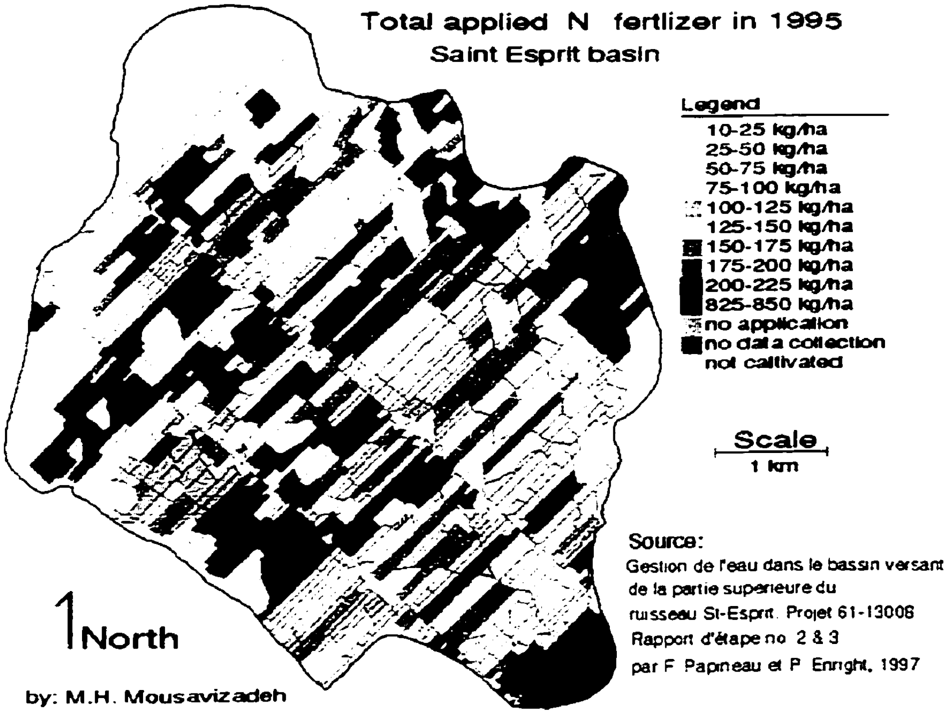
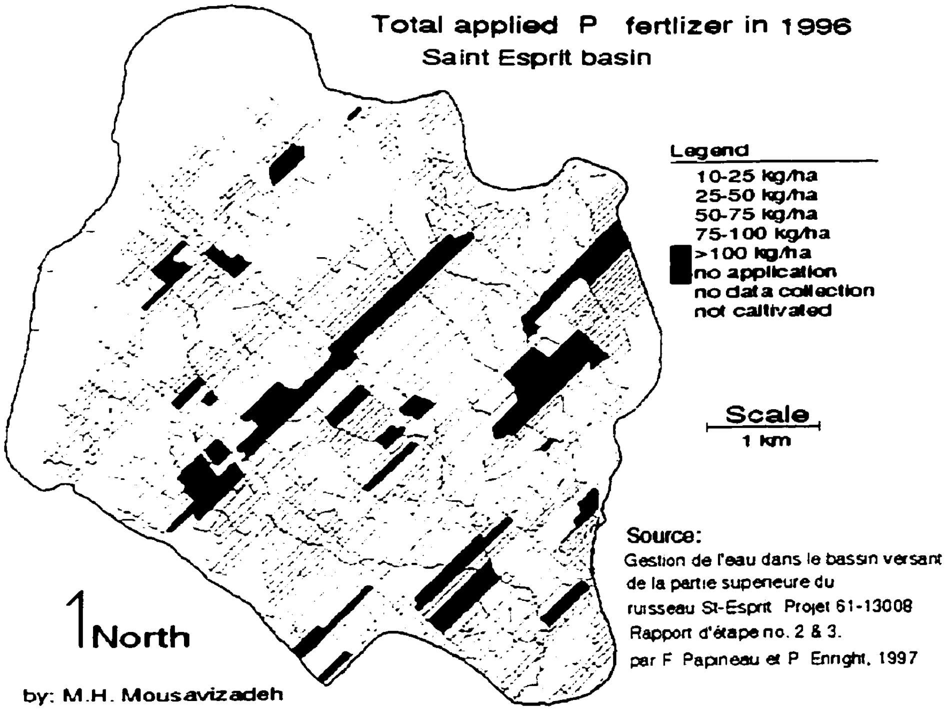


Figure 4.20 1994 Soil phosphorous fertility analysis map


Total applied N fertlizer in 1995
Saint Esprit basin

Source:
Gestion de l'eau dans le bassin versant de la partie superieure du ruisseau St-Esprit. Projet 61-13008 Rapport d'étape no 2 & 3 par F Papineau et P Enright, 1997

Figure 4.21 1995 applied N fertilizer map


Total applied P fertlizer in 1996
Saint Esprit basin

Source:
Gestion de l'eau dans le bassin versant de la partie superieure du ruisseau St-Esprit Projet 61-13008 Rapport d'étape no. 2 & 3. par F Papineau et P Enright, 1997

Figure 4.22 1996 applied P fertilizer map

This technique eliminated the need for further digitizing and was selected as a method to develop new data layers.

4.4 Discussion and conclusions

Approximately 300 hours were spent to complete the digitizing phase. To perform further effective operations with digitized files in SPANS, they should be free of any mistakes or errors. Our experience indicates that digitizing the different layers in separate directories is helpful. Digitizing complex layers such as the farm field map (Figure 4.7) or soil map (Figure 4.3), which has numerous irregular areas, usually involves errors. Finding the errors is a tedious job. In order to find the errors easily and fix them, it is recommended that each polygon be assigned an identity attribute.

When the project began in 1994 consideration was given to scanning the maps, instead of digitizing them. Digitizing was selected because at the time scanning software was expensive to both purchase and support, and commercial scanning services were not readily available. A second consideration was the fact that we had only four maps to digitize. Today with improved scanning software and the relative reduction in costs, it is recommended that scanning be considered in projects when data must be transferred from many maps.

All of the necessary information layers to build the Saint Esprit spatial database were successfully digitized and appropriate ".vec/.veh" file pairs were exported. They were copied to the corresponding SPANS GIS subdirectory. All digitized layers are stored in the TYDIG directory on the attached CD ROM.

SPANS met all of the research GIS software requirements. It provided a wide variety of tools and by selecting the most appropriate one, different data layers were created. Approximately 1000 hours were spent to create the Saint Esprit spatial database in SPANS GIS. It was also necessary to invest a great deal of time and energy to become sufficiently familiar with SPANS to fully utilize its maximum capabilities.

The field attribute database method was developed. It was selected as a method to create new data layers. With this method it was possible to manage large amounts of field-by-field information. It also eliminated the need for further digitizing.

CHAPTER 5

APPLICATION OF THE SAINT ESPRIT DATABASE

5.1 Introduction

The Saint Esprit spatial database was used in four applications. There was a need to establish a clear picture of the agricultural activities and derive various statistics on both the intervention and control watersheds. In the first application (section 5.2) the required statistics were provided.

In the second application (section 5.3) non-numerical modeling was performed to delineate the area with high erosion potential. This type of application helped to interpret the water quality measurements.

A research team from the Department of Agricultural Economics of McGill University was also involved in the project. Their task was to assess the economic impacts of the soil and water conservation projects implemented at the farm and watershed scale. One of their approaches was to use the Revised Universal Soil Loss Equation for Application in Canada (RUSLEFAC). The third application was to create the required database to build different RUSLEFAC factors. This is presented in Figures B1 and B2 in Appendix B.

Complex NPS models such as ANSWERS 2000 need a very detailed input file. Preparing such a file without GIS is impractical. In the fourth application, the Saint Esprit spatial database was used to prepare the model input. This application is described in Chapter 7.

5.2 Baseline statistics for the study area

The Saint Esprit watershed is 26.1 km^2 in area and the Desrochers basin 17.9 km^2. Figure 4.12 presents the physical layout of the watersheds. Because of the size of the basins, it is impossible to comprehend the different layers of information and land management characteristics without using maps, and summary statistics. Subsequent sections describe how the GIS presented spatially varying information, and tabulated baseline statistics. Information for the Desrochers basin is presented when the data were available, such as soil texture, soil series, land use, etc.

5.2.1 Field data availability

Most of the activities taking place on the Saint Esprit basin are agricultural. There are no industries and no villages within the limits of the basin. The total population is approximately 700. There are 27 farms, of which 18 are participating in the project. The participating producers account for approximately 67 % of the agricultural land of the watershed. The location and boundaries for each field of the cooperating farmers were developed on the "Field map" (Figure 4.13). The field map contains 1185 plots. A total of 812 plots were agricultural fields and 373 plots were forest and non-agricultural areas. Of the 812 fields, 514 belong to farmers participating in the project and 271 were non-participating farmers' fields. A wide range of field level data was collected on a field-by-field basis from the participating farmers on the Saint Esprit watershed. Figure 4.18 shows the data availability within the watershed. Table 5.1 indicates that data was collected for about 40 % of the basin. Taking into account that 36 % of the basin is non-agricultural, the data collected covered a good portion of the watershed.

Table 5.1 Saint Esprit data availability analysis

Map Legend	%	ha
available field data	40.5	1055.1
no data collection	23.3	608.5
forest	25.1	654.9
non agricultural	11.1	289.4
Total	100.0	2607.9

5.2.2 Soil series and textures

There are twenty-one soil series in the Saint Esprit watershed (Figure 4.11). Table 5.2 shows the soil series analysis for both watersheds.

About 44 percent of the total area is covered by Perrot (P), Ste-Rosalie (Rl), Belle-Riviere (Br), and Aston (Ac) series. The Perrot (P), by itself, covers 20.2 percent of the Saint Esprit watershed. It is a sandy loam soil texture with good natural drainage. The Desrochers watershed has seventeen soil series. Ste-Bernard (Bn), Baudette (Bd), Achigan (Acf), and Ste-Rosalie (Rl) cover 72 percent of the watershed. Ste-Bernard (Bn) , the most dominant, is a loamy textured soil with good natural drainage.

Table 5.2 Soil series analysis

Map Legend		St. Esprit Area		Desrochers Area	
		%	ha	%	ha
Achigan	(Ac)	---	----	0.8	14.9
Achigan	(Acf)	---	----	16.2	290.3
Aston	(Ac)	7.9	205.8	1.2	21.5
Alluvium	(Auh)	4.5	118.5	----	----
Alluvium	(Aul)	2.1	55.3	----	----
Baudette	(Bd)	1.6	42.0	20.2	361.5
Ste-Bernard	(Bn)	4.0	103.2	24.8	444.0
Ste-Bernard	(Bns)	0.1	2.5	---	----
Belle-Riviere	(Br)	13.1	342.2	2.5	44.3
Chicot	(C)	0.7	9.4	---	----
Châteauguay	(Ch)	0.6	14.4	---	----
Coteau	(Ct)	---	----	0.2	3.3
Dalhouse	(D)	0.5	14.0	---	----
Joliette	(Jo)	1.5	39.0	0.8	14.6
Laplaine	(Lp)	1.8	46.2	---	----
Ste-Laurent	(Lr)	9.1	237.5	9.0	160.4
Ste-Laurent	(Lrl)	9.1	237.9	0.3	5.6
Morin	(Mo)	---	----	0.3	5.4
Perrot	(P)	20.2	527.1	2.8	37.2
Péningue	(Pg)	4.5	117.0	---	----
Ste-Rosalie	(R)	10.7	278.1	10.4	186.9
Ste-Rosalie	(Rl)	3.4	89.0	---	----
Ste-Rosalie	(Rs)	1.0	27.1	2.3	41.6
Soulanges	(S)	0.7	18.2	7.4	133.0
Ste-Urbain	(U)	3.3	87.2	----	----
Vaudreuil	(V)	---	----	0.6	10.7
Escarpment & Gullies	(Xs)	---	----	1.0	18.4
Total		100.0	2611.4	100.0	1793.3

Soil textures in both watersheds vary from light to heavy (Figure 4.10). Table 5.3 shows the soil texture map analysis for both watersheds.

To further facilitate the presentation of the soil textural information, they were reclassified as light, medium, and heavy soils. The reclassification was based on the percentages of sand and clay of each soil series. Table 5.4 presents the grouping of the various soil textures in the new

Table 5.3 Soil texture analysis

Map Legend	St. Esprit Area %	St. Esprit Area ha	Desrochers Area %	Desrochers Area ha
Sand	8.2	214.1	2.3	41.5
Escarpment sandy surface	---	----	1.0	18.4
Loamy sand	5.7	145.1	---	----
Loamy v. f. sand to sandy loam	0.1	2.5	3.6	65.1
Sandy loam	33.4	871.7	4.5	81.5
Fine and v. f. sandy loam	3.2	82.9	7.5	135.1
Sandy clay loam	---	----	3.2	57.6
Loam	3.4	89.0	8.5	153.0
Loam to sandy loam	0.5	14.2	28.8	516.2
Silt loam to silty clay loam	1.6	42.0	14.8	263.1
Sandy clay	1.0	27.1	---	----
Silty clay loam	2.3	58.9	5.5	98.4
Clay loam	14.1	369.2	2.9	52.0
Clay to clay loam	9.1	237.5	2.2	40.2
clay	17.5	457.2	14.5	260.7
Stony land	---	----	0.6	10.7
Total	100.0	2611.4	100.0	1793.3

classification. According to this classification a reclassified soil map for both watersheds was developed (Figures 5.1 and 5.2).

Table 5.4 Reclassified soil texture groups

Light	*Medium*	*Heavy*
escarpment sandy surface,	loam to sandy loam,	clay,
very fine sand, 3.sand,	loam, sandy clay,	clay to clay loam
fine and very fine sandy loam,	sandy clay loam,	clay loam
fine sand to loamy sand,	silty surface,	silty clay loam,
sandy loam, loamy sand,	silt loam to silty clay loam,	
loamy very fine sand to sandy loam,		

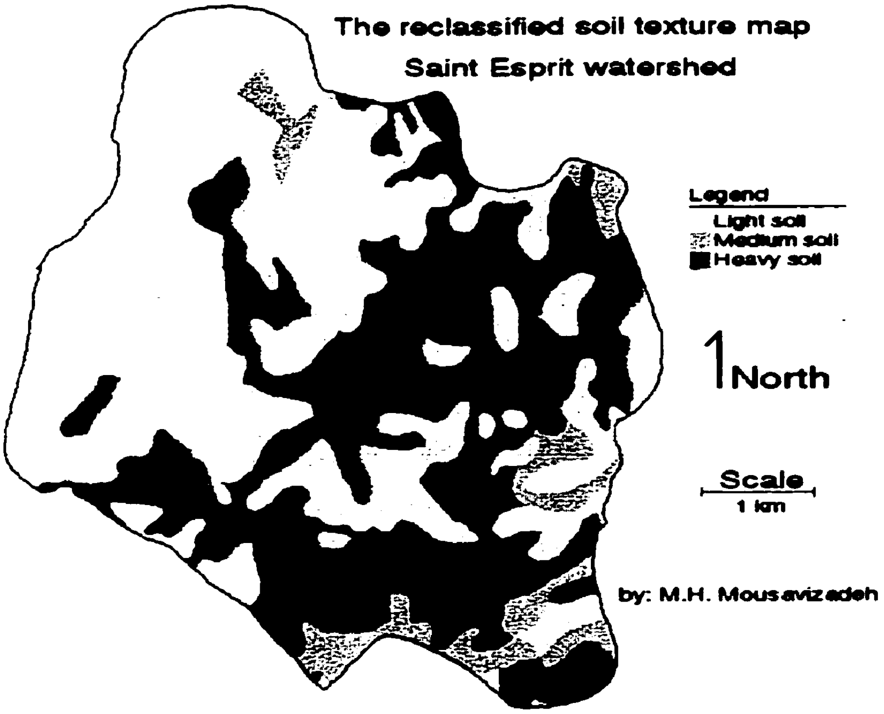


Figure 5.1 St. Esprit reclassified soil map

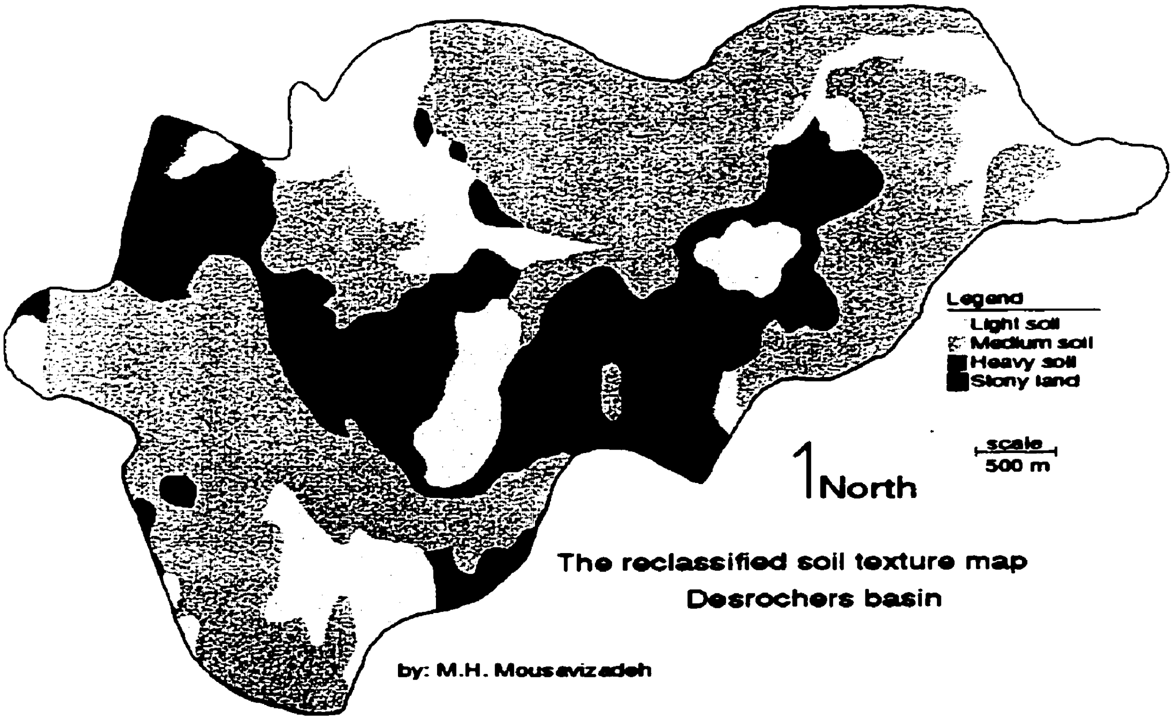


Figure 5.2 Desrochers reclassified soil map

Table 5.5 shows the area analysis of the reclassified soil map for both watersheds.

Table 5.5 Reclassified soil texture analysis

Map Legend	St. Esprit Area		Desrochers Area	
	%	ha	%	ha
Light soil	50.4	1316.3	21.4	383.0
Medium soil	6.6	172.3	52.9	948.3
Heavy soil	43.0	1122.8	25.2	451.3
Stony land	---	-----	0.6	10.7
Total	100.0	2611.4	100.0	1793.3

About 50 percent of the total area of the Saint Esprit basin has light soils; coarse sand to silt. In the Desrochers watershed most of the area, 53 percent, has medium soils; loam to silty clay loam.

5.2.3 Topography and slope

The topography of the Saint Esprit watershed is flat to rolling. The drop in elevation from the highest point at the top of the basin to the outlet is about 40 meters (Figure 4.14). Most of area of the watershed, 87.25 %, has slopes ranging from 0 to 3 % (Figure 4.15). The Desrochers basin (Figure 4.15) is flatter than the Saint Esprit basin. More than 99 percent of the Desrochers basin has slopes ranging from 0 to 3 %. Slope variation on both basins is described in Table 5.6.

Table 5.7 summarizes the result of the slope map overlay with the reclassified soil map. Only 0.13 % of the Desrochers basin has a slope

Table 5.6 Slope analysis

Map Legend	St. Esprit Area %	St. Esprit Area ha	Desrochers Area %	Desrochers Area ha
< 1 %	42.9	1120.4	77.1	1376.96
1 - 3 %	44.4	1158.3	22.4	400.29
3 - 5 %	7.7	201.5	0.4	6.94
5 <= %	5.0	131.2	0.1	2.44
Total	100.0	2611.4	100.0	1786.6

Table 5.7 Slope and reclassified overlay analysis

Map Legend	St. Esprit Area %	St. Esprit Area ha	Desrochers Area %	Desrochers Area ha
Slope<1% and light	19.7	514.2	16.7	297.3
Slope<1% and medium	3.0	78.9	37.9	672.9
Slope<1% and heavy	20.2	527.3	22.3	396.4
Slope 1-3 % and light	23.6	616.0	4.8	85.2
Slope 1-3 % and medium	3.0	78.4	14.8	261.9
Slope 1-3 % and heavy	17.8	463.9	3.0	52.8
Slope 3-5 % and light	4.6	120.2	0.0	0.4
Slope 3-5 % and heavy	0.4	11.2	0.3	5.1
Slope 3-5 % and heavy	2.7	70.1	0.1	1.5
Slope>5% and light	2.5	65.9	---	----
Slope>5% and medium	0.2	3.9	0.1	1.8
Slope>5% and heavy	2.4	61.5	0.0	0.6
Total	100.0	2611.4	100.0	1776.0

greater than 5 %, compared to 5.03 % for the Saint Esprit watershed. More than half of the Desrochers basin, 53 %, has medium soil textures, on slopes between 0 to 3 %.

5.2.4 Land use

The detailed analyses of annual land use for the Saint Esprit (Figure 4.17) and Desrochers watersheds are presented in Tables 5.8 and 5.9. They are summarized in Table 5.10. Although the Desrochers basin is 860 ha

Table 5.8 Saint Esprit land use analysis

Map Legend	Saint Esprit watershed					
	Area - 1994		Area - 1995		Area - 1996	
	%	ha	%	ha	%	ha
Corn	24.0	626.0	23.1	601.2	26.2	682.8
Cereal	13.3	347.6	12.6	329.6	8.5	220.5
Soya	3.3	85.8	3.8	100.0	6.3	163.0
Vegetable	3.2	82.8	3.1	80.7	3.0	79.0
Hay	11.3	294.4	12.5	325.0	12.0	312.5
Forest	25.3	658.8	25.1	654.9	25.1	654.9
Pasture	3.5	91.1	3.4	87.4	2.8	72.8
Non agri.	6.2	161.4	6.2	162.4	6.1	159.2
Resident	4.8	124.5	4.9	127.0	4.9	127.0
Cruciferes	3.5	90.3	3.5	91.4	3.2	82.1
Cuks	1.7	45.2	1.6	48.2	2.1	54.2
Total	100.0	2607.9	100.0	2607.9	100.0	2607.9

Table 5.9 Desrochers land use analysis

Map Legend	Desrochers watershed					
	Area - 1994		Area - 1995		Area - 1996	
	%	ha	%	ha	%	ha
Residential	4.2	74.8	4.2	73.8	No qualified data available for 1996	
Forested	15.5	277.6	16.3	284.5		
Vegetable	8.7	155.9	6.4	112.6		
Soya	4.9	88.5	13.5	236.4		
Corn	38.3	686.5	32.3	564.2		
Hay, Pasture	19.4	347.6	12.1	211.2		
Forage	----	-----	1.0	17.7		
Cereal	9.1	162.5	8.0	139.2		
Potato	----	-----	0.5	9.5		
Sod	----	-----	1.8	30.7		
Pasture	----	-----	4.0	69.3		
Total	100.0	1748.5	100.0	1746.7		

Table 5.10 Land use distribution for both basins

	St. Esprit		Desrocherss	
	%	ha	%	ha
Agricultural area	64	1669	80	1398
Non agricultural area	36	939	20	349
Total area	100	2608	100	1747

smaller than the Saint Esprit basin, the difference in the agricultural area was only about 270 ha. Corn was the major annual crop in both watersheds. The total area under corn in both basins was similar; about 600 ha, between 1994 to 1996. An overlay of land use and reclassified soil texture map was performed for both watersheds.

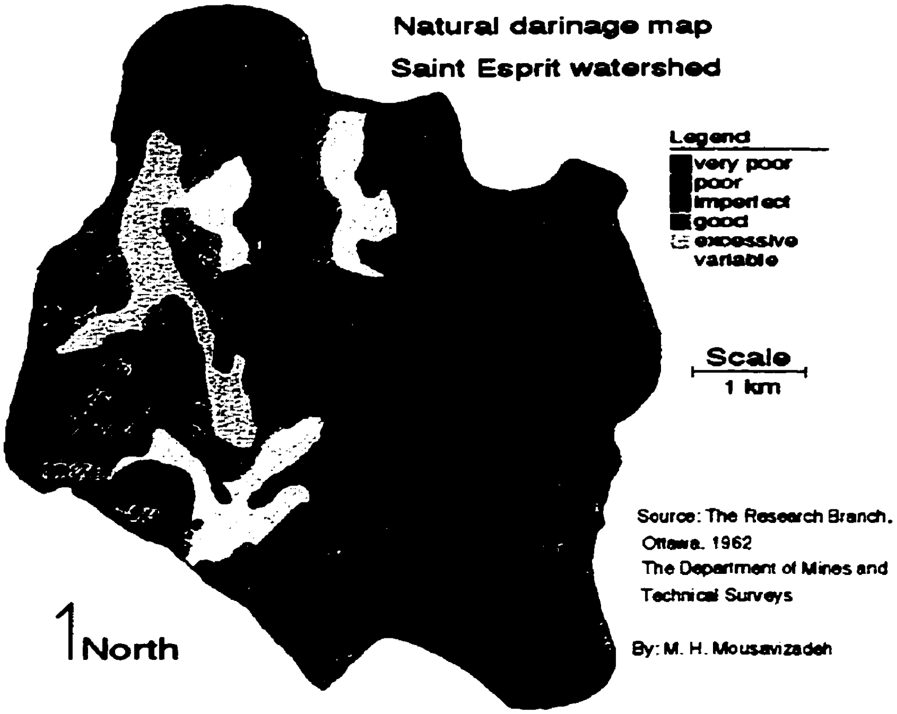
Table 5.11 shows the condensed land use distribution on the different soil textures for both basins. In the Saint Esprit basin, it was found that about 37 % of the agricultural area was on heavy, 21 % on light, and 5 % on medium textured soil. In the Desrochers basin, the distribution of agricultural land over soil texture was about 41 % on medium, 23 % on heavy, and 16 % on light soils.

Table 5.11 Land use and reclassified soil overly analysis

	Esprit		Desrochers		Esprit		Desrochers		Esprit		Desrochers	
	light				medium				heavy			
	%	ha	%	ha	%	ha	%	ha	%	ha	%	ha
corn	7.8	202	6.5	114	1.6	41	19.3	340	15.1	393	9.4	165
cereal-soy	5.1	133	3.3	59	1.4	35	8.3	146	9.5	247	6.1	107
vegetable	3.0	79	2.1	38	0.6	16	4.6	80	4.7	123	2.5	45
hay-pasture	5.5	143	4.4	77	1.6	43	8.6	152	8.0	208	4.7	83
forest	19.8	516	3.7	66	1.2	31	10.0	175	4.2	109	2.3	40
non-agri.	9.3	242	1.2	21	0.2	5	2.6	46	1.5	40	0.4	7

5.2.5 Natural soil and subsurface drainage conditions

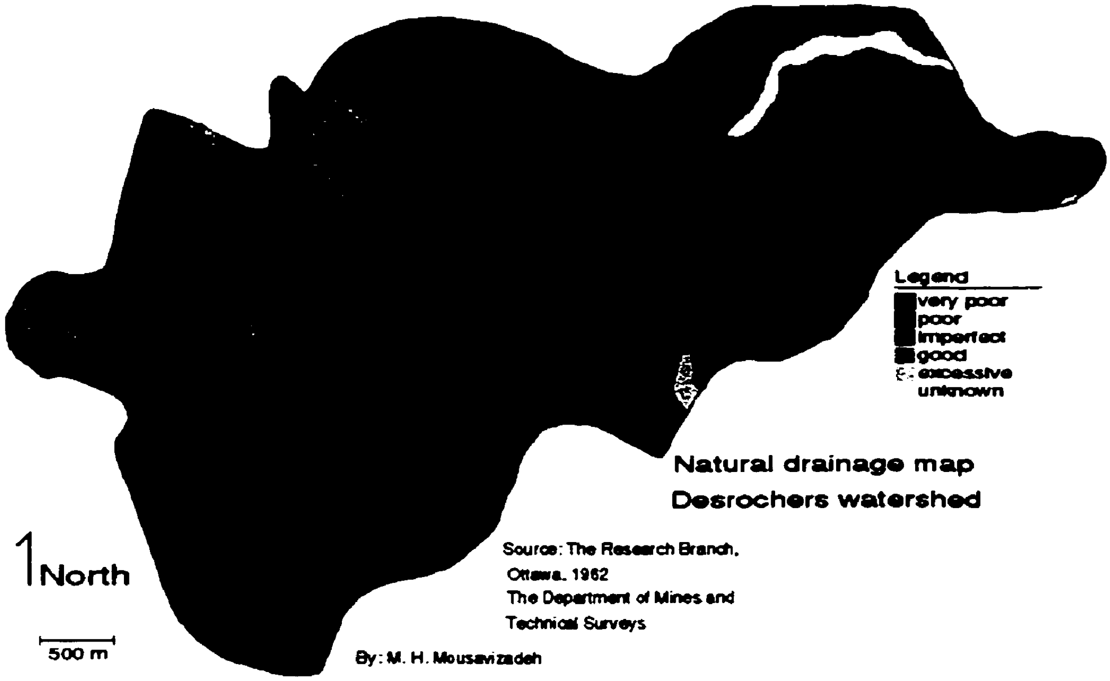
Almost 45 % of the Saint Esprit watershed area has naturally poor drainage. Figures 5.3 and 5.4 present the natural soil drainage conditions of both basins.


Natural darinage map
Saint Esprit watershed

Source: The Research Branch, Ottawa. 1962
The Department of Mines and Technical Surveys

By: M. H. Mousavizadeh

Figure 5.3 St. Esprit natural soil drainage


Natural drainage map
Desrochers watershed

Source: The Research Branch, Ottawa. 1962
The Department of Mines and Technical Surveys

By: M. H. Mousavizadeh

Figure 5.4 Desrochers natural soil drainage

Table 5.12 shows the soil natural drainage map area analysis for the both watersheds.

Table 5.12 Natural soil drainage analysis

Map Legend	St. Esprit Area %	St. Esprit Area ha	Desrochers Area %	Desrochers Area ha
very poor	1.8	46.3	0.6	10.7
poor	43.5	1136.0	23.2	416.0
imperfect	4.3	113.0	45.4	814.0
good	39.3	1025.4	29.5	529.0
excessive	4.5	117.0	0.3	5.4
variable	6.7	173.7	----	----
unknown	---	------	1.0	18.3
Total	100.0	2611.4	100.0	1793.3

Figure 4.19 and Table 5.13 illustrate the subsurface tile drain information of the Saint Esprit watershed. About 50 % of the agricultural land is tile drained.

Table 5.13 Saint Esprit land drainage analysis

Map Legend	Area %	Area ha
subsurface drainage	16.8	436.8
no subsurface drainage	23.1	602.4
no data collection	23.9	624.4
not cultivated	36.2	944.3
Total	100.0	2607.9

5.2.6 1994 soil fertility analysis

In the fall of 1994, the *comité d'administration* (CA) gave priority to development of fertilizer management plans for each farm. There was a general lack of soil fertility data to develop these plans. The CA therefore supported a soil sampling program in the Saint Esprit watershed. Soil samples were collected from 403 fields, mainly from annual crop fields, and analyzed for total available phosphorous and percentage of organic matter. Table 5.14 shows in detail the soil fertility map area analysis.

Table 5.14 1994 Saint Esprit soil fertility area analysis

Phosphorous			**Organic matter**		
Legend	%	ha	Legend	%	ha
10-25 kg/ha	0.5	11.9	0-0.5 %	0.03	0.8
25-50 kg/ha	0.7	18.4	1.0-1.5 %	0.1	3.0
50-75 kg/ha	1.7	43.9	1.5-2.0 %	0.1	2.7
75-100 kg/ha	1.9	49.4	2.0-2.5 %	3.1	81.1
100-125 kg/ha	3.4	88.2	2.5-3.0 %	2.2	58.4
125-150 kg/ha	4.1	107.9	3.0-3.5 %	4.5	116.7
150-175 kg/ha	2.8	71.7	3.5-4.0 %	6.0	157.3
175-200 kg/ha	2.2	58.2	4.0-4.5 %	7.2	187.8
200-225 kg/ha	1.9	48.8	4.5-5.0 %	4.1	107.4
225-250 kg/ha	1.6	40.9	5.0-5.5 %	2.3	59.0
250-275 kg/ha	1.1	28.0	5.5-6.0 %	1.1	27.8
275-300 kg/ha	0.3	8.3	6.0-6.5 %	0.7	17.1
300-325 kg/ha	1.2	30.1	6.5-7.0 %	0.5	12.0
325-350 kg/ha	2.6	67.7	7.0-7.5 %	0.04	1.0
350-375 kg/ha	1.1	28.3	7.5-8.0 %	0.4	9.2
375-400 kg/ha	0.5	11.9	8.5-9.0 %	0.1	2.6
400-425 kg/ha	0.4	9.5	9.0-9.5 %	0.1	1.4
425-450 kg/ha	0.7	19.3	11.5-12.0 %	0.1	1.5
450-475 kg/ha	0.7	17.9	12.0-12.5 %	0.03	0.7
475-500 kg/ha	0.5	13.0	no data collection	31.3	815.9
500-525 kg/ha	0.1	1.3	not cultivated	36.2	944.6
525-550 kg/ha	0.5	14.1			
550-575 kg/ha	0.6	16.7	Total	100.0	2607.9
650-675 kg/ha	0.1	3.7			
675-700 kg/ha	0.5	12.9			
750-777 kg/ha	0.1	3.3			
775-800 kg/ha	0.4	9.8			
900-925 kg/ha	0.4	11.3			
no data collection	31.3	816.9			
not cultivated	36.2	944.6			
Total	100.0	2607.9			

About 30 percent of the Saint Esprit agricultural fields had organic matter between 2 to 6 % in 1994. The total available phosphorous levels ranged from 0 to 925 kg/ha. Figures 4.20, 5.5, and 5.6 delineate the distribution of soil organic matter and phosphorous in the basin.

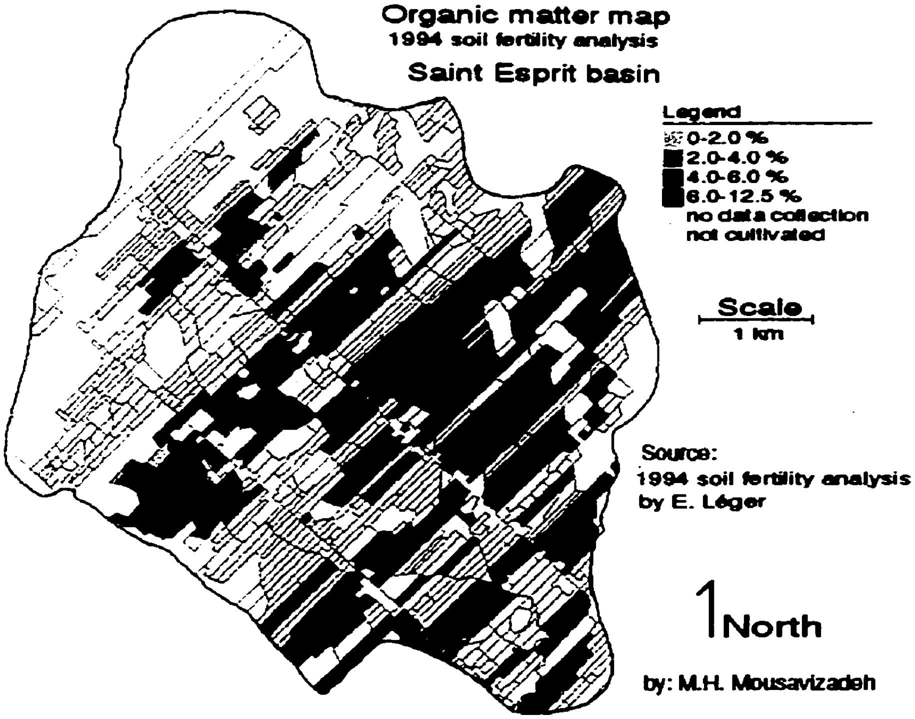


Figure 5.5 1994 Saint Esprit organic matter map

Table 5.15 summarizes the results of overlay of the soil organic matter and phosphorous maps with agricultural area overlay in 1994.

Table 5.15 1994 Saint Esprit organic matter analysis

	1994 Soil fertility analysis				
	Phosphorous		**Organic matter**		
Map Legend	%	ha		%	ha
0-100 kg/ha	4.7	123.7	0-2.0 %	0.3	6.5
100-200 kg/ha	12.5	326.0	2.0-4.0 %	15.9	415.1
300-400 kg/ha	4.8	126.0	4.0-6.0 %	14.7	383.7
>400 kg/ha	10.4	270.7	6.0-12.5 %	1.8	45.8
no data collection	31.3	816.9	no data collection	31.2	813.1
not cultivated	36.2	944.6	not cultivated	36.2	944.9
Total	100.0	2609.1		100.0	2609.1

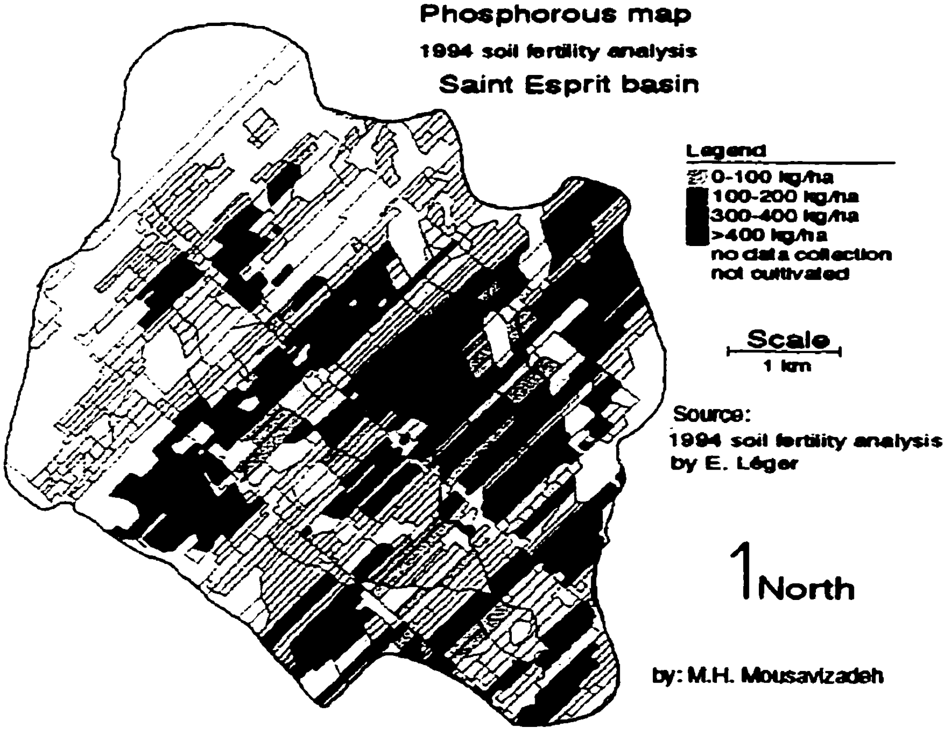


Figure 5.6 1994 Saint Esprit phosphorous map

About 270 ha of the basin received high range of phosphorous of more than 400 kg/ha. Most of the area received the range of 100-200 kg/ha.

5.2.7 N and P fertilizer applications

The map area analysis of N and P fertilizer application from 1994 to 1996 is summarized in Table 5.16 and 5.17.

The N fertilizer application varied between 25 to 200 kg/ha. About 11 % of the annual crop land received 175 to 200 kg/ha of N fertilizer. Almost 27 % of the agricultural lands received P fertilizer application between 25 to 75 kg/ha. More than 100 kg/ha of P was applied on 7 % of the land. Figures

4.21 and 4.22 show 1995 applied N and 1996 applied P fertilzer, respectively.

Table 5.16 Applied N fertilizer in the Saint Esprit watershed

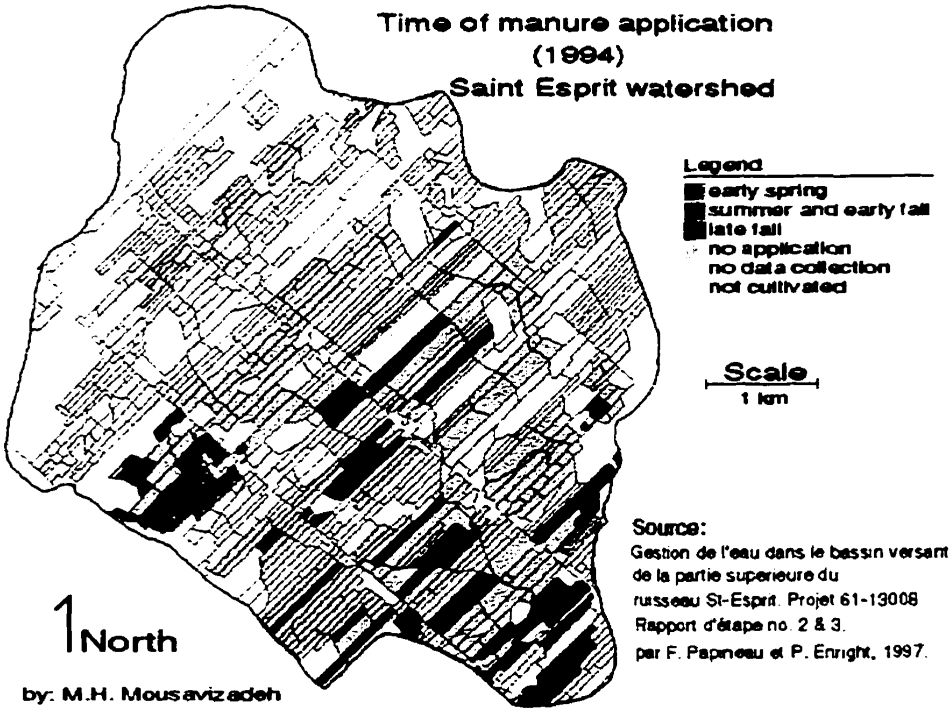
	1994		1995		1996	
Legend (N levels)	%	ha	%	ha	%	ha
10-25 kg/ha	0.4	9.0	1.4	36.9	2.5	64.9
25-50 kg/ha	4.9	128.5	6.0	156.2	5.9	154.4
50-75 kg/ha	7.0	183.6	6.4	166.6	5.9	153.1
75-100 kg/ha	4.2	110.5	5.8	150.9	2.7	69.8
100-125 kg/ha	2.2	58.4	2.5	65.5	3.8	98.4
125-150 kg/ha	3.9	101.8	5.5	142.9	4.6	119.2
150-175 kg/ha	4.4	114.0	8.4	219.0	12.6	327.5
175-200 kg/ha	11.0	287.9	3.4	87.3	3.6	85.1
200-225 kg/ha	0.8	20.2	0.2	4.0	0.5	4.0
825-850 kg/ha	----	-----	0.0	0.1	----	-----
no application	0.9	23.1	0.6	16.4	0.4	9.4
no data collection	24.0	626.3	23.7	617.9	22.3	581.0
not cultivated	36.2	944.6	36.2	944.3	36.1	941.1
Total	100.0	2607.9	100.0	2607.9	100.0	2607.9

Table 5.17 Applied P fertilizer in the Saint Esprit watershed

	1994		1995		1996	
Legend (P levels)	%	ha	%	ha	%	ha
10-25 kg/ha	0.1	3.3	1.8	46.3	3.1	80.9
25-50 kg/ha	11.6	301.8	12.6	329.7	18.7	488.0
50-75 kg/ha	15.9	414.1	12.9	337.4	7.0	183.5
75-100 kg/ha	3.6	93.8	3.3	86.0	4.5	117.0
100-125 kg/ha	3.4	88.2	0.8	21.3	0.6	15.1
125-150 kg/ha	1.7	43.8	2.2	56.6	1.4	35.9
150-175 kg/ha	0.5	12.3	0.6	16.7	0.5	12.6
175-200 kg/ha	0.7	18.3	1.0	25.1	-----	----
200-225 kg/ha	0.1	2.7	----	-----	0.3	9.0
225-250 kg/ha	0.2	4.5	----	-----	-----	----
250-275 kg/ha	----	-----	0.1	2.9	-----	----
475-500 kg/ha	----	-----	----	-----	0.2	4.3
725-750 kg/ha	0.4	11.0	----	-----	-----	----
750-775 kg/ha	----	-----	----	-----	0.3	7.9
no application	1.7	43.2	4.7	123.7	5.1	131.8
no data collection	24.0	626.3	23.7	617.9	22.3	581.0
not cultivated	36.2	944.6	36.2	944.3	36.1	941.1
Total	100.0	2607.9	100.0	2607.9	100.0	2607.9

5.2.8 Manure application

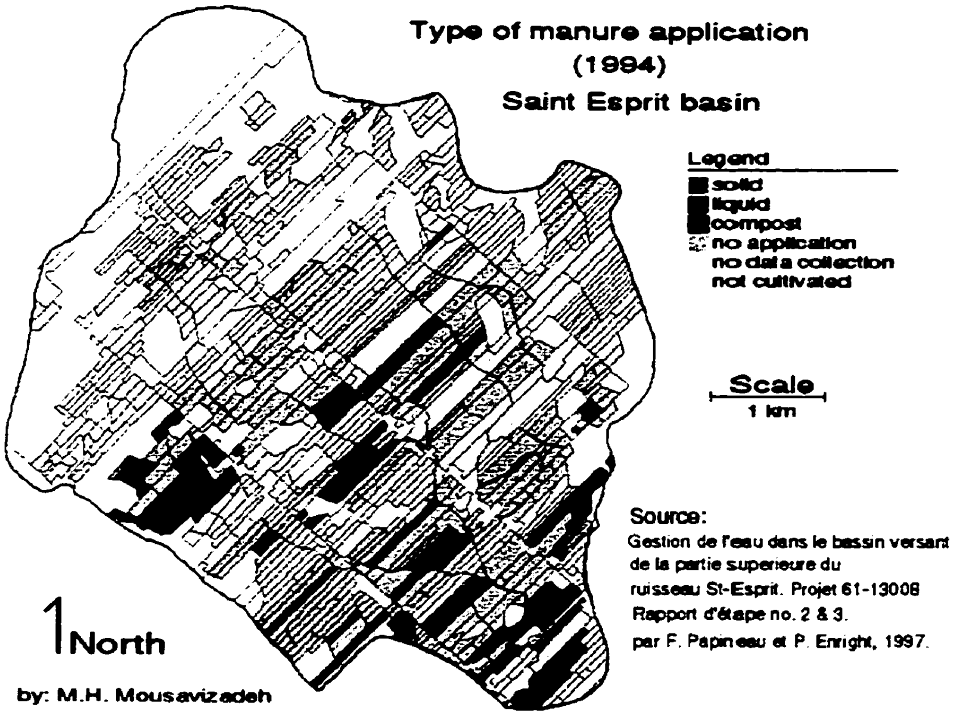
Figures 5.7, 5.8, and 5.9 present the time, type, and method of manure application practices.


Time of manure application
(1994)
Saint Esprit watershed

Source:
Gestion de l'eau dans le bassin versant de la partie superieure du ruisseau St-Esprit. Projet 61-13008
Rapport d'étape no. 2 & 3.
par F. Papineau et P. Enright, 1997.

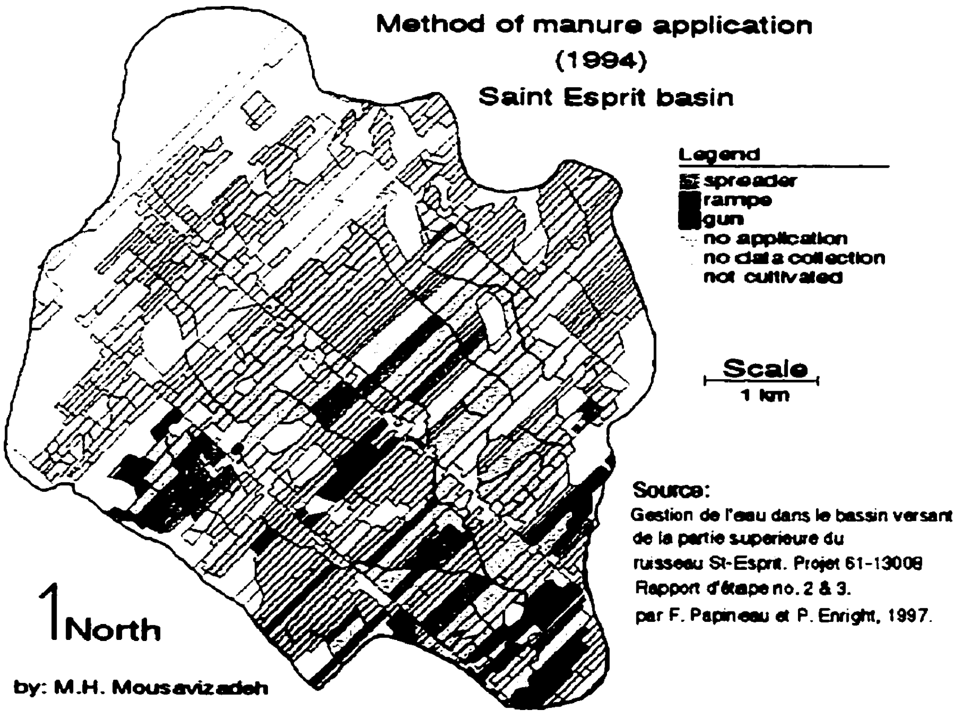
Figure 5.7 Time of manure application map (1994)

Table 5.18 indicates that the farmers applied manure mainly in the late fall. The principle animal production on the Saint Esprit watershed is dairy cattle. Therefore, solid manure practice predominates. The spreader method was practiced more than other methods. Manure was applied only on 8.5 % of the agricultural lands compare to application of chemical fertilizer which was applied on more than 50 % of the lands.



Source:
Gestion de l'eau dans le bassin versant de la partie superieure du ruisseau St-Esprit. Projet 61-13008 Rapport d'étape no. 2 & 3.
par F. Papineau et P. Enright, 1997.

Figure 5.8 Type of manure application map (1994)



Source:
Gestion de l'eau dans le bassin versant de la partie superieure du ruisseau St-Esprit. Projet 61-13008 Rapport d'étape no. 2 & 3.
par F. Papineau et P. Enright, 1997.

Figure 5.9 Method of manure application map (1994)

Table 5.18 Manure application in Saint Esprit

	1994		1995		1996	
Legend	%	ha	%	ha	%	ha
Time:						
early spring	2.2	54.2	1.64	42.7	1.0	25.1
summer and early fall	3.1	81.5	2.41	62.8	3.8	97.9
late fall	3.4	87.3	4.20	109.5	4.9	127.7
Type:						
solid	3.3	85.2	4.7	123.0	5.3	138.2
liquid	4.0	105.2	1.9	49.6	3.1	81.5
compost	1.2	31.5	1.6	42.4	1.0	26.5
solid/liquid	---	-----	---	-----	0.1	3.6
Method:						
spreader	4.7	122.5	6.3	165.4	6.6	170.9
injected	---	-----	0.7	18.5	0.7	17.7
rampe	3.3	86.9	0.5	12.3	1.7	44.1
gun	0.5	13.7	0.7	18.8	0.7	18.2
no application	23.6	614.5	32.0	835.0	30.9	806.3
no data collection	31.7	825.1	23.5	613.6	23.4	609.7
not cultivated	36.2	944.6	36.2	944.3	36.1	941.1
Total	100.0	2607.9	100.0	2607.9	100.0	2607.9

Details of total N and P_2O_5 content in the manure application are presented in Table B1, in Appendix B.

5.2.9 Saint Esprit sub-basin information

The Saint Esprit watershed can be divided into 18 sub-basins. The location of each sub-basin is shown in Figure 4.12. Table 5.19 shows the area analysis for the sub-basins map. Interpretation of sub-basin water quality data required the use of Figure 4.12 and Table 5.19. The sub-basin map (Figure 4.12) was overlaid with the reclassified soil texture map (Figure 5.1), the land use map (Figure 4.17), and the stream patterns. The

Table 5.19 Saint Esprit sub-basin area analysis

Map Legend	%	ha		%	ha
Sub-basin 1	1.5	38.8	Sub-basin 11	2.9	74.4
Sub-basin 3	2.4	61.3	Sub-basin 12	7.9	205.0
Sub-basin 4	3.9	102.4	Sub-basin 13	2.5	63.8
Sub-basin 5	3.2	83.1	Sub-basin 14	3.1	80.0
Sub-basin 6	3.6	93.6	Sub-basin 15	1.2	31.0
Sub-basin 7	4.5	116.2	Sub-basin 16	1.3	34.9
Sub-basin 8	18.3	477.1	Sub-basin 17	1.8	45.5
Sub-basin 9	13.2	344.4	Sub-basin 18	15.1	392.2

result of this overlay helped to determine the upstream surface area, soil texture, and land management for each sampling site (Table B2 in Appendix B).

5.3 Non-numerical modeling

Table 5.20 shows the average measured concentration of suspended sediments, nitrates (NO^{-}_{3}-N), ammonia (NH^{+}_{4}-N), orthophosphate (PO^{-}_{4}-P), potassium (K), and total phosphorous (TP) in the water samples taken at the outlet of the two watersheds during 1994.

The averages, except for suspended sediment concentrations, were similar. The average measured suspended sediment concentration for the Saint Esprit basin was 53 mg/l, compared to 32 mg/l for the Desrochers watershed. Different layers of the database and the SPANS overlay modelling function were used to create an "*Erosion Risk map*". This map helped to understand the difference in the average measured suspended sediment concentrations in the watersheds.

Table 5.20 Average annual concentrations of pollutants in both basins in 1994

Parameter (mg/l)	St. Esprit	Desrochers
NO^-_3-N	2.82	2.92
NH^+_4-N	0.25	0.23
PO^-_4-P	0.05	0.07
K	4.03	4.96
TP	0.30	0.32
Suspended sediment	**53.0**	**32.0**

Source: Enright et al. (1998)

The combination of rolling topography (Figure 4.15), intensive cultivation (Table 5.8) and light soil texture on a large portion (Table 5.5) of the Saint Esprit basin compared to the Desrochers basin indicated a greater risk of erosion. Visits to the fields confirm this hypothesis. "Erodible areas" were defined as corn and vegetable cropping, on light and medium soils, and on slopes greater than one percent. To delineate these areas, the following procedures were used to create the "Erosion Risk map" (Figure 5.10) for both watersheds:

i. the soil texture map (Figure 4.11) was reclassified into three classes, light, medium, and heavy (Figures 5.1 and 5.2), based on the percentage of sand, loam and clay of the soils,

ii. two patterns (corn and vegetable) from the land use map and the reclassified soil texture map were overlaid with model 1 (Box 5.1),

iii. three classes (1-3, 3-5, >= 5 %) from the slope map and output map from the second procedure were overlaid with model 2 (Box 5.1).

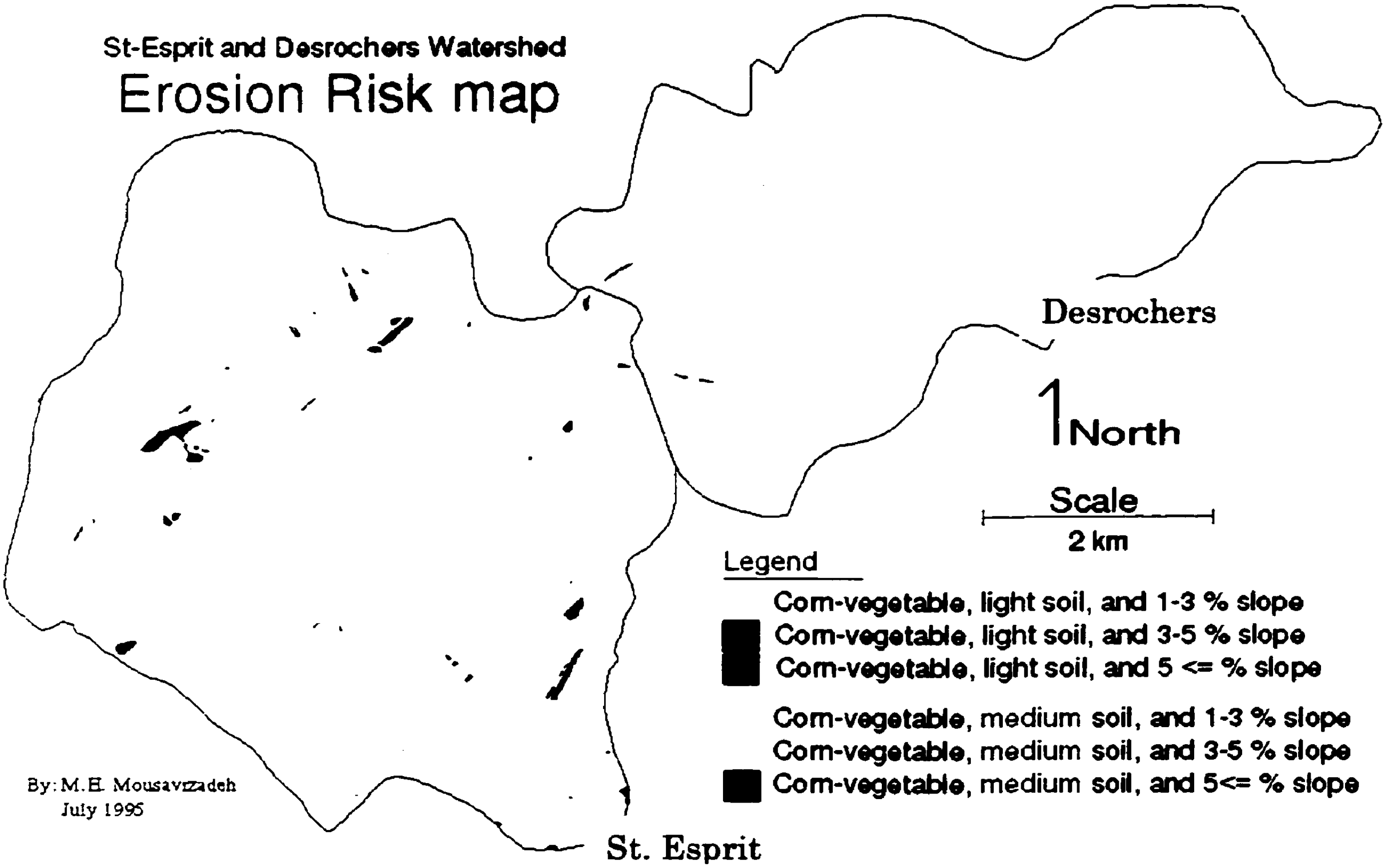


Figure 5.10 The Erosion Risk Map

The area of the "Erosion Risk map" was analyzed for both basins. Table 5.21 summarises the result of this analysis. The "Erosion Risk map" (Figure 5.10) showed more erodible areas in the Saint Esprit basin. Area analysis of the "Erosion Risk map" (Tables 5.21) indicated that the total area under corn and vegetable on light and medium soils with slope greater than one percent for both watersheds was almost, 226.8 ha in the Saint Esprit basin and 236.9 ha in the Desrochers basin. Corn and vegetables on light soil with slopes greater than one percent was found to be much

Box 5.1 SPANS/GIS modelling language

Model 1

```
E ocnvgs6 corn and vegetable overlay with reclassified soil texture map
:
: Date: July 6, 1995
: This model overlays the corn and vegetable area from lndu9.map and three
: soil classes (light, medium, and heavy) from the soil6.map. The output shows
: only the corn and vegetable area with different soil classes.
:
c=class('lndu9');
s=class('soil6');
cs={1 if c==5 and s==1, 2 if c==5 and s==2, 3 if c==5 and s==3, 4 if c==3 and s==1,
   5 if c==3 and s==2, 6 if c==3 and s==3, 0};
result(cs)
```

Model 2

```
E erosion1  corn-vegetable-reclassified soil overlay with slope
:
: Date: July 7, 1995
: This model overlays the corn-vegetable-reclassified soil (ocnvgs6.map) with slope.map. In
: this model the heavy class of soil map and <1 % class from soil map are excluded. Also :
: both corn and vegetable have been taken as one class.
 s=class('slope');
c=class('ocnvgs6');
sc={ 1 if s==2 and c==1 or c==4,
    2 if s==3 and c==1 or c==4,
    3 if s==4 and c==1 or c==4,
    4 if s==2 and c==2 or c==5,
    5 if s==3 and c==2 or c==5,
    6 if s==4 and c==2 or c==5, 0};
result(sc)
```

Table 5.21 Saint Esprit and Desrochers erosion risk area analysis

Class	Legend	Area (%) Esprit	Area (%) Desrochers	Area (ha) Esprit	Area (ha) Desrochers
1	corn-veg., light s., 1-3 % slope	78.7	23.8	178.4	56.4
2	**corn-veg., light s., 3-5 % slope**	**5.0**	**0**	**11.2**	**0**
3	**corn-veg., light s., 5<= % slope**	**4.1**	**0**	**9.2**	**0**
4	corn-veg., medium s., 1-3 % slope	9.9	74.4	22.3	176.1
5	corn-veg., medium s., 3-5 % slope	1.8	1.5	4.1	3.5
6	corn-veg., medium s., 5<= % slope	0.7	0.4	1.5	0.9
Total of 6 classes		100	100	**226.8**	**236.9**

greater in the Saint Esprit basin (198.8 ha) compared to the Desrochers basin (56.4 ha). Also, corn and vegetables on light soil with slopes greater than three percent were found only on the Saint Esprit basin. More corn and vegetable cultivation on light soils and areas with greater slopes on the Saint Esprit indicated more erosion potential. This analysis explained the differences in suspended sediment concentrations.

5.4 Summary and conclusions

The Saint Esprit spatial database was used to perform a variety of analyses. These analyses tended to be one of four different types. Using the Saint Esprit spatial database, a clear picture of the agricultural activities and various statistics on both watersheds was obtained.

The following points can be concluded from the non-numerical modelling application:

i. It is possible to identify the area at risk to erosion with simple modelling overlays without taking into account complex erosion procedures (detachment, transport, and deposition) and stream network conditions.

ii. This type of application is useful to identify the areas at risk i.e. with respect to erosion, but it does not provide any information as to actual levels of soil erosion. Also, it does not allow for an evaluation of the potential effects that soil conservation practices could have on reducing soil erosion.

Using SPANS modelling functions, several models were developed to meet different application requirements (Box 1). They are available on the "MODEL.INP" file on the Saint Esprit study area directory on the attached CD ROM. The tables that are presented in this chapter were condensed from the original detailed GIS area analysis for related maps. Not all of the maps were printed. The original tables and maps from the Saint Esprit database are also available on the attached CD ROM.

CHAPTER 6

ANSWERS 2000 AND SPANS INTEGRATION

6.1 Introduction

The input files used by the continuous version of the ANSWERS model provide a detailed description of the watershed climate, topography, soils, land use, drainage network, fertilizer applications, and BMPs. The main input data file, ANSWERS.INP, can be constructed in two parts (Beasley and Huggins, 1991). The first or "predata" part contains all general information necessary to describe the various simulation requirements; soil infiltration, drainage, and groundwater constants; surface roughness and crop data; and channel specifications. The second part or "element specification" part contains the individual element information. It is the largest body of data and the most time consuming to prepare. ANSWERS 2000 subdivides the watershed into a uniform element or grid of square cells. Topography, soil, land use, and management practices are assumed uniform within each cell. Typical cell sizes range from 0.4 to 4 hectare. Eighteen to twenty two parameter values must be provided for each cell. Preparing the input data in a traditional way, by hand, for a watershed of the size of Saint Esprit is not practical. On the other hand, the capability of SPANS to manage, manipulate, and spatially organize data led to the idea of developing an integrated tool between ANSWERS 2000 and SPANS. The goal of the integration tool is to interact with the user to prepare, edit and store watershed information to be formatted into an ANSWERS input file. It also serves to visualize and analyse the model outputs.

6.2 Integration strategy

SPANS and ANSWERS-2000 can be integrated in different ways. Four possible structures for linking a model and a GIS are shown in Figure 6.1.

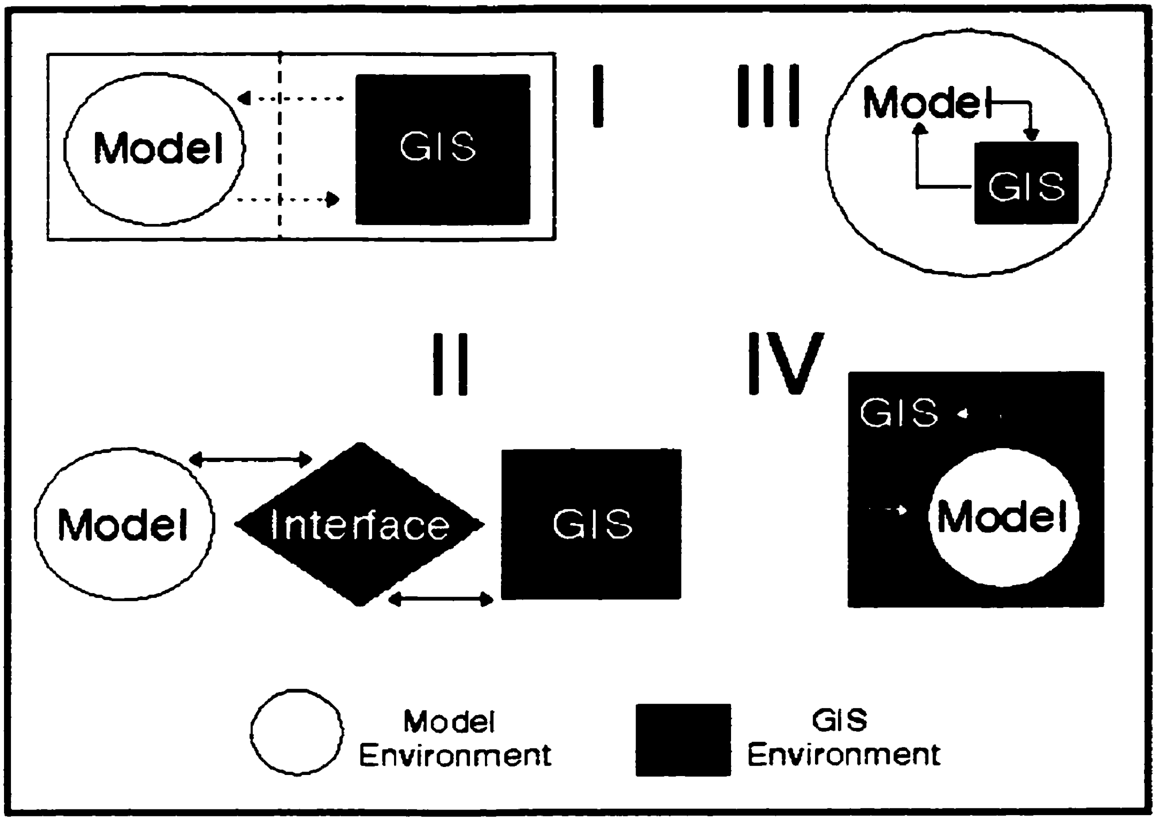


Figure 6.1 A GIS and a model integration possibility

The most elementary strategy (Figure 6.1 I) is to use the GIS for data storage and management, as well as for visualization of model output. In this case GIS and model environments are separate. The linking occurs through manual operation or weak coupling by a small program and there is no time saving advantage to provide model input by this technique. This procedure does not meet the research objectives. Another technique for integration of a GIS and a model is shown in Figure 6.1 II. With such a method, it is possible to attain the benefits of an integration tool by writing a comprehensive interface program between the GIS and the model. However, this approach is not as user friendly as method IV of Figure 6.1, which is described in detail below. The basic components of a GIS might be explicitly drawn into the program code of the model (Figure 6.1 III). In this design, all GIS functions, such as zoom, overlay, search, and query either could not be used or were substantially slow. This strategy does not provide a strong analytical tool. The ideal scheme for linking ANSWERS 2000 and SPANS, which was selected as the strategy for the integration in this study, is displayed in Figure 6.1 IV. In this method, the interface between the user and system is in the SPANS environment (Figure 6.2).

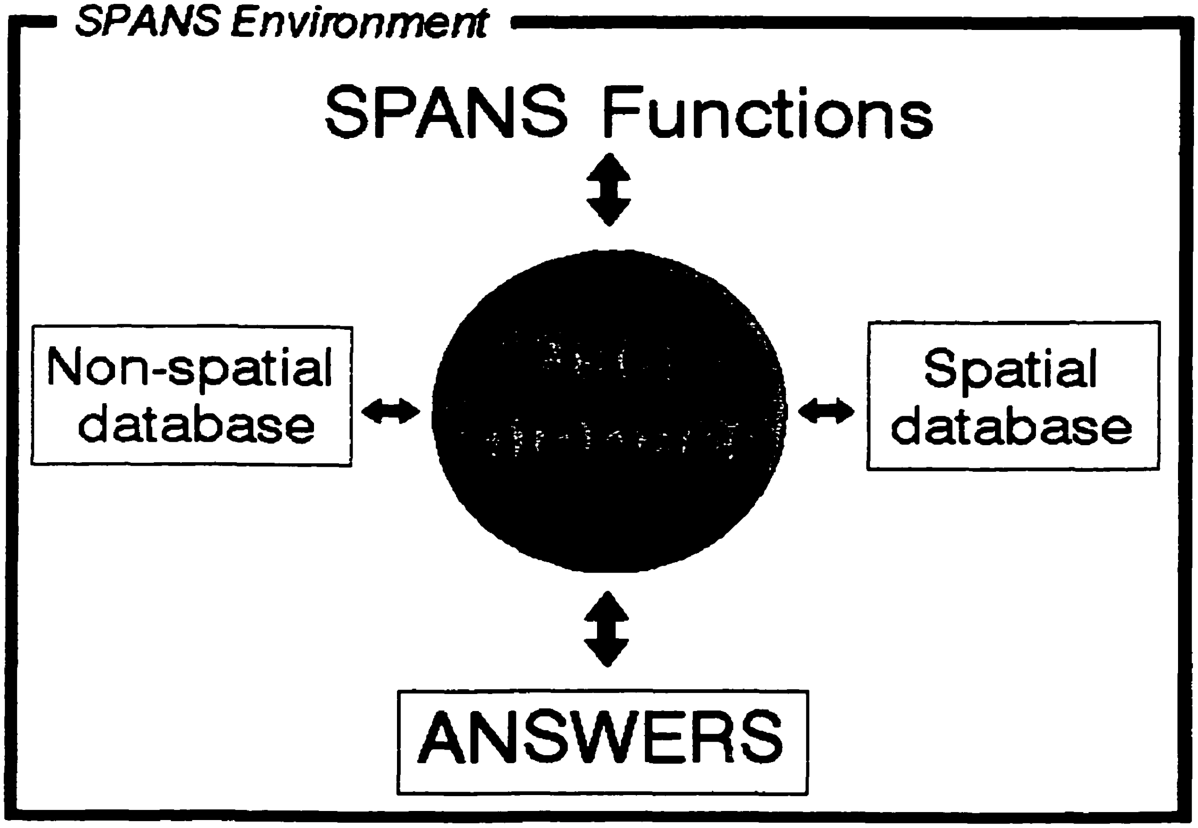


Figure 6.2 User interface of SPANS and ANSWERS 2000 integration

To integrate ANSWERS within SPANS a user interface, the "*NPS MODEL*" menu, was designed (Figure 6.3). The integrated menu was added to the latest version of the SPANS (version 7.0) menu. Using the integrated menu, the user can provide the model input requirements and run the model. In addition it provides the option for creating different maps from the model outputs as well as visualizing them. It is assumed that the user has a basic understanding of ANSWERS and SPANS.

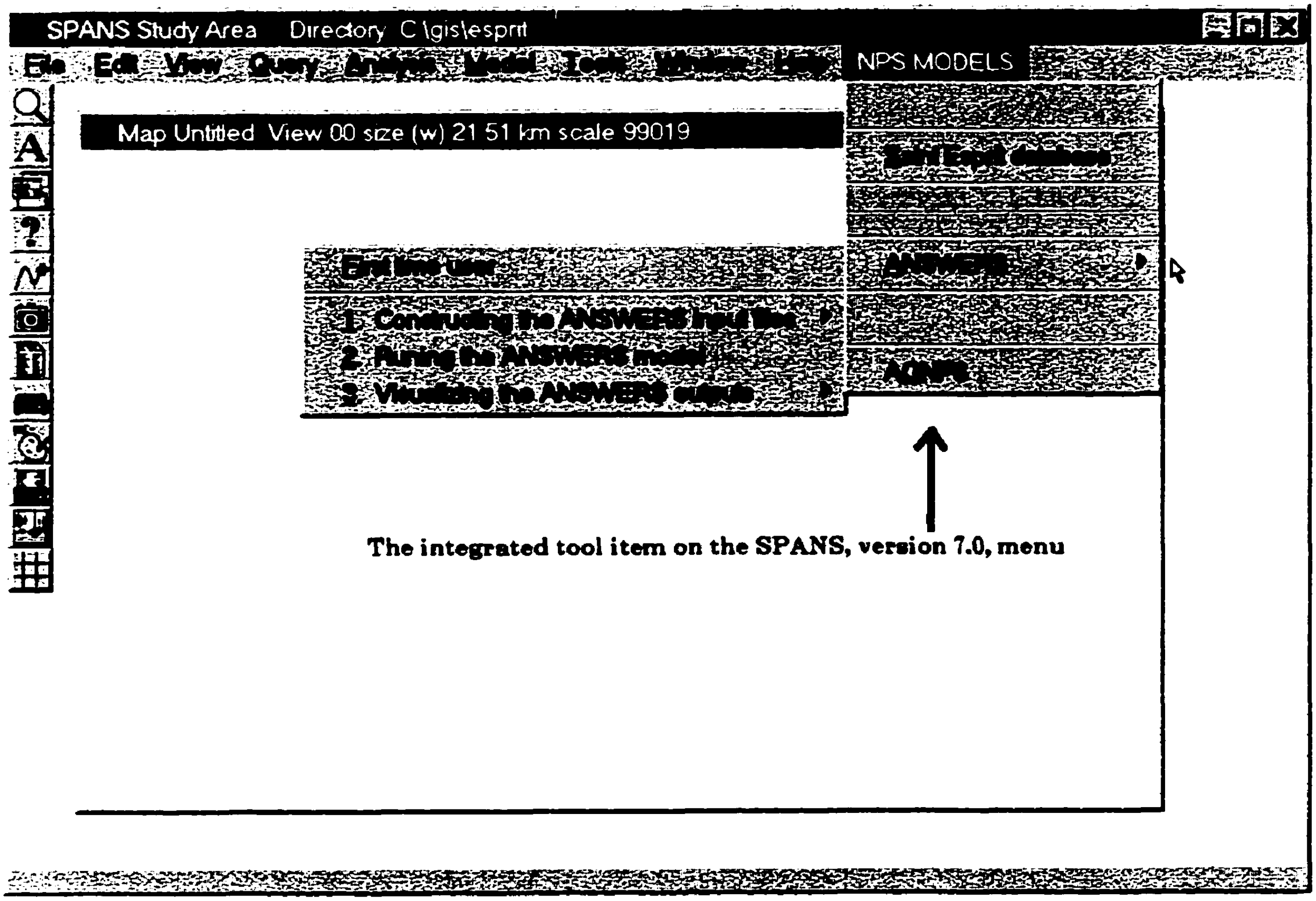
6.3 Building the integrated menu

To build the integrated menu some interactions with the SPANS main program were essential. The current version of SPANS, version 7.0, has provided such flexibility as to allow one to customize the SPANS menu and add a new menu item. Starting with version 6.0, SPANS uses the "Engineering Analysis and Scientific Interface" (EASI) programming language. It is a scripting language useful for the execution of tasks and the construction of applications. Several sets of commands were placed in an ordinary text file, called EASI scripts, to specify parameter values and execute tasks. Box 6.1 shows the EASI script file which was prepared to run the ANSWERS model.

Box 6.1 SPANS EASI script file

```
! SPANS TITLE: RUN ANSWERS 2000
! This 5204a.eas script file runs the ANSWERS model
CALL OpenStudyArea (D:\GIS\ESPRIT)
SYSTEM “ANSWERS.EXE”
```

The SPANS ASCII file "spans.mnu" contains the menu structure. This is stored in the SPANS system directory. Figure 6.3 shows the integrated tool, NPS MODELS submenu created on the SPANS primary window.



The integrated tool item on the SPANS, version 7.0, menu

Figure 6.3 The integrated tool submenu on the SPANS primary window

All of the EASI script files and modified SPANS menu related to the integrated tool are available on the "Integrated tool" directory on the attached CD ROM. More detailed information on customizing the SPANS menu is available under the advanced SPANS operations topic in the SPANS EXPLORER manual (TYDAC 1997).

6.4 Components of the integrated menu

The integrated tool menu, NPS MODELS, consists of main, primary and secondary menus (Figure 6.4).

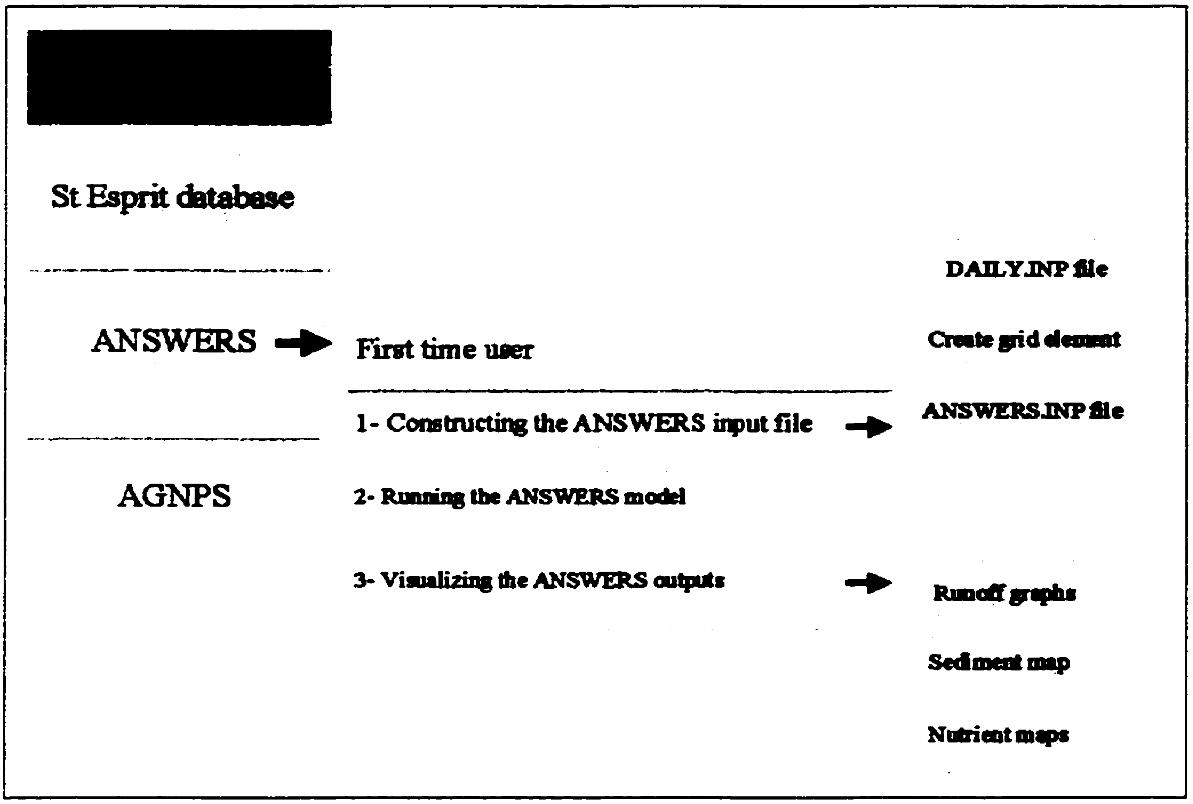


Figure 6.4 The integrated tool menus

There are two submenus in addition to “ANSWERS” submenu in the main menu. “Saint Esprit database” explains the Saint Esprit project and its spatial database. The “AGNPS” submenu shows the integrated tool flexibility to apply with other NPS models such as AGNPS. On the “ANSWERS” primary submenu, there is a help for the first time user. Three subsequent items on the “ANSWERS” primary submenu guides the users on how to construct the input file, run, and visualize the ANSWERS outputs.

Constructing the input file for a complex NPS model such as ANSWERS-2000 requires guidance. The event version of ANSWERS has a user manual, but the continuous version does not have complete documentation for the new input parameters which are used in the model. Box 6.2 lists all input parameters in the "ANSWERS.INP" file. Item 1 (simulation requirements) to item 7 (channel descriptions) are the "predata" section of the input. These 66 parameters are general data for all of the watershed elements. Item 18 (Box 6.2) is "element specification". It contains 22 parameters for describing, in detail, the watershed and its special characteristics. Information on topography (slope steepness and slope direction), soil type, crop type, channel size category and channel slope steepness, rain gauge designator, tillage system, BMP, nutrient application, element size and outlet address on the grid are included in the "element" section of the model input file.

The user has access to a database within the "Constructing the ANSWERS input file menu". The database helps the user to select soil and crop parameters based on the previous ANSWERS applications. It also has explanations about channel and climatic input parameters.

Depending on the simulation requirements and watershed size, users need to use a different grid element size. The SPANS EXPLORER function of *Analysis\Grid* can be used to generate a grid of square cells based on the Projection X/Y or the Longitude/Latitude coordinates. This function is

Box 6.2 ANSWERS 2000 predata information requirements

1- Simulation requirements:
• watershed (or project) name
• the system unit for input and output files, option to echo predata information on the output
* beginning (day of the year) of simulation
• duration of simulation days
* number of gauge station
• number of lines of hydrograph output
• time increment
• infiltration capacity time calculation
* expected runoff peak

3- Soil infiltration, drainage, and groundwater constants follow:
• number of soil layers
* soil layer number, total porosity (TP), field capacity (FP), steady state infiltration rate (FC), difference between steady state and maximum infiltration rate (A), exponent in infiltration equation (P), infiltration control zone depth (DF), antecedent soil moisture (ASM), USLE erodibility factor (K)
• percentage of clay, silt, and sand
* pH, extraction coefficient for nitrate, ammonium, and phosphate

4- Sediment parameters:
• number of particle size classes
• number of wash load classes
• description of each particle class (size, specific gravity, and fall velocity-if known)
• total specific surface area for soil type
• specific surface area for particle size class for soil type

5- Subsurface drainage information:
• drainage exponent
* drainage coefficient for tile drains
• groundwater release fraction

6- Surface roughness and crop constants follow:
* number of crop and surfaces
* crop number, crop type, potential interception storage volume (PIT), fraction of element area covered by foliage (PER), surface depth storage (RC), maximum height differential on soil surface (HU), Manning's n (N), maximum physical retention depth for cropping practice (DIRM), relative erosiveness of a particular land use (C)
* canopy area, area outside canopy, bare area under canopy, bare area outside canopy
* leaf area index
* data of planning, data of harvest, exponent for nitrogen content, dry matter ratio, yield potential, maximum rooting depth for crop, erosion parameter practices at planning day, maximum leaf area index
* number of all possible rotations
* rotation number, crop number, year, month, and day

7- Channel descriptions:
* number of channels
• channel width and roughness

8- Element specifications:
* size of each element
* outlet row and column number
• row number, column number, flag to show end of file, slope steepness, direction of flow, size of channel and soil type, crop/management, channel slope steepness, BMP identifier, BMP identifier #1, BMP identifier #2, soil organic P, effective depth of interaction, mineral P, stable P pool, labile P, potentially mineralizable N, ammonium pool, stable N pool, nitrate pool

accessible under "Create grid element" on the secondary menu of the integrated tool (Figure 6.4). The user can specify the resolution of the cells in the grid density.

The grid can be overlaid with information layers required by the ANSWERS model, "element specification section" of the input file. A SPANS modelling language (Box 6.3) is provided in the integrated tool. The user can use the SPANS modelling language and other functions of the integrated tool to create the grid cell, overlay it with the information layer, and prepare the ANSWERS input file. "Run the ANSWERS model" section on the primary

Box 6.3 SPANS model in the integrated tool

```
E  2hacell2 create a table with 5 map classes
:
: The output of this eq. is cell2.TBB
: point dataset: 2hacell1.tbb
: equation: cell3
: new point dataset: 2hacell2.tbb
:
result(class(2hacell1),class(serieans),class(slopans2),class(195ans1),
class(aspct360));

E 2hacell1 create 2 ha grid cell inside the st. esprit basin
: select points inside watersheds
:
: The output of this eq. contains the grid only inside
: the saint esprit watershed
: point dataset: 2hacell.tbb
: equation: cell1
:new point dataset: 2hacell1.tbb
:
{select if class(wtbnes) == 1, omit};

E 2hacell create 2 ha grid cell for ANSWERS model
: Create grid of points
:
:  create a sampling grid of points, one point
: represents 0.02 km2 = 20000 m2 = 2 ha
:
: The output of this eq. is 2hacell.TBB
:
result(0.02);
```

menu of the integrated tool checks the ANSWERS input files and executes the ANSWERS model. The output file of the ANSWERS model contains information on runoff, sediment, and nutrient. "Visualizing the ANSWERS outputs" submenu of the integrated tool helps users to visualize the runoff as a graph, and sediment and nutrients as maps. All of the components of the integrated tool are available on the "Integrated tool" directory on the attached CD ROM. Installation instructions, hardware, and software requirements are also available on the CD ROM.

6.5 Summary and conclusions

Powerful NPS pollution models such as ANSWERS 2000 are suitable tools for evaluating the hydrologic response of an agricultural watershed. However, ANSWERS 2000 and other complex NPS models have a detailed input file to describe a watershed. Also, their outputs are in numerical format and using these outputs for analysis is difficult. Without using the GIS function, preparing the input file is time consuming and with high grid cell resolution it is impractical. Also, it is impossible to map, with correct geo-reference, the model outputs such as sediment. Using the advanced SPANS operation and EASI script language, the ANSWERS 2000 model was successfully integrated into the latest version of SPANS EXPLORER GIS. The integrated tool provided explanations about the ANSWERS input parameters and also references to use in estimating the input parameters. Using the integrated tool, the user can select and save watershed information in the model input file format, run the model, and visualize the model outputs.

CHAPTER 7

INTEGRATED TOOL APPLICATION: EVALUATION OF THE ANSWERS 2000 MODEL

7.1 Introduction

The integrated ANSWERS and SPANS tool was used to evaluate the continuous ANSWERS model for the Saint Esprit watershed. Different functions of the integrated tool (Figure 6.4) were used to prepare the model input file. The model was validated for the Saint Esprit basin after performing a sensitivity analysis. This analysis was used to assess the relative importance of most input parameters on runoff. The model does not simulate soil freezing and snowmelt conditions. Therefore, the period from May 1st, to the end of November, in years 1994 to 1997, was selected for simulations. Rainfall events in 1994 and 1995 were used for the sensitivity analysis. Thirteen parameters were varied by 25% and 50%. They were: slope, steady state infiltration rate of the soils, groundwater release factor, drainage coefficient factor, antecedent soil moisture, clay, sand, silt, soil horizon depth, air and soil temperatures, solar radiation, and leaf area index.

The effects of the most influential parameters on runoff were tabulated and plotted. Predicted and observed stream runoff were compared using the coefficient of performance CP'_A (James and Burgess, 1982):

$$CP'_A = \sum_{i=1}^{n}(S(i)-O(i))^2 / \sum_{i=1}^{n}(O(i)-O_{avg})^2 \qquad 7.1$$

where:

$O(i)$ is the i^{th} observed stream runoff (mm)

O_{avg} is the mean of the observed stream runoff (mm)

$S(i)$ is the i^{th} simulated runoff (mm)

n is the total number of the events

The coefficient of performance (CP'_A) approaches zero as the observed stream and predicted runoff get closer.

7.2 Rainfall and stream runoff in the Saint Esprit watershed

Table 7.1 shows four years measured rainfall and stream runoff data for the months of May through November in the Saint Esprit watershed. It also contains the long term monthly average rainfall for the area. In 1994, May to August and November were wetter than the long term monthly average rainfall of the area, while September and October were drier than the average. 1995 was a dry year. Only July rainfall was above average. In 1996, May, June, and August were drier than the average and the other months were above the long term average rainfall. 1997 was similar to 1995 and the whole period of May to November except July was under the average. The rainfall and stream runoff patterns for the period of May to November of 1994 to 1997 are presented in Figures 7.1 to 7.4

In general, the period of May to the end of November in 1994 and 1996 was wetter than the long term average, while it was drier in 1995 and 1997.

Table 7.1 Saint Esprit rainfall and stream runoff

	(mm)	May	June	July	Aug.	Sept.	Oct.	Nov.	Total
1994:	rainfall	102.6	196.2	131.8	107.1	42.9	15.7	92.8	689.1
	runoff	72.6	81.3	49.4	30.3	4.4	6.6	20.3	265.0
1995:	rainfall	68.6	35.5	117.8	81.6	61.3	93	88	545.8
	runoff	48.4	14	6.5	3.1	2	32.7	69	175.6
1996:	rainfall	75.1	100.6	118.4	91.2	146.4	140.7	126.3	798.7
	runoff	67.7	15.6	23.5	9	14.3	72.1	78.2	280.5
1997:	rainfall	54.9	66.1	89	72.1	62.8	28	61.5	434.4
	runoff	48.7	15.3	6.8	1.4	1.9	5.4	29.1	108.6
20-year average rainfall of the area (1971-1990):		93	113.6	85.8	102	100.4	96.7	87.2	678.7

Years 1994 and 1995 data were used for validation of the model while 1996 and 1997 data were used for testing the model.

7.3 ANSWERS 2000 input and output files

The integrated tool was used to develop the input data file. The "predata" section of the "answers.inp" file (Beasley and Huggins, 1991) was prepared using the non-spatial part of the tool. A design drainage coefficient of 10 mm/day and a groundwater release factor of 0.005 were assumed. The

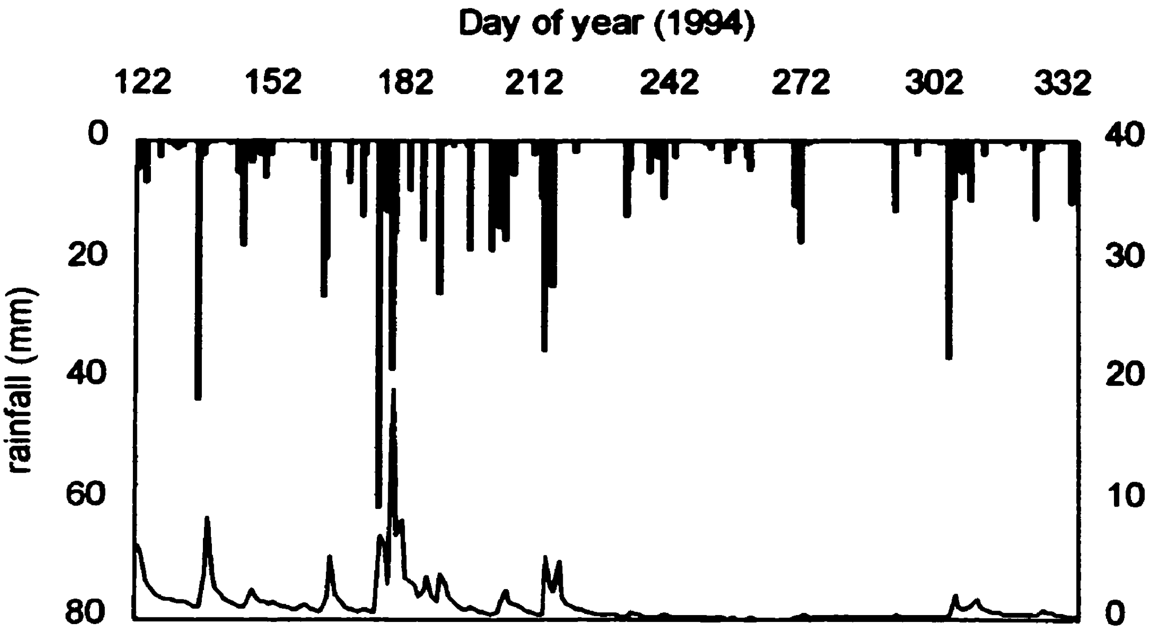


Figure 7.1 Rainfall and runoff – May-November 1994

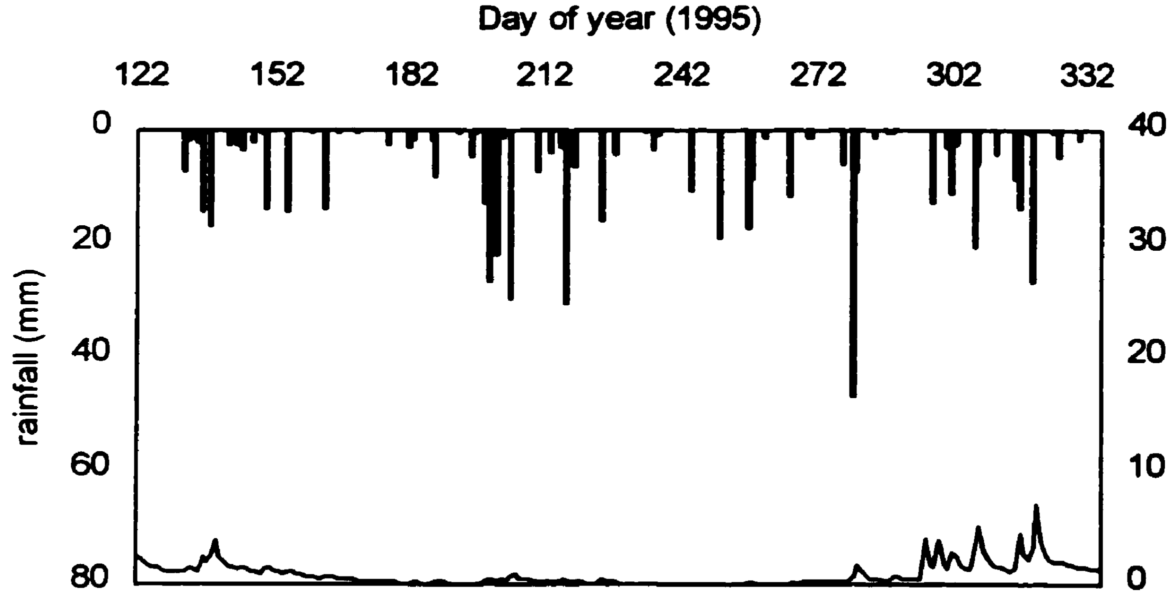


Figure 7.2 Rainfall and runoff – May-November 1995

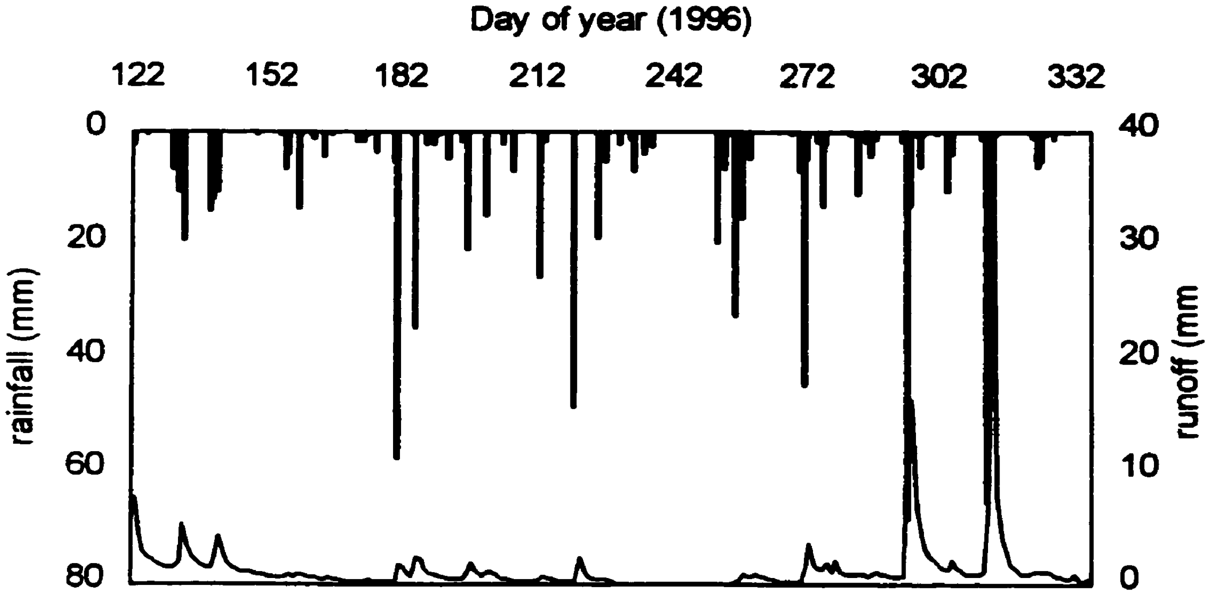


Figure 7.3 Rainfall and runoff – May-November 1996

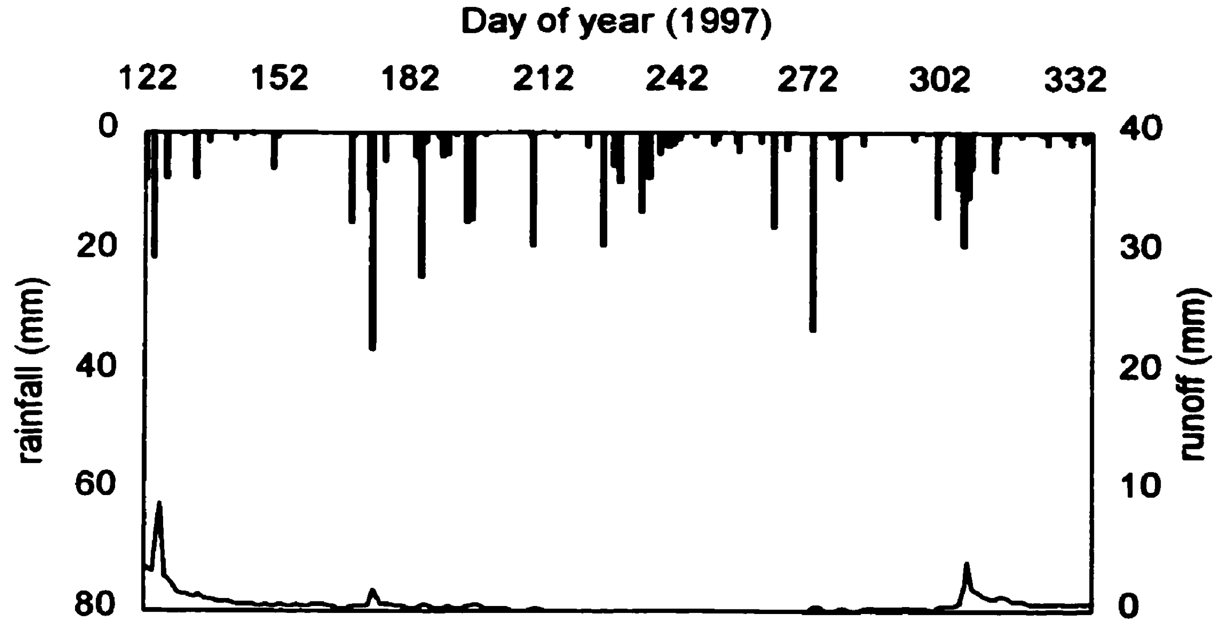


Figure 7.4 Rainfall and runoff – May-November 1997

spatial part of the tool was used to make the “element” section of the “answers.inp” file. First, a two hectare grid cell was created for the Saint Esprit watershed (Figure 7.5). Then, all necessary data such as percentages of slope, aspect, soil texture, channel type, and crop patterns, were extracted from the spatial database.

The meteorological input data file, “daily.inp”, including hourly rainfall intensity (mm/h), daily average air temperature, daily average temperature in the top 5 cm of soil (°C), and solar radiation (Ly/d) was prepared for 1994 through 1997. The entire model input and output files for the sensitivity analysis and final simulations are accessible on the attached CD ROM.

7.4 Sensitivity analysis

The process of monitoring relative changes in the model predictions with respect to changes in model input can be defined as a sensitivity analysis process. It is usually conducted by taking the derivative of model outputs with respect to given input parameters, and assumes that all other model input parameters remain constant. The result of sensitivity analysis increases the accuracy of the model outputs. It allows the determination of the sensitivity of input parameters on model outputs, and the effects that uncertainty of various input parameters can have on model outputs. It also gives a better understanding of the interrelationships of the parameters and shows how they affect the physical processes.

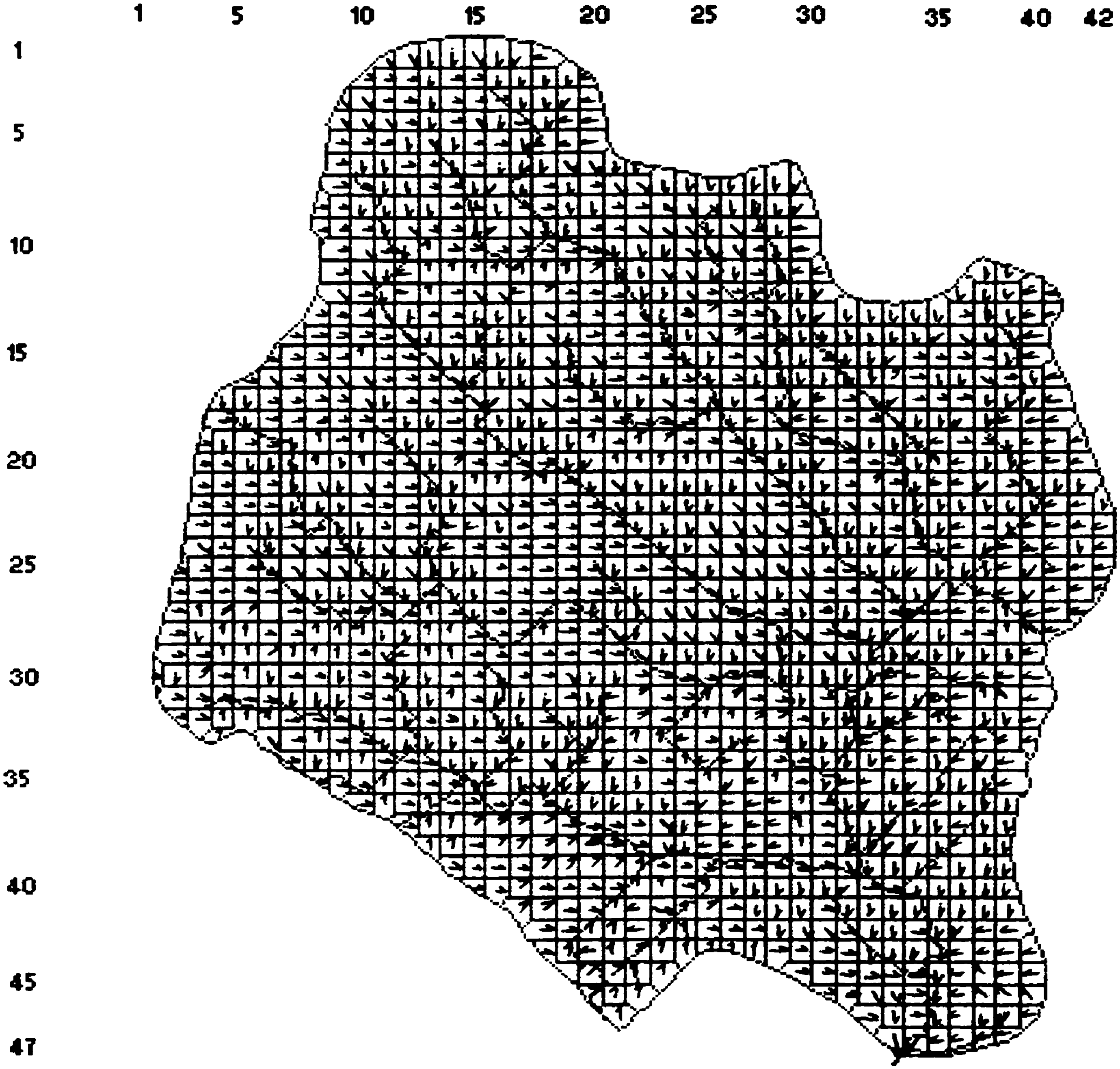


Figure 7.5 Saint Esprit watershed flow path and channel network with a two hectare grid cell

The sensitivity analysis was conducted in three steps to determine the effect of various input parameters on runoff. In the first step the effect of slope, steady state infiltration rate of the soils (FC), groundwater release factor (GRF), and rainage coefficient factor (DCF) were studied (Figure 7.6).

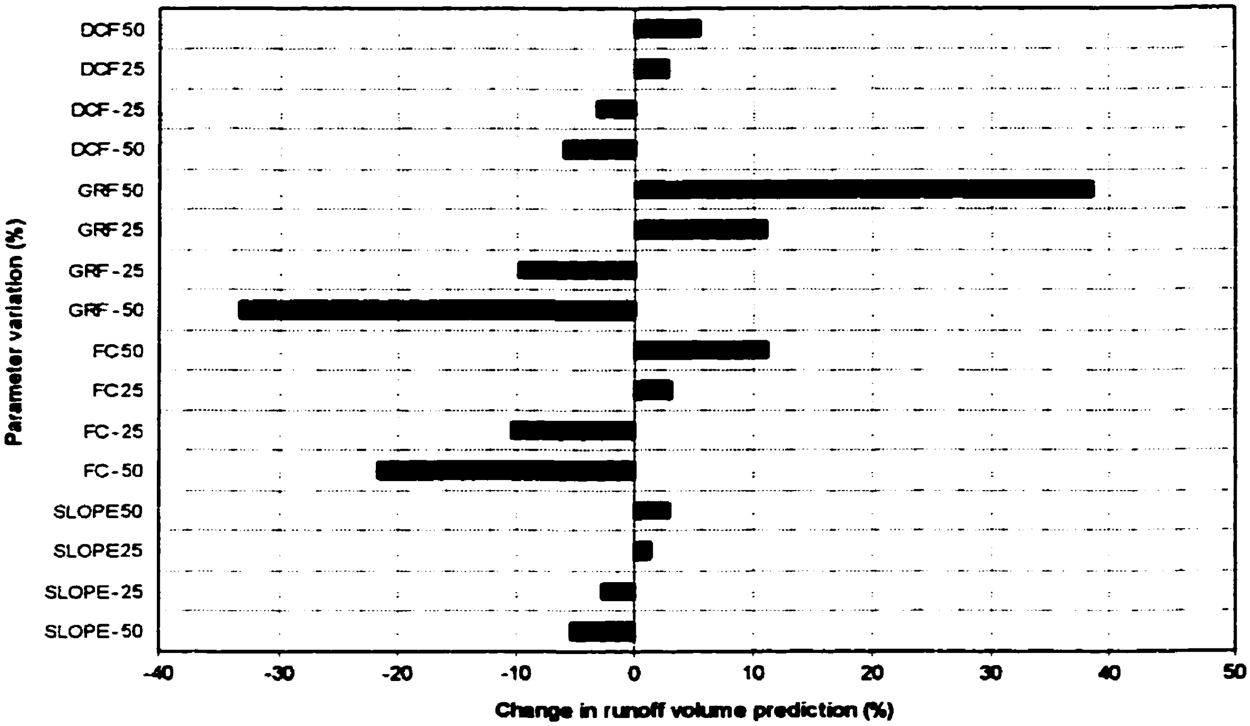


Figure 7.6 Variation in predicted runoff (%) due to a variation in slope, steady state infiltration (FC), groundwater release factor (GRF), and drainage coefficient factor (DCF)

Increasing the values of these parameters caused an increase in the predicted runoff. In this regard, the model showed the greatest sensitivity to GRF. A 50 % increase in GRF resulted in a 39 % increase in predicted runoff. NPS models are usually very sensitive to slopes steepness. The Saint Esprit watershed is flat. About 88 % of the basin has slopes of less than 3 %; and nearly half of this has slopes of less than 1 %. Therefore, slope variation did not influence the simulated runoff. However, the steady state infiltration rate and antecedent soil moisture had a direct effect on predicted runoff.

The second step of the sensitivity analysis focused on the effect of soil texture and depth of soil horizon on the runoff. The sensitivity of runoff to these parameters is shown in Figure 7.7.

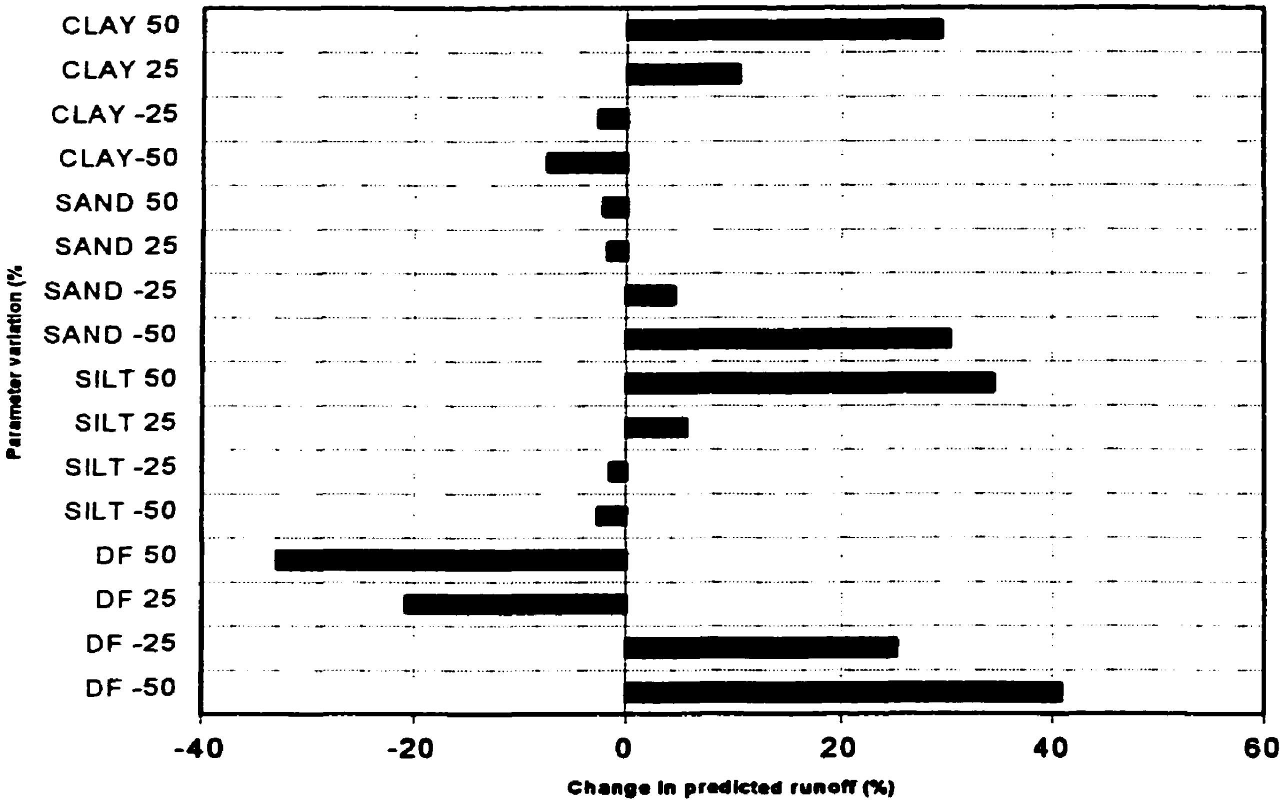


Figure 7.7 Variation in predicted runoff (%) due to a variation in soil texture and depth of soil horizon (DF)

The model was sensitive to variations in the clay, silt, and sand contents. An increase in clay or silt content of the soil resulted in a decrease in the hydraulic conductivity of the soil. Lower infiltration rates increased runoff. On the other hand, an increase in the sand content of the soil resulted in a higher infiltration rate and lower runoff . The model was more sensitive to a 50% increase in silt content than to the same increase in clay content. A 50% increase in the silt content resulted in an increase of 34.4% of the runoff, while the same increase in clay content resulted in an increase of only 29.5 %. However, for a 25% increase, 25% decrease or a 50% decrease in the silt content the resultant variation in runoff was lesser than for equivalent variations of the clay content.

Sensitivity of runoff to variations in the depth of the soil horizon (DF) was considered. The model assumes a single homogeneous soil layer. The depth of this layer should be based on soil characteristics and cultural practices. The runoff was very sensitive to changes in the soil horizon depth. A decrease in soil depth of 50% resulted in an increase in runoff of 18 %. This increase was expected, the shallower the soil zone depth, the faster soil moisture increases and runoff starts.

Evapotranspiration like infiltration is involved in the soil water balance. Therefore, runoff is also related to evapotranspiration. The effects of important evapotranspiration parameters on runoff were analyzed in the third step of the sensitivity analysis. Air and soil temperature, solar radiation, and leaf area index (LAI) are major factors affecting evapotranspiration. The sensitivity of runoff to variations in these parameters is presented in Figure 7.8.

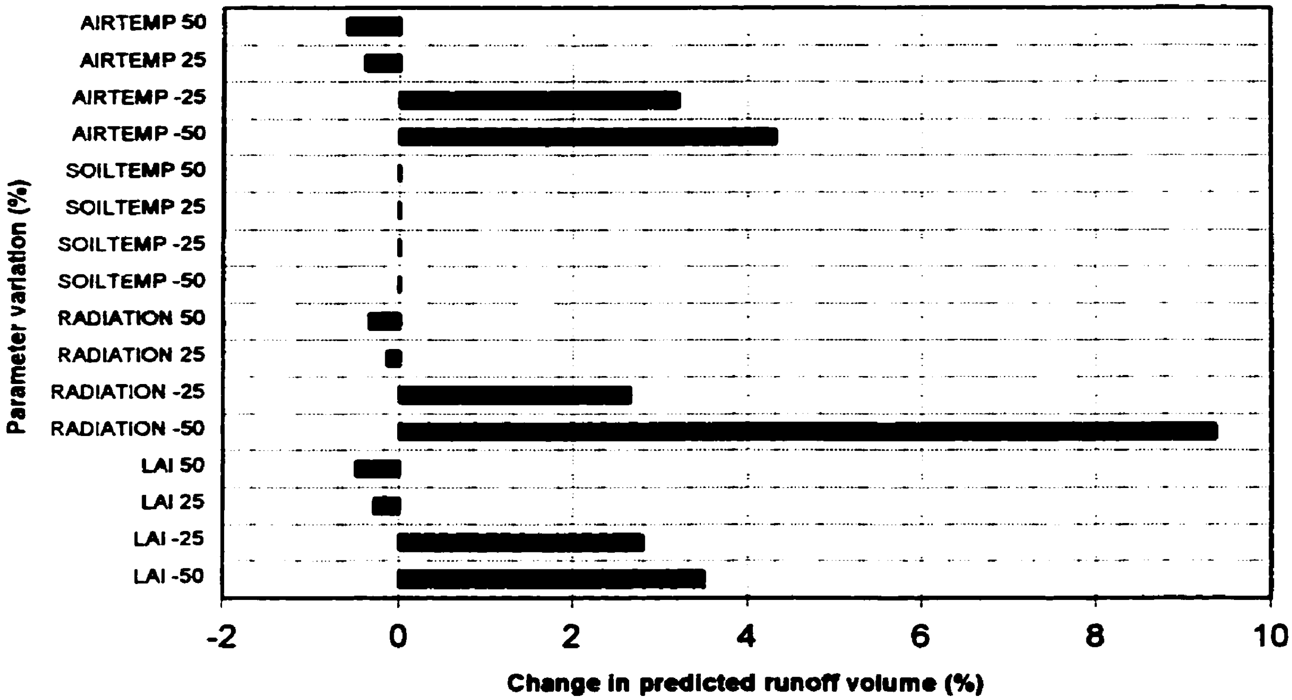


Figure 7.8 Variation in predicted runoff (%) due to a variation in evapotranpiration parameters

Runoff was not sensitive to soil temperature. The sensitivity of runoff to variations in air temperature, solar radiation and leaf area index were similarly small. A decrease in each of air temperature, solar radiation and leaf area index increased runoff. A lower air temperature or solar radiation or leaf area index resulted in lower evapotranspiration and higher runoff. The runoff was most sensitive to solar radiation. A decrease in solar radiation of 50 %, increased runoff by 9.4 %.

7.5 Results and discussion of the model predictions

The model was applied to simulate runoff for the period of May 1st to the end of November, for 1994 through 1997. Results of model predictions is discussed in two sections. In the first, daily, monthly, seasonal cumulative predicted runoff from 1994 to 1997 are compared with the measured depth of stream runoff of the watershed. Given that an analysis of individual rainfall events was available for 1994 and 1995 (Lapp, 1996), in the second section, predicted events runoff is compared with Lapp's observed runoff hydrograph data for 17 events in 1994 and 7 events in 1995.

7.5.1 Results of daily, monthly, and seasonal cumulative predicted runoff from 1994 to 1997

Tile drainage coefficients and ground release factors in the model input were taken into account to enable a comparison between the predicted cumulative runoff and measured stream runoff at the outlet of the watershed (Figures 7.9, 7.10, 7.11, and 7.12). The results of predicted runoff as well as observed rainfall and measured stream runoff for 1994-1995 and 1996-1997 are presented in Tables 7.2 and 7.3, respectively.

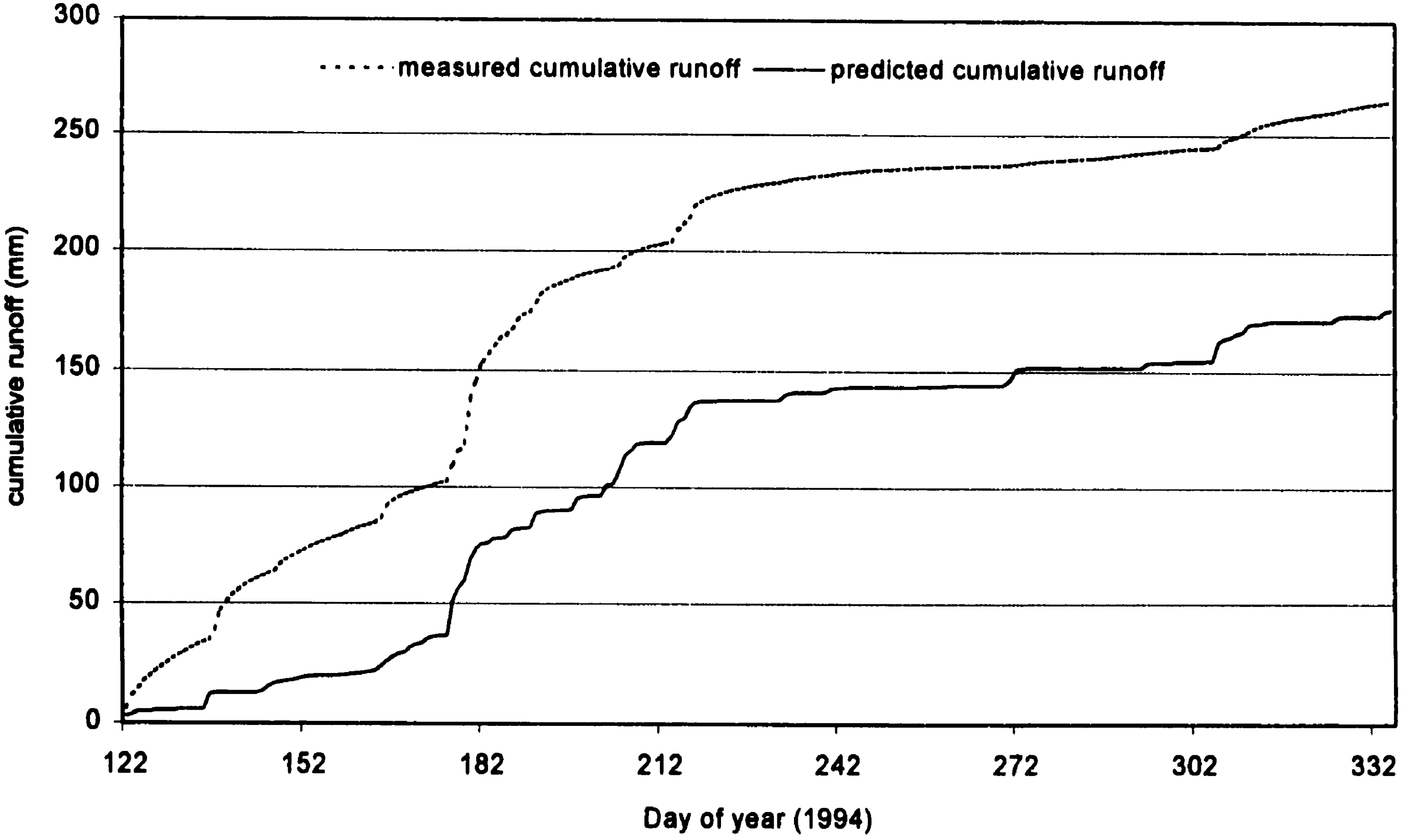


Figure 7.9 Measured cumulative runoff vs. predicted cumulative runoff in 1994

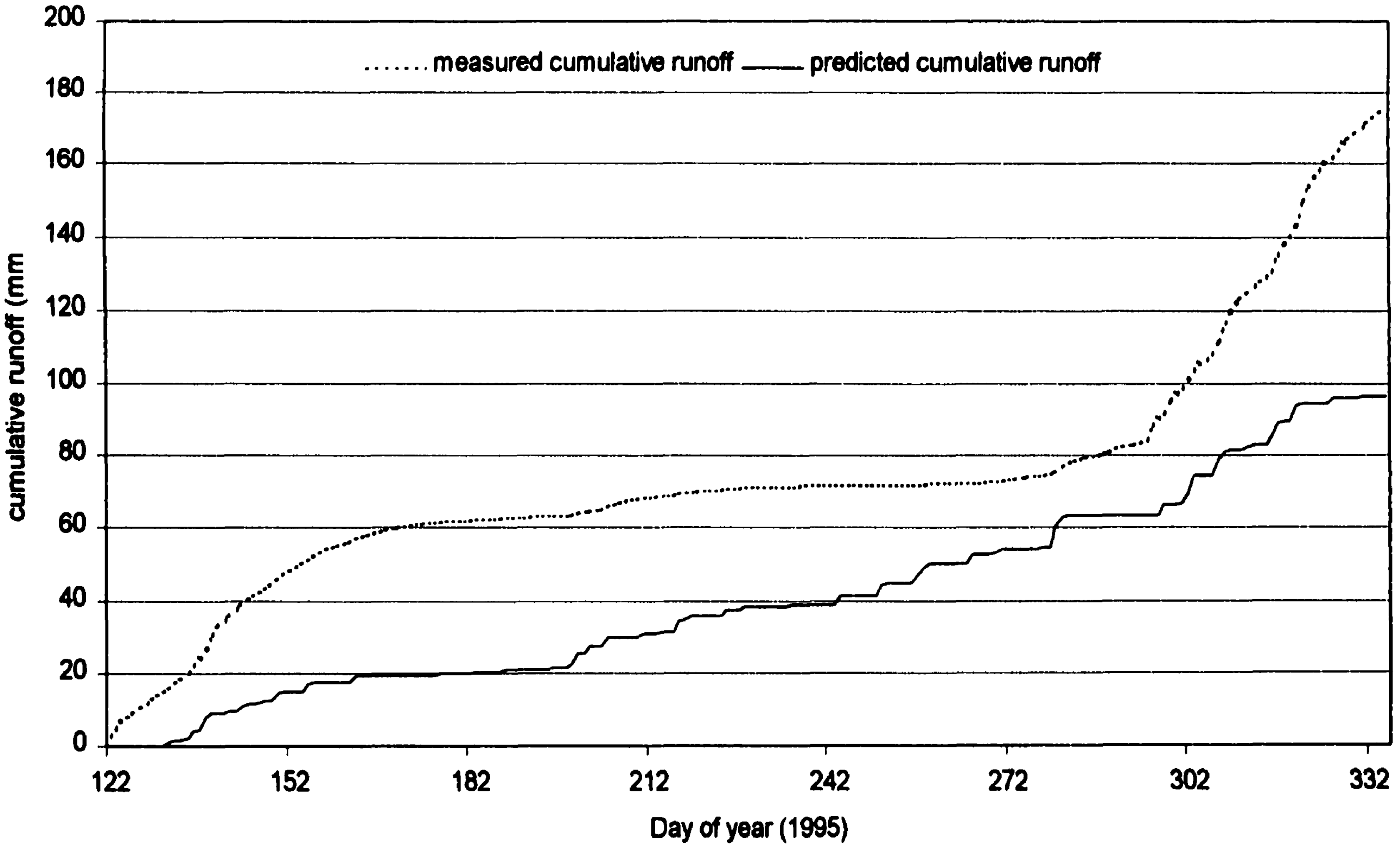


Figure 7.10 Measured cumulative runoff vs. predicted cumulative runoff in 1995

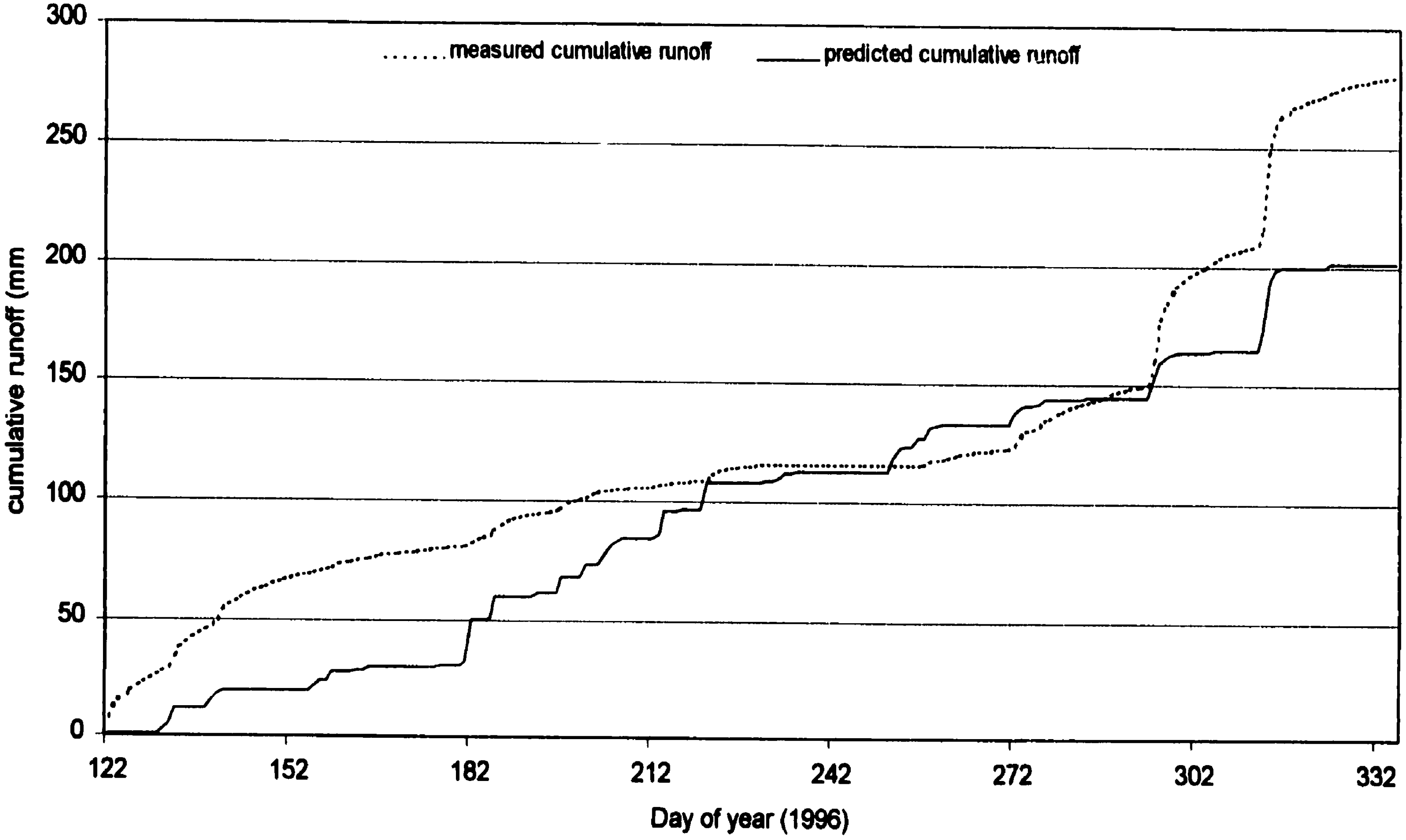


Figure 7.11 Measured cumulative runoff vs. predicted cumulative runoff in 1996

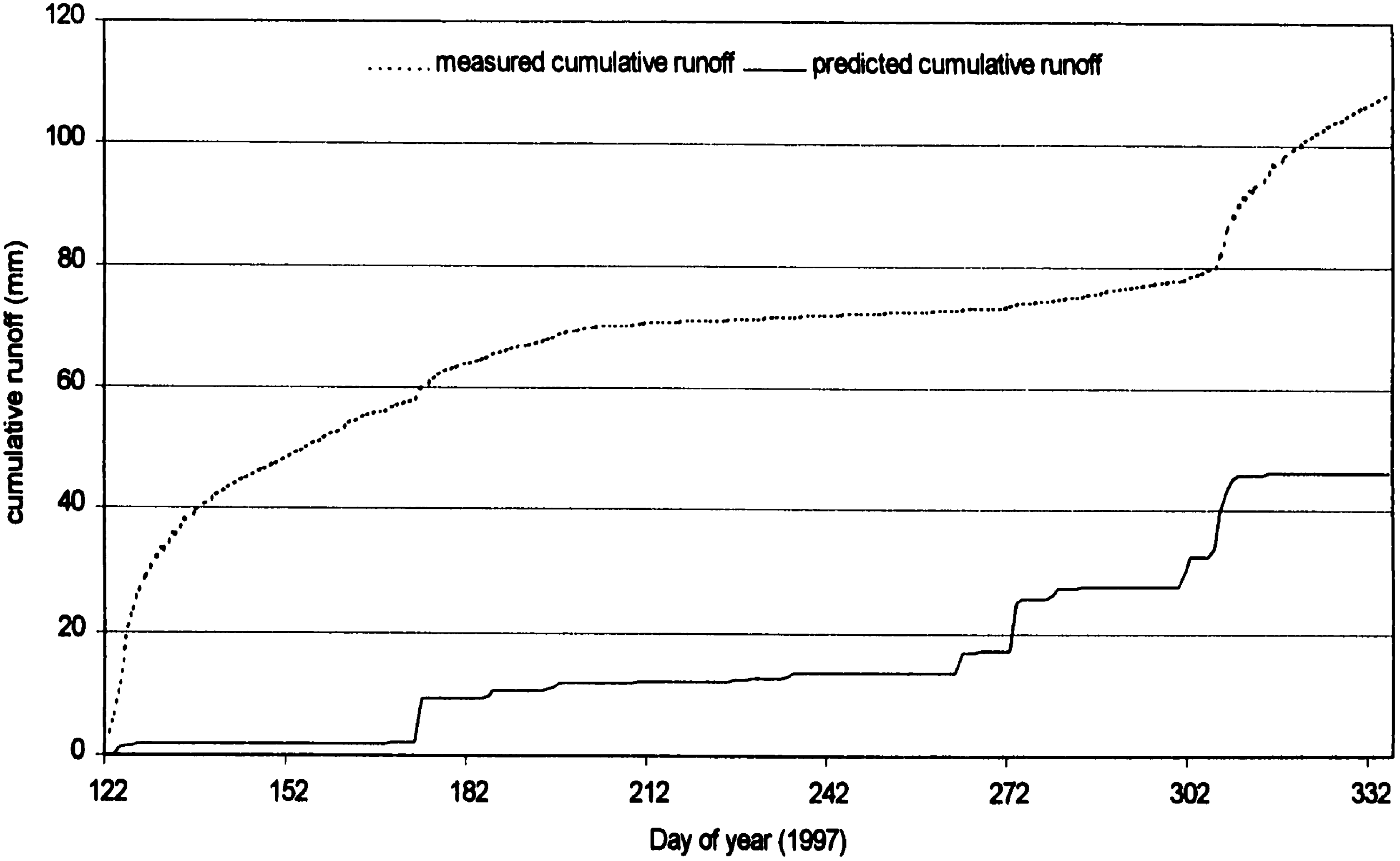


Figure 7.12 Measured cumulative runoff vs. predicted cumulative runoff in 1997

Table 7.2 **Measured and predicted cumulative runoff in 1994 and 1995**

	May	June	July	Aug.	Sept.	Oct.	Nov.
1994:							
rainfall (mm)	102.6	196.2	131.8	107.1	42.9	15.7	92.8
Total rainfall = 689.1							
measured runoff (mm)	72.6	81.3	49.4	30.3	4.4	6.6	20.3
predicted runoff (mm)	19.6	56.2	43.9	24	8.2	3.0	21.5
cumulative measured runoff (mm)	72.6	153.9	203.3	233.7	238	244.7	265
cumulative predicted runoff (mm)	19.6	75.8	119.7	143.7	151.9	154.9	176.4
measured runoff/rainfall (%)	70.7	41.4	37.5	28.3	10.2	42.4	21.9
predicted runoff/rainfall (%)	19.1	28.7	33.3	22.4	19.2	19.1	23.1
total measured runoff / rainfall = 38.5 %							
total predicted runoff / rainfall = 25.6 %							
predicted runoff/measured runoff (%)	27	69.1	88.7	79.1	188.6	45.1	105.5
total predicted runoff / total measured runoff = 66.6 (%)							
1995:							
rainfall (mm)	68.6	35.5	117.8	81.6	61.3	93	88
Total rainfall = 545.8							
measured runoff (mm)	48.4	14	6.5	3.1	2	32.7	69
predicted runoff (mm)	15.2	4.8	10.9	10.3	13.1	20.6	21.6
cumulative measured runoff (mm)	48.4	62.3	68.9	71.9	73.9	106.6	175.6
cumulative predicted runoff (mm)	15.2	20	30.9	41.2	54.3	74.9	96.5
measured runoff/rainfall (%)	70.5	39.3	5.5	3.8	3.2	35.1	78.5
predicted runoff/rainfall (%)	22.1	13.5	9.3	12.6	21.4	22.2	24.5
total measured runoff / rainfall = 32.2 %							
total predicted runoff / rainfall = 17.7%							
predicted runoff/measured runoff (%)	31.3	34.4	167.4	335.3	659.3	63.1	31.3
total predicted runoff / total measured runoff = 54.9 (%							

Table 7.3 **Measured and predicted cumulative runoff in 1996 and 1997**

	May	June	July	Aug.	Sept.	Oct.	Nov.
1996:							
rainfall (mm)	75.1	100.6	118.4	91.2	146.4	140.7	126.3
Total rainfall = 798.7							
measured runoff (mm)	67.7	15.6	23.5	9	14.3	72.1	78.2
predicted runoff (mm)	19.8	30.2	36.3	26.2	27.8	23.6	37.2
cumulative measured runoff (mm)	67.7	83.3	106.8	115.8	130.2	202.3	280.5
cumulative predicted runoff (mm)	19.8	50.0	86.3	112.5	140.3	163.9	201.1
measured runoff/rainfall (%)	90.1	15.5	19.9	9.9	9.8	51.2	62.0
predicted runoff/rainfall (%)	26.4	30.0	30.7	28.7	19.0	16.8	29.5
total measured runoff / rainfall = 35.1 %							
total predicted runoff / rainfall = 25.2 %							
predicted runoff/measured runoff (%)	29.3	193.9	154.2	290.3	194.0	32.7	47.5
total predicted runoff / total measured runoff = 71.7 (%)							
1997:							
rainfall (mm)	54.9	66.1	89	72.1	62.8	28	61.5
Total rainfall = 434.4							
measured runoff (mm)	48.7	15.3	6.8	1.4	1.9	5.4	29.1
predicted runoff (mm)	1.7	7.8	2.7	1.5	12.0	6.7	13.6
cumulative measured runoff (mm)	48.7	64.0	70.8	72.2	74.1	79.5	108.6
cumulative predicted runoff (mm)	1.7	9.5	12.2	13.8	25.8	32.5	46.1
measured runoff/rainfall (%)	88.7	23.1	7.6	1.9	3.0	19.3	47.3
predicted runoff/rainfall (%)	3.1	11.7	3.1	2.1	19.2	23.9	22.1
total measured runoff / rainfall = 25 %							
total predicted runoff / rainfall = 10.6 %							
predicted runoff/measured runoff (%)	3.5	50.7	40.4	110.2	633.6	124.1	46.7
total predicted runoff / total measured runoff = 42.4 (%)							

The model predicted a total of 176.4, 96.5, 201.1, and 46.1 mm of cumulative runoff for the period of May 1st to the end of November from 1994 through 1997, respectively. It was a relatively good prediction of total runoff,66.6% in 1994, 54.9% in 1995, 71.7 % in 1996, and 42.4 % in 1997. However, there was a tendency to underpredict total cumulative runoff in all years. There was also no close agreement between predicted and observed values in each month of the specified period.

In 1994, the model underpredicted runoff by 73, 30.9, 11.3, 20.9, and 54.9 %, for the month of May, June, July, August, and October, respectively. On the other hand, the model overpredicted runoff in September and November by 88.6 and 5.5 % respectively (Table 7.2).

In 1995, the model underpredicted runoff by 68.7, 65.6, 36.9, and 68.7% for the month of May, June, July, October, and November, respectively. It overpredicted runoff in July, August, and September by 67.4, 235.3, and 559.3 % respectively (Table 7.2).

In 1996, the model underpredicted runoff by 71, 67, and 52 %, for the month of May, October, and November, respectively. On the other hand, the model overpredicted runoff in June, July, August, and September by 94, 54, 190, and 94 % respectively (Table 7.3). It predicted 40 % of the total runoff in May, October, and November and 60 % from June to September. While 78 %

of observed stream runoff occurred in May, October, and November and only 22 % from of June to September.

In 1997, the model underpredicted runoff by 96, 49, 60, and 53 % for the month of May, June, July, and November, respectively. It overpredicted runoff in August, September, and October by 10.2, 534, and 24 % respectively (Table 7.3). The model predicted 56 % of the total runoff in May, June, July, and November and 44 % from August to October. Of observed stream runoff 92% occurred in May, June, July, and November and only 8 % from August to October. Figures 7.13 to 7.16 show the difference between predicted runoff and observed stream runoff for each month in 1994 to 1997.

This version of ANSWERS is one of the attempts to develop a distributed *continuous* nonpoint source model. However, it was developed from the original event based version of the ANSWERS model. The continuous model responded to individual rainfall events through the simulation period (Figure 7.13 and 7.16), based on the hydrologic conceptual structure of the event based version. This may explain why it predicted runoff events in all four years for which there was no observed runoff.

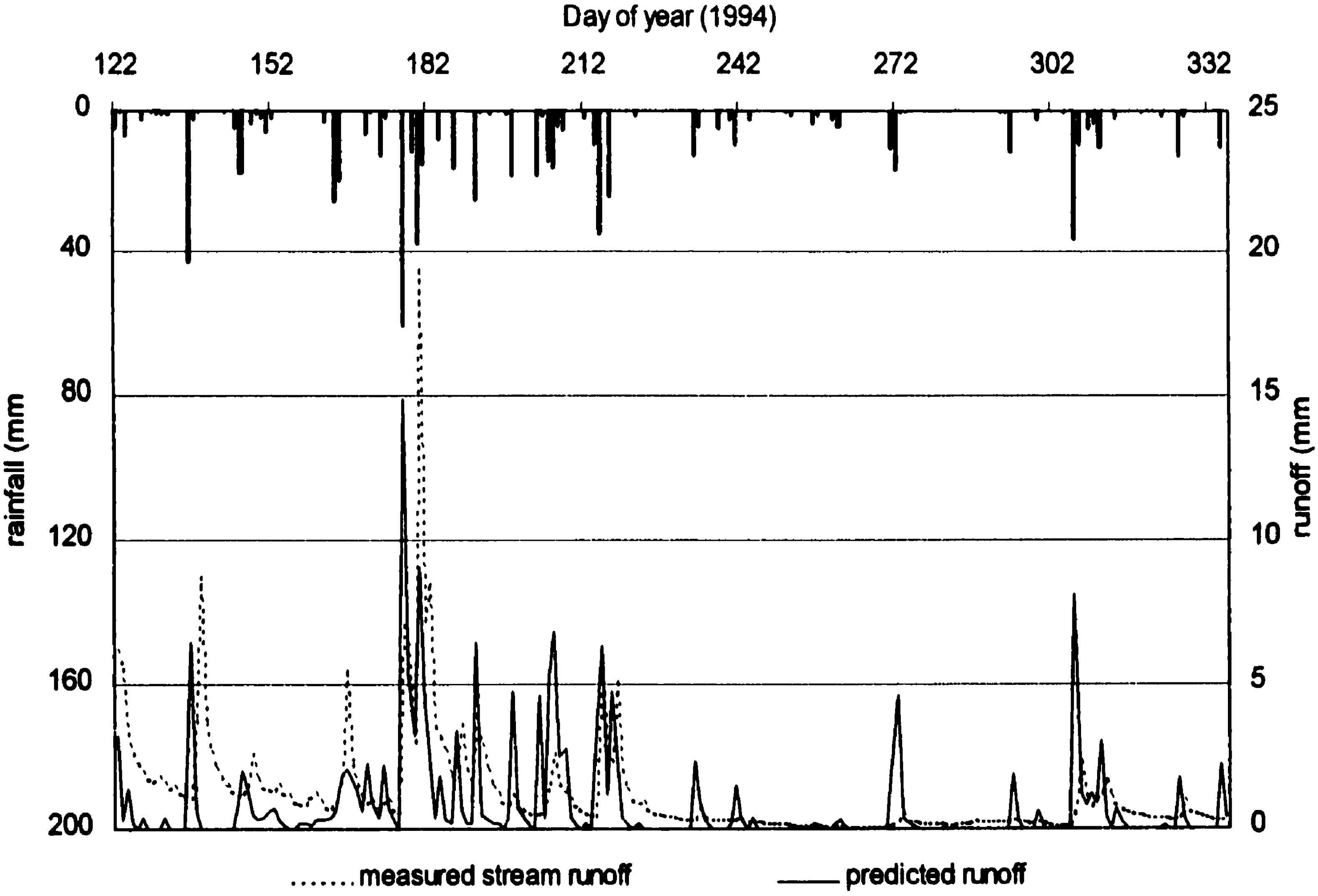


Figure 7.13 Measured runoff vs. predicted runoff in 1994

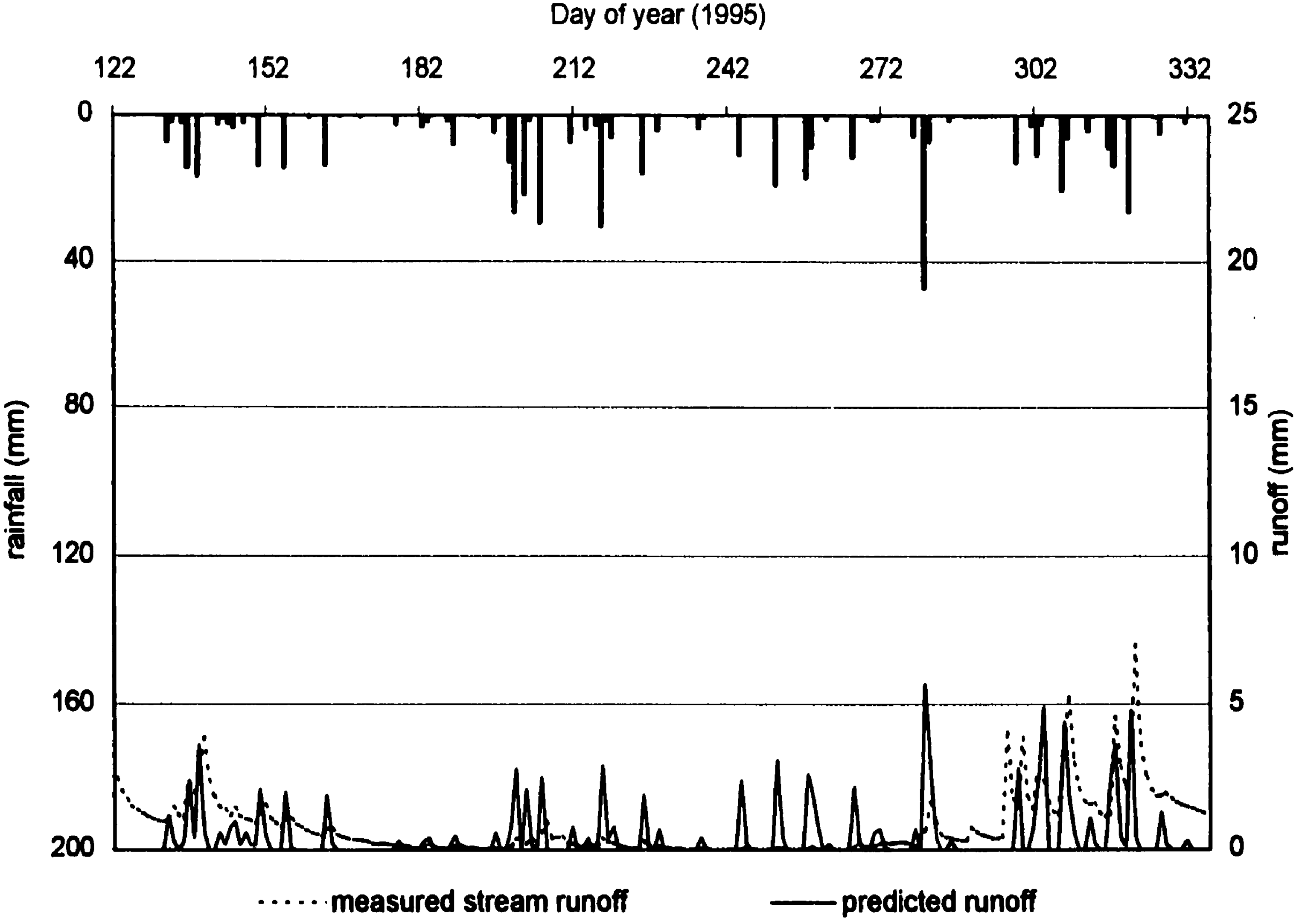


Figure 7.14 Measured runoff vs. predicted runoff in 1995

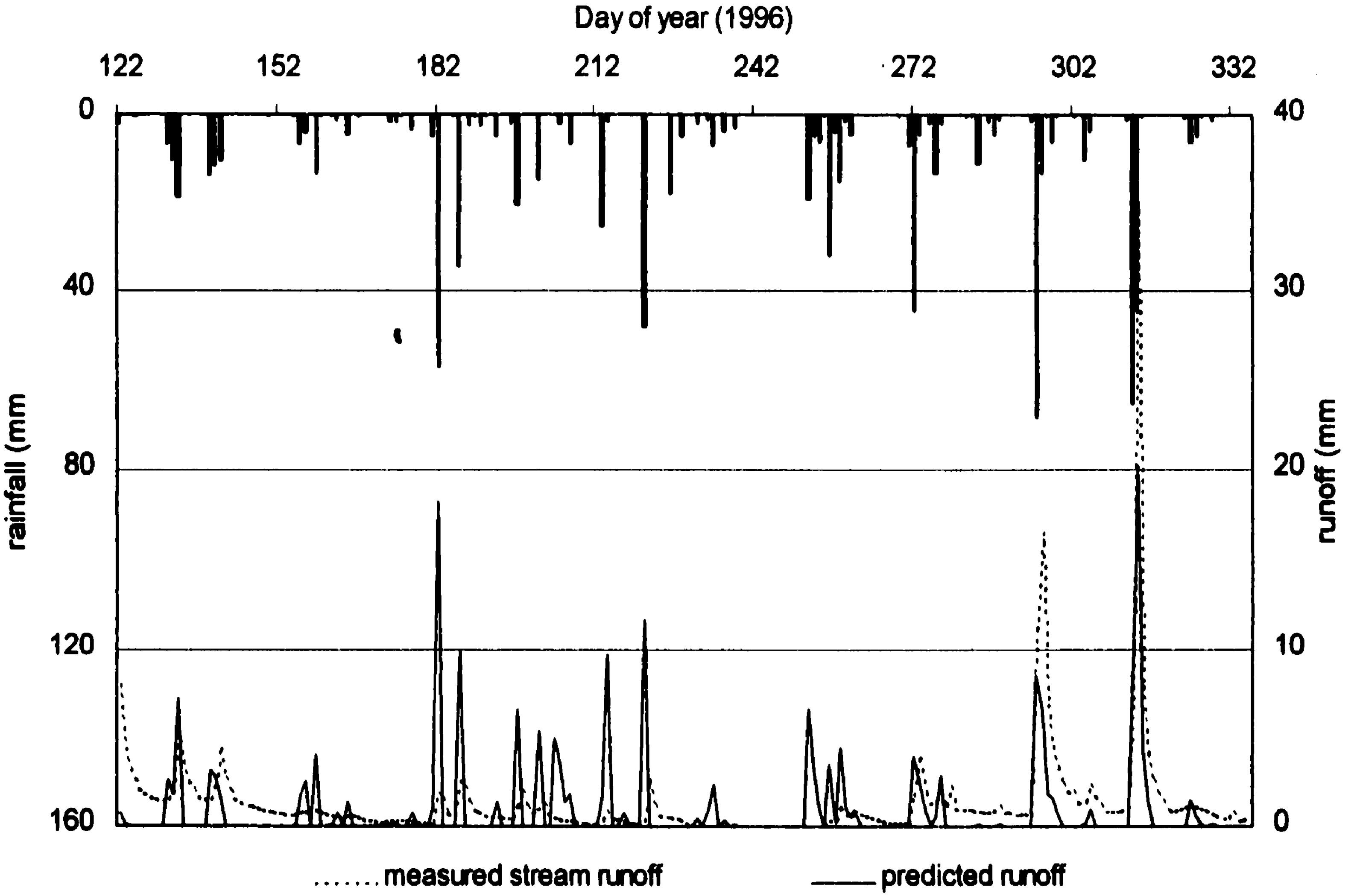


Figure 7.15 Measured runoff vs. predicted runoff in 1996

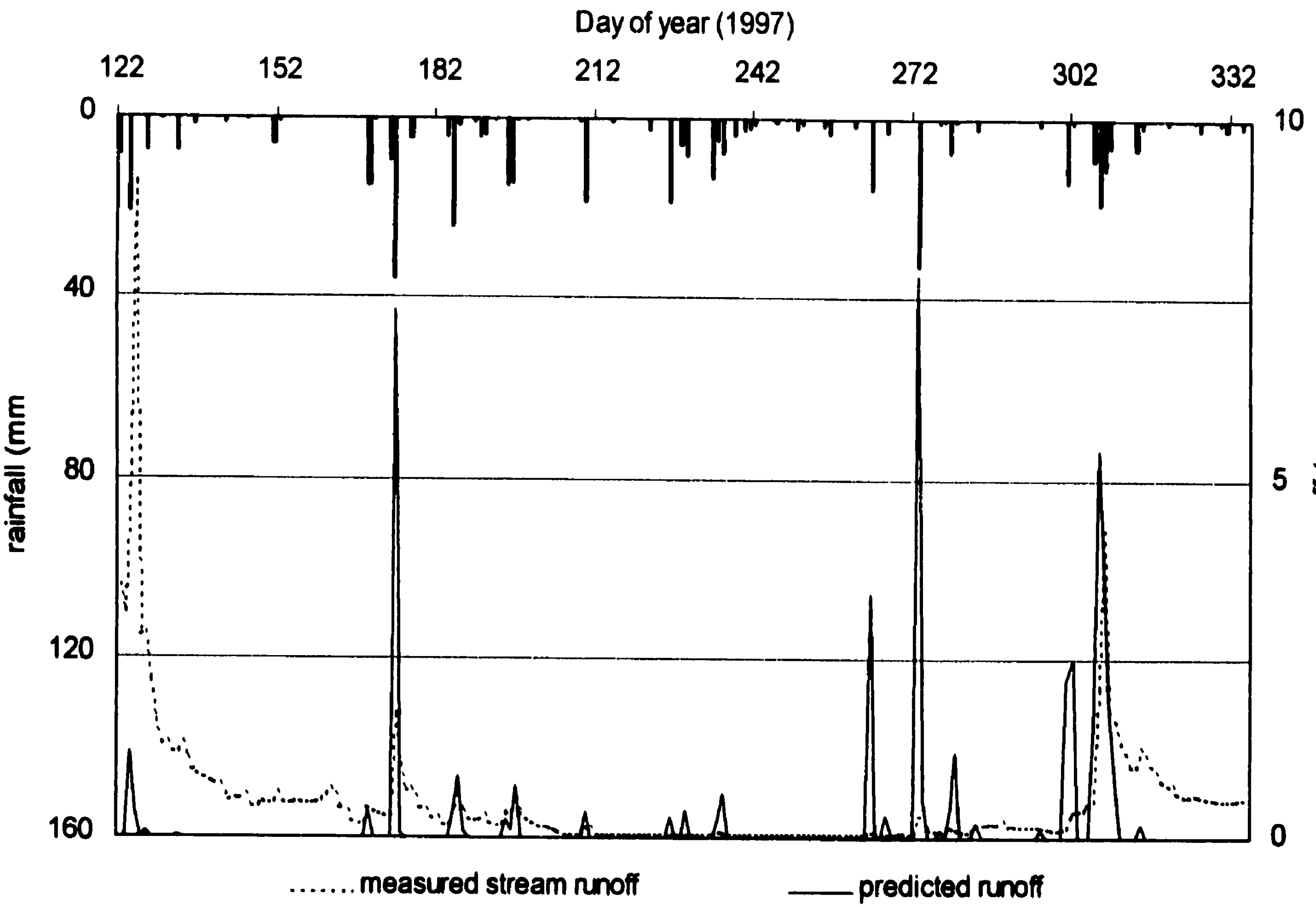


Figure 7.16 Measured runoff vs. predicted runoff in 1997

Table 7.2 and 7.3 also contain the ratio between observed runoff and rainfall, and between predicted runoff and rainfall. The maximum ratio between observed runoff and rainfall was 70.7%, 70.5%, 90.1%, and 88.7% in May of all four years, from 1994 to 1997. The minimum ratio between observed runoff and rainfall was 10.2% in September of 1994, 3.2% in September of 1995, 9.8% in September of 1996, and 1.9% in August of 1997. The maximum ratio between predicted runoff and rainfall was 33.3% in July of 1994, 24.5% in November of 1995, 30.7% in July of 1996, and 23.9% in October of 1997. The minimum ratio between predicted runoff and rainfall was 19.1% in May and October of 1994, 9.3% in July of 1995, 16.8% in October of 1996, and 2.1% in August of 1997. The ratio between total predicted runoff and rainfall was 25.6% in 1994, 17.7& in 1995, 25.2% in 1996, and 10.6% in 1997. The ratio between total observed runoff and rainfall was 38.5% in 1994, 32.2% in 1995, 35.1% in 1996, and 25% in 1997.

The continuous version of ANSWERS maintains a water balance between rainfall events. Runoff, infiltration, evapotranspiration, and percolation are four components of the water balance of the model. During the summer, evapotranspiration has an important effect in reducing runoff. However, the results of 1996 indicated that the model predicted almost three times more runoff than was observed between June to September. It, therefore, appears that more research is needed to evaluate the evapotranspiration submodel of the continuous ANSWERS model.

7.5.2 Results of individual rainfall analyses for 1994 and 1995

In 1994 and 1995 only 24 rainfall events produced substantial runoff from the watershed. Lapp (1996) measured these hydrologic events and analysed their hydrographs. Of these 24 events, 17 were from the 1994 season with the remainder from the 1995 season.

In both 1994 and 1995, the predicted runoffs were generally less than measured runoffs (Table 7.4). The average relative error was –34.5 % in 1994 and –55.6 % in 1996. This underprediction of runoff was previously reported by Montas and Madramootoo (1991), Von Euw et al. (1989), Beasley et al. (1980), and Dickey et al. (1979) who all applied the ANSWERS event based model in different watersheds in North America.

The predicted and observed runoff for June 27th, 1994 were in close agreement (Table 7.4); having the lowest relative error (7 %). The accuracy of this prediction probably occurred because the model could keep track of antecedent soil moisture conditions, since a large rainfall event had occurred only two days earlier. Predicted runoff for July 9th 1994 and July 26th 1995 showed poor agreement with observed values, with relative errors of -88.9 and -84.6 %, respectively. The intensity of these rainfall events was 21.6 and 24.4 mm/hr, but their duration was less than one hour. Therefore, the watershed could not respond to these events due to the high value of the time of concentration. As a result only 1.56 and 0.16 mm of runoff were observed for these events, respectively. The model prediction for these

Table 7.4 Selected hydrologic events* and predicted runoff for 1994 and 1995

Date 1	rainfall mm 2	duration hr 3	intensity mm/hr 4	measured runoff (mm) 5	predicted runoff (mm) 6	absolute error (mm) 7	relative error % 8
1994:							
May 1	20.8	17.0	1.2	2.98	3.21	0.23	7.6
May 16	46.4	24.25	1.9	5.78	1.59	-4.19	-72.5
May 26	18.2	10.5	1.7	0.86	0.03	-0.83	-96.5
June 13	23.8	5	4.8	1.94	3.31	1.37	70.8
June 25	47	7.5	6.3	4.14	2.75	-1.39	-33.6
June 27	41	5.25	7.8	9.68	10.36	0.68	7
June 29	19.8	4	5	3.24	0.07	-3.17	-97.8
July 2	9.2	2.75	3.3	0.47	0.13	-0.34	-73.4
July 5	20.2	3.5	5.8	1.22	0.01	-1.21	-99.1
July 9	16.2	0.75	21.6	1.56	0.17	-1.39	-88.9
July 16	12	2.25	5.3	0.16	0.29	0.13	82.5
July 23	21.2	5.25	4	1.51	0.17	-1.34	-89.1
July 26	4.2	1.25	3.4	0.16	0.02	-0.14	-84.6
August 2	42.6	6.5	6.6	3.55	2.75	-0.80	-22.6
August 4	19.2	5	3.8	2.39	0.02	-2.37	-99.3
November 1	52.2	26.5	2	1.85	3.06	1.21	65.3
November 6	13.8	16	0.9	0.63	0.87	0.24	37.8
						Average =	**-34.5 %**
						CP'_A =	**0.49**
1995:							
May 17	15.8	6.5	2.4	0.88	0.005	-0.88	-99.4
July 20	12.2	2.75	4.4	0.17	0.002	-0.17	-98.9
July 23	35.8	7.25	4.9	0.81	0.321	-0.49	-60.4
July 26	12.2	0.5	24.4	0.19	0	-0.19	-100
October 6	54	30	1.8	2.25	4.32	2.07	92.0
October 22	39.3	8	4.9	2.05	0.75	-1.30	-63.5
November 2	32.8	13	2.5	2.80	1.15	-1.66	-59.1
						Average =	**-55.6 %**
						CP'_A =	**1.47**

---

* Columns 2, 3, and 5 are adapted from Lapp (1996)

events was 0.17 and 0.0 mm, much lower than the observed values. In this watershed, the model seems unable to predict runoff for short duration storms of less than one hour.

The model predicted a lower runoff for most events which had relatively dry antecedent soil moisture conditions. Also, the model tended to overpredict runoff for events with durations longer than 24 hr (November 1st, 1994 and October 6th, 1995). It therefore appears that the model was unable to accurately simulate runoff for very wet or very dry antecedent soil moisture conditions.

Improper prediction of runoff values could also be due to inaccurate estimation of soil physical properties. Seasonal variations in parameters, such as macropores, due to faunal activity and root penetration, would also increase infiltration during the summer months. The impacts of these infiltration parameters are not considered by the model or in the input preparation.

In general, the results show relatively better agreement between predicted and observed runoff for 1994 (Table 7.4). The coefficient of performance (CP'_A) was 0.49 in 1994 compared to 1.47 in 1995. The year 1995 was drier than normal, with 10 rainfall events fewer than 1994, in the period of May 1st to the end of November. Therefore, fewer rainfall events in 1995, resulted in fewer runoff events to be predicted by the model, and a higher average relative error and coefficient of performance compared to 1994.

7. 6 Summary and conclusions

The continuous version of ANSWERS was originally run on a VAX (VMS operating system) machine. Running the program on a watershed with 1100 one hectare cells, for a five month period, required approximately five hours (Bouraoui, 1994). It was modified and run successfully on a PC machine. The model simulated the Saint Esprit watershed with 1300 two hectare cells, for a 7 month period, in approximately 24 minutes on a Pentium 100 with 32 meg RAM, or 7 minutes on a Pentium 233 II with 64 meg RAM. The original and modified source codes are available on the attached CD ROM.

The sensitivity analysis was performed on thirteen parameters to determine their effects on runoff. The model was found to be most sensitive to depth of soil horizon, silt and clay contents of soil texture, and solar radiation.

Four years of runoff prediction by the model were analysed using observed hydrologic data. Overall, the model predicted runoff, in the Saint Esprit watershed, with a fairly good agreement with observed runoff in wetter years. The coefficient of performance (CP'_A) between predicted and observed values was 0.5 and 1.5 for 1994 and 1995, respectively. The model predictions of total cumulative runoff were 66.6% in 1994, 54.9% in 1995, 71.7% in 1996, and 42.4% in 1997, of measured cumulative runoff values.

CHAPTER 8

SUMMARY AND CONCLUSIONS

8.1 Summary

To reduce the environmental impact of agricultural activities on water quality, a three year study of agricultural NPS pollution was initiated on two sub-watersheds of the L'Assomption river in Quebec. The sub-watersheds studied were the Saint Esprit (26.1 km^2) and Desrochers (17.9 km^2). Development of a methodology and associated tools for targeting conservation activities and assessing the potential impacts of conservation practices was one of the study's components. Integration of a NPS model with a GIS can provide assistance in creating a tool to handle the extensive input and output data for models, evaluate the model output, and delineation of critical areas. Development of such a tool using NPS models capability and GIS tools was the goal in this research.

The ANSWERS 2000 model and SPANS GIS software were selected for integration. ANSWERS 2000 is a physically based, distributed parameter, watershed scale model, developed to simulate runoff, sediment, and nutrient losses from agricultural watershed continuously. SPANS has a raster data structure and allows for the exchange of data and links with the NPS model. It works on an IBM compatible PC. It has modelling capabilities to be used for establishing a clear picture of agricultural activities in a watershed.

8.2 Conslusions

The Saint Esprit database was developed within SPANS GIS. Collection of the spatial data was conducted at two scales. In the initial phases of the project, general data, most of it public domain, was collected for both Saint Esprit and Desrochers watersheds. In the second phase, field level management data were collected on a field-by-field basis for the Saint Esprit basin. About 1300 hours were spent to transfer the data, to the GIS format, and create the database. However, given the experience gained from this work creating a similar database for another watershed would not take as long. Alternative methods, not available when the project began, now exist for creating databases for larger watersheds. Some of these are mentioned in Chapter 9.

The field attribute database method was developed. It was selected as a method to create new data layers. With this method it was possible to manage large amounts of field-by-field information. It also eliminated the need for further digitizing. This method can be used in similar projects.

The Saint Esprit spatial database was used to perform a variety of analyses. These analyses tended to be one of four different types. Using the Saint Esprit spatial database:

- a clear picture of the agricultural activities and various statistics on both watersheds was obtained,
- non-numerical modeling was performed to delineate the areas with high erosion potential,
- a database was created to build different factors of the RUSLEFAC model, and create the input file for the ANSWERS 2000 model.

Using the advanced SPANS operation and EASI script language, the ANSWERS 2000 model was integrated into the latest version of SPANS EXPLORER GIS. The integrated tool provided explanations about the ANSWERS input parameters and references to use in estimating the input parameters. Using the integrated tool, the user can select and save watershed information in the model input file format, run the model, and visualize the model outputs.

The continuous version of ANSWERS was originally run on a VAX (VMS operating system) machine. It was modified and run on a PC machine. The integrated tool was used to evaluate the ANSWERS model. The effects of the most influential parameters on runoff were tabulated and plotted. The sensitivity analysis was performed on thirteen parameters to determine their effects on runoff. The model was found to be most sensitive to depth of soil horizon, silt and clay contents of soil texture, and solar radiation.

Four years of runoff prediction by the model were analysed using observed hydrologic data. Overall, the model predicted runoff, in the Saint Esprit watershed, with a fairly good agreement with observed runoff in wetter years. The coefficient of performance (CP'_A) between predicted and observed values was 0.5 and 1.5 for 1994 and 1995, respectively. The model predictions of total cumulative runoff were 66.6% in 1994, 54.9% in 1995, 71.7% in 1996, and 42.4% in 1997, of measured cumulative runoff values.

CHAPTER 9

RECOMMENDATIONS FOR FUTURE RESEARCH

1. Although the integration of ANSWERS 2000 with SPANS created for this study has satisfied the objectives, there is room for future changes and improvement. The following areas for further investigation are recommended:

   1.1 GIS provided an ideal environment for the development of the model giving computational power and facilities of data handling. However, more work is needed to make the model and GIS integration more user friendly.

   1.2 With the new trend of GIS to represent temporal changes and variability, enhanced integration can be developed to analyze and visualize model simulations relative to time. This creates an effective tool to investigate temporal and spatial variability of rainfall intensities and their effects on runoff.

2. Traditional methods of digitizing data from maps was used in this project. The watershe dunder study was fairly small. However, were this method to be used for a larger watershed it would become costly and time consuming. There have been a number recent developments that could greatly reduce the level of effort required to generate data sets for this model. Three of these include the import of data from existing color thematic maps using digital cameras; advances in mobile mapping

techniques that would allow the collection of georeferenced large scale digital images to update existing data sets; and the availability of high resolution geospatial imagery (Lawrence *et. al.*, 1996, Li, 1997, Khuen, 1997, and Ridley et. al., 1997).

3. More work can be done to make the ANSWERS and SPANS integration tool available on the Internet using a tool such as ActiveX. ActiveX is a set of technologies developed by Microsoft that allows for interactive content to be used over the web, for desktop applications and development tools. It allows programmers to develop components in different languages and package them to be viewed through a web browser as part of a web page. More information is available on "What is ActiveX" (Microsoft, 1996), Chapel (1997), and
"http://www.apexsc.com/gcgi/mfs/cgvbsite/activex.html" home page.

4. The ANSWERS 2000 model is a complex NPS model. Many assumption and simplification were made to run the model for watersheds of up to 2000 hectare. There is room for working on the model and reducing its limitations. Investigation of the following limitations can be considered in future research:

   4.1 The model does not simulate base flow and interflow which may be a problem on agricultural watershed where they are major contributors to runoff.

4.2 ANSWERS simulates only one soil layer. It is assumed that soil moisture, soil characteristics, and nutrient concentrations are homogeneous. With this assumption it is impossible to model changes in the soil profile with respect to soil properties, nutrient concentration, etc.

4.3 ANSWERS 2000 allows crop parameters to be dynamic by considering rotations. However, soil parameters are assumed constant.

4.4 The model does not consider the effect of tillage, management practices on soil characteristics, and soil compaction.

4.5 A detailed sensitivity analysis needs to be conducted in order to investigate the sediment and nutrient component of the model and validate it for the Saint Esprit watershed. Agricultural crops cover more than 80 % of some of the sub-basins of the Saint Esprit watershed area, for example sub-basin 18 (Figure 4.18). Since these sub-basins are of a smaller size compared to the whole watershed, the variation in crop and soil parameters is much less. Therefore, they are ideal for further use in modeling.

4. Practical use of the ANSWERS model requires a database to be consulted for the estimation of parameter values required for land cover and soil information. Further improvement in the non-spatial database (Chapter 6) can allow the user to perform sequential simulations if values for crop conditions and soil information could be estimated properly.

6. Continued monitoring of the Saint Esprit watershed would provide a greater amount of observed events available for simulation and improve the model's performance.

References

Al-Abed, N and H.R. Whiteley. 1995. Water Quality Modelling Using Hydrological Simulation and GIS. CSAE Paper no. 95-109. Saskatoon, Canada: CSAE.

Arakere, S. and M. Molnau. 1994. Performance of AGNPS in the Pacific Northwest. ASAE Paper No. 94-2156. ASAE, St-Joseph, Mich.: ASAE.

Aronoff, S. 1991. *Geographic Information Systems: A Management Perspective*, 2nd Ed. Ottawa, Canada: WDL Publications.

Arnold, J.G., J.R. Williams, and A.D. Nicks. 1988. SWRRB A Basin Scale Simulation Model for Soil and Water Resources Management. Unpublished Manual, USDA-ARS.

Bajjali, W. and B. Daneshfar. 1995. Determining the suitability of the groundwater resources for Drinking Purposes in North Jordan by using a fuzzy logic model in a GIS Environment. Proceeding of the 1995 International SPANS workshop. Ottawa, Canada: TYDAC.

Bailey, G.W. and T.E Waddell. 1979. Best Management Practices for Agriculture and Silviculture: An Integrated overview. In *Best Management Practices for Agriculture and Silviculture*, eds. R.C. Loehr, D.A. Haith, and M.F. Martin. Ann Arbor, MI: Ann Arbor Science Publisher, Inc.

Batty, M. 1994. Using GIS for visual simulation modeling. Gis World Magazine. 7(10): 46-48.

Beasley, D.B. and L.F. Huggins. 1991. ANSWERS User's Manual, second edition, second printing. Agricultural Engineering Department Publication No. 5., UGA-CPES.

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

Beasley, D.B., L.F. Huggins and E.J. Monke. 1982. A monitoring/modelling strategy for 208 implementation water pollution programs, nonpoint source water quality problems Indiana. Transaction of the ASAE 25(d3):654-660.

Berryman D., et I. Grioux. 1994. La contamination des cours d'eau dans les régions de culture intensive du maïs au Québec. Campagnes d'échantillonnage 1992 et 1993. Direction des écosytèmes aquatiques, MFE. Envirodoq EN940594. 134p et 5 annexes.

Beven, K. and M.J. Kirkby, 1979. "A Physically Based, Variable Contributing Area Model of Basin Hydrology. "Hydrological Sciences Journal, 24(1),pp. 43-69.

Bingner, R.L., C.K. Mutchler, and C.E. Murphree. 1992. Predictive capabilities of erosion models for different storm sizes. Trans of the ASAE 35(2):505-513.

Blankenship, K. 1994. Runoff is target of administration's clean water plan. In: Bay Journal. Alliance for the Chesapeake Bay, Baltimore, Md. 4(1):1-6.

Bonham-Carter, G.F. 1994. *Geographic Information Systems for Geoscientists Modelling with GIS.* Ottawa, Canada: Unpublished.

Bouraoui, F. 1994. Development of a Continuous, Physically-Based, Distributed Parameter, Nonpoint Source Model. Ph.D. Dissertation, Department of Agricultural Engineering of State University. VPI and SU, Blacksburg, VA.

Bouraoui, F., T.A. Dillaha, and S. Mostaghimi. 1993. ANSWERS 2000: A watershed model for sediment and nutrient transport. ASAE Paper No. 93-2079. ASAE, St-Joseph, Mich.: ASAE.

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 Plain. ASAE Paper No. 89-2044. ASAE, St-Joseph, Mich.: ASAE.

Burrough, P.A. 1986. *Principles of Geographic Information Systems for Land Resources Assessment.* New York: Oxford University Press.

Campbell, J. 1991. *Introductory Cartography,* 2nd Ed. Dubuque, IA: Wm. C. Brown Publishers.

Carsel, R,F., C.N. Smith, L.A. Mulkey, J.D. Dean, and P. Jowise. 1984. User's Manual for the Pesticide Root Zone Model (PRZM): Release 1 EPA-600/3-84-109, U.S. EPA, Athens GA.

CCREM. 1994. Canadian Water Quality Guidelines. Canadian Council of Resource and Environmental Ministers. Water Quality Branch, Inland Waters Directorate, Environmental Canada, Ottawa.

Chapel, D. and D.S. Linthicum. 1997. ActiveX Demystified, It's invasive, It's ubiquitous, But what, exactly, is ActiveX? BYTE. Vol. 22, Number 9. Pp. 56-64.

Chen, Z., D.F. Storm, M.D. Smolen, C.T. Haan, M.S. Gregory, and G.J. Sabbagh. 1994. Prioritizing Nonpoint Source Phosphorus Loading Using a GRASS-Medalling System. Water Resource Bulletin. 30(4): 589-594.

Cho, S.M., G.D. Jennings, C. Stallings, and H.A. Devine. GIS-based water quality model calibration in the Delaware river basin. ASAE Paper No. 95-2404. ASAE, St-Joseph, Mich.: ASAE.

Chow, V T 1972. Hydrologic modeling. Boston Soc. Civ. Eng. 60:1-27

Clark, R.T. 1973. A review of some mathematical models used in hydrology with observation on their calibration and use. J. Hydrology. 19:1-20.

Clemente, R.S and S.O. Prasher. 1993. PESTFADE, a new pesticide fate and transport model: Model Development and Verification. Transaction of the ASAE, (36)2: 357-367.

Connolly, R.D., D.M. Silbum, C.A.A. Ciesiolka, and J.L. Foley. 1991. Medalling hydrology of agricultural catchments using parameters derived from rainfall simulator data. Soil and Tillage Research 20:33-44.

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

Corwin, D.L., P.J. Vaughan, H. Wang, J.D. Rhoades, and D.G. Cone. 1993. Predicting Areal distribution of salt-loading to the groundwater. ASAE Paper No. 93-2566. ASAE, St-Joseph, Mich.: ASAE.

Crawford, N.H. and R.K. Linsley. 1966. The synthesis of continuous streamflow hydrographs on a digital computer. Technical Report No. 12. Department of Civil Engineering, Stanford University, Palo Alto, CA.

D'Elia, C.F., J.G. Sanders, and D.G. Capine. 1989. Analytical chemistry for environmental sciences: a question of confidence. Environ. Sci. Technol. 23(7):768-774.

Delimand, P.N., and M.L. Wolfe. 1990. Assessing the nonpoint pollution potential of surface water using a geographic information system. Watershed Planning and Analysis in Action, R.R. Riggins (ed.) New York: ASCE.

De Roo, A.P.J., L. Hazelhoff, and P.A. Burrough. 1989. Soil Erosion Modelling Using 'ANSWERS' and Geographical Information Systems. Earth Surface Processes and Landforms. 14:517-532.

DeVries, J.J, and T.V. Hromadka. 1993. Computer models for surface water. In *Handbook of Hydrology*, ed. Maidment, D.R. New York: McGraw-Hill Inc.

Dickey, T.A., 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. and D.B. Beasley. 1983. Distributed parameter medalling of sediment movement and particle size distributions. Transaction of the ASAE 26(6):1766-1772.

Dissart, J.C. 1998. The economics of erosion and sustainable practices: The case of the Sain-Esprit watershed. M.S. thesis, Department of Agricultural Economics, McGill University, Montreal, Canada.

Donigian, A.S.J., D.C. Beyerlein, H.H. Davis, and N.H. Crawford. 1977. Agricultural Runoff Management Model (ARM), version II: refinement and testing. Report No. EPA-600/3-77-098. U.S. Environmental Research Laboratory, US Environmental Protection Agency (EPA), Athens, GA.

Drungil, C.E.C., W.F. Geter, and K.J. Wickey. 1993. A GIS data interface for water quality medalling. ASAE Paper No. 93-2565. ASAE, St-Joseph, Mich.: ASAE.

Eastman, J.R. 1995. IDRISI for windows. User's Guide, version 1.0. Clark lab for cartographic technology and geographic analysis. Clark University, Worcester, USA.

Enright, P., F. Papineau, C.A. Madramootoo. 1997. Water quality and pollutant concentrations on paired agricultural watershed in Quebec. CSAE Paper no. 97-142. Saskatoon, Canada: CSAE.

Enright, P., F. Papineau, and C.A. Madramootoo. 1998. Gestion Del'eau Dans le Bassin Versant de la Partie Superieure du Ruisseau St-Esprit. Rapport Final, Projet 61-13008.

Enright, P., F. Papineau, C.A. Madramootoo, and E. Leger. 1995. The impacts of agricultural production on water quality in two small watersheds. CSAE Paper no. 95-101. Saskatoon, Canada: CSAE.

ESRI, 1992. Arc/Info user manuals and on-line software documentation. Environmental Systems Research Institute, INC., Redlands, CA.

Feezor, D.R., M.C. Hirschi, and B.J. Lesikar. 1989. Effect of cell size on AGNPS prediction. ASAE Paper No. 89-2662. ASAE, St-Joseph, Mich.: ASAE.

Ferreira, V.A. and B.G. Faber. 1994. A linked-groupware system for decision-making. ASAE Paper No. 94-2507. ASAE, St-Joseph, Mich.: ASAE.

Fortin, J.P., J.P. Villeneuve, J. Benit, C. Blanchette, M. Montminy, H. Proulx, R.

Moussa, and C. Bocquillon. 1991. HYDROTEL 2.1 User's Guide, Scientific Report INRS-Eau No 286, Université du Québec, Institut national de la recherche scientifique INRS-Eau, Québec, Canada.

Fraisse, C.W., K.L. Campbell, J.W. Jones, W.G. Boggess. 1994. Integration of GIS and GLEAMS for alternative dairy waste management analysis. ASAE Paper No. 94-2508. ASAE, St-Joseph, Mich.: ASAE.

Frere, M.H., C.A. Onstad, and H.N. Holtan. 1975. ACTMO, an agriculture chemical transport model. ARS-H-3. Agricultural Research Service, U.S. Department of Agriculture, Washington, D.C.: USDA.

Frere, M.H. 1982. Medalling the quality of water from agricultural land. In: Hydrologic Medalling of Small Watersheds. ASAE Monograph No. 5. Hann et al. (eds.). pp.383-401. American Society of Agricultural Engineers, St Joseph, MI.

Gagné, J.C. 1995. Aide à L'entreposage des fumiers: 3500 producteurs sur la liste d'attende. Terre de Chez Nous. Semaine du 23 au 29 november 1995.

Gasser, P. 1995. Evaluating Soil Sampling Techniques. Proceeding of the 1995 International SPANS workshop. Ottawa, Canada: TYDAC.

Ghallab, A., S.O. Prasher, and H.G. Hassanein. 1994. Soil salinity buildup in irrigated farmlands of upper Egypt. NABEC paper no. 94408. NABEC-94, Guelph, Ontario, Canada, July 24 to 27, 1994.

Ghadiri, H., and C.W. Rose (eds). 1992. *Modelling Chemical Transport in Soils, Natural and Applied Contaminants*. Center for Catchment and In-stream Research. Division of Environmental Sciences, Griffith University, Brisbane, Queensland, Australia. Boca Raton: Lewise publishers.

Ghidey, F., E.E.Alberts, and S.J. Birrell. 1994. Spatial and temporal variability in agrochemical from a claypan soil. ASAE Paper No. 94-2556. ASAE, St-Joseph, Mich.: ASAE.

GIS World. 1993. *International GIS Sourcebook*. GIS World, Fort Collins, Co.: GIS World.

Gorres, J., A.J. Gold, and J. Conrad. 1994. Modeling NO_3 leaching at the aquifer scale using field enhanced GIS coverage. ASAE Paper No. 94-3520. ASAE, St-Joseph, Mich.: ASAE.

Green, W.H. and G.A. Ampt. 1911. Studies in soil physics. 1. The flow of air and water through soils. J. Agric. Sci. 4:1-24.

Gregersen, HM, KN Brooks, JA Dixon, and LS Hamilton. 1987. *Guidelines for economic appraisal of watershed management projects.* Food and Agriculture Organization of the United Nations Conservation Guide 16. Rome: FAO.

Griffin, M.L., D.B. Beasley, J.J. Fletcher, and G.R. Foster. 1988. Estimating soil loss on topographically nonuniform field and farm units. J. of Soil and Water Conservation, 43(2):326-331.

Haliday, S.L., and M.L. Wolfe. 1991. Assessing Ground Water Pollution From Nitrogen Fertilizer Using A Geographic Information System. Water Resources Bulletin, 27(2), pp: 237-245.

Hamlett, J.M., G.W. Petersen, J. Russo, D.A. Miller, G.M. Baumer, and R.L. Day. 1990. GIS-Based watershed rankings for nonpoint pollution in Pennsylvania. ASAE Paper No. 90-2619. ASAE, St-Joseph, Mich.: ASAE.

Heatwole, C. (ed.) 1995. *The International Symposium on Water Quality Medalling,* Proceedings of the International Symposium. April 2-5, 1995, Orlando, Florida. Sponsored by ASAE. St Joseph, Ml.: ASAE.

Heatwole, C.D., V.O. Shanholtz and B.B. Ross. 1982. Finite element model to describe overland flow on an infiltrating watershed. Transaction of the ASAE 25(3):630-637.

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, Mich.: ASAE.

Hession, W.C., V.O. Shanholtz, S. Mostaghimi, T.A. Dillaha. 1994. Uncalibrated performance of the finite element storm hydrograph model. Transaction of the ASAE 37(3):777-783.

Hodge, W, M. Larson, and W. Goran. 1988. Linking the ARMSED watershed process model with the GRASS geographic information system. In *Modelling Agricultural , Forest, and Rangeland Hydrology,* ASAE Publication 07-88. St. Joseph, Michigan: ASAE.

Holtan, H.N. 1961. A concept for infiltration estimates in watershed engineering. USDA-ARS Bulletin 41-51, 25pp.

Horton, S.E. 1939. Estimating soil permeability rates. Proc. Soil Sci. Soc. Am.5:399-417.

Hudak, P.F., H.A. Loaiciga, and F.A. Schoolmaster. 1993. Application of geographic information systems to groundwater monitoring network design.

Water Resource Bulletin, 29(3): 383-390.

Huggins, L.F. and E.J. Monke. 1966. The mathematical simulation of the hydrology of small watersheds. Technical Report No. 1. Water Resources Research Center, Purdue University.

James, L.D., and S.J. Burgess. 1982. Selection, calibration and testing of hydrologic models. In Hydrologic Modeling of Small Watershed, eds. C.T. Hann, H.P. Johnson and D.L. Brakensiek.

Johanson, R.C., J.C. Imhoff, J.L. Kittle, and A.S. Donigan. 1984. Hydrologic Simulation Program-Fortran (HSPF): User's Manual for Release 8.0. United States Environmental Protection Agency (EPA)-600/3-84-066.

Johnson, A.I., C.B. Petterson, and J.L. Fulton, (eds.). 1992. *Geographic Information Systems (GIS) and Mapping-Practices and Standards*. American Society for Testing and Materials (ASTM). Ann Arbor, MI: ASTM.

Khuen, C., 1997. Commercial Applications for High Resolution Geo-spatial Imagery. . Photogrammetric Engineering & Remote Sensing. Vol. 63, No. 8, August, 1997, pp.933-941.

Kiker, G.A., K.L. Campbell, and J. Zhang. 1992. CREAMS-WT linked with GIS to simulate phosphorus loading. ASAE Paper No. 92-2016. ASAE, St-Joseph, Mich.: ASAE.

Kinsel, W.G. 1980. "CREAMS: A Field-Scale Model for Chemical, Runoff, and Erosion from Agricultural Management Systems." USDA-Science and Education Administration, Conservation Report No. 26. 643 pp.

Lal, R. and B.A. Stewart. 1994. Soil Processes and Water Quality. In *Advances in soil science, soil processes and water quality*, eds. Lal, R. and B.A. Stewart. London: Lewis publisher.

Landreville, M. 1990. Determining Physiographic Parameters For Hydrologic Modelling Using a SPANS Geographic Information System. A report submitted to Engineering and Development Division Water Planning and Management Branch Inland Water Directorate Environment Canada. April 30, 1990.

Lane, L.J. and M.A. Nearing (eds.). 1989. USDA-Water erosion prediction project: Hill slope profile model documentation. National Soil Erosion Laboratory report No. 2. U.S. Government Printing Office, Washington, D.C., 279 pp.

Lapp, P. 1996. The Hydrology and Water /quality of an Intensive Agricultural Watershed in Quebec. M.S. thesis, Agricultural Engineering and Biosystems

Department, McGill University, Montreal, Canada.

Lapp, P., P. Enright, F. Papineau, C.A. Madramootoo. Preliminary Evaluation of the Hydrology and Water Quality of an Intensive Agricultural Watershed. CSAE Paper no. 95-102. Saskatoon, Canada: CSAE.

Laroche, A.M., J. Gallichand, R. Lagacé, and A. Pesant. 1995. Simulation of Pesticide Transport at the Watershed Scale. CSAE Paper No. 95-1-3. Saskatoon, Canada: CSAE.

Laurini, R. and D. Thompson. 1992. *Fundamentals of Spatial Information Systems*. London: Academic Press.

Lawrence, R.L., Joseph E. Means and William Ripple, 1996. An Automated Method for Digitizing Color Thematic Maps. Photogrammetric Engineering & Remote Sensing. Vol. 62, No. 11,November, 1996, pp.1245-1248.

Leonard, R.A., W.G. Knisek, and D.A. Still. "GLEAMS: Groundwater Loading Effects of Agricultural Management Systems." ASAE Winter Meeting, Chicago Illinois, 1986. ASAE Paper No. 86-2511. ASAE, St-Joseph, Mich.: ASAE.

Li, Rongxing, 1997, Mobile Mapping: An Emerging Technology for Spatial Data Acquisition. Photogrammetric Engineering & Remote Sensing. Vol. 63, No. 9, September, 1997, pp.1085-1092.

Littleboy, M., D.M. Silburn, D.M. Freebairn, D.R. Woodruff, and G.L. Hammer. 1989. PERFECT: A Computer Simulation Model of Productivity Erosion Runoff Function to Evaluate Conservation Techniques. Bulletin QB89005. Queensland Department of Primary Industries, Brisbane, Australia.

Luo, X. 1995. Erosion Risk Modelling in Mountain Environments. Proceeding of the 1995 International SPANS workshop. Ottawa, Canada: TYDAC.

Madramootoo, C.A. 1990. Assessing Drainage Benefits on a Heavy Clay Soil in Quebec. Transactions of the ASAE 33(4):1217-1223.

Madramootoo, C.A. and P. Enright. 1988. Applicability of the Soil Conservation Service equations for runoff prediction in the Ottawa-St. Lawrence Lowlands. Canadian Journal of Civil Engineering 15(5):759-765.

Maguire, D.J., M.F. Goodchild, and D.W. Rhind (Editors). 1991. *Geographic Information Systems, Principles and Applications*. Volume 2: Applications. New York: Longman Scientific and Technical.

Maidment, D.R. 1993. GIS and hydrologic modelling. In: Environmental

Medalling with GIS. Goodchild et al. (eds.), pp: 147-167.

Mannion, A.M. 1995. Agriculture and Environmental Change: Temporal and Spatial Dimensions. Wiley & Sons, Inc., New York, Ny, USA.

MEF. 1995. Statistiques Annuelles et Mensuelles – Station 7017380 (St. Jacques). Direction des reseaux atmospheriques. Ministere de l'environment et faune, Quebec.

Mellerowicz, K.T., H.W. Rees, T.L. Chow, and I. Ghanem. 1993. Soil conservation planning at the watershed level using the Universal Soil Loss Equation with GIS and microcomputer technologies: A case study. J. of Soil and Water Conservation. 49(2) 194-200.

Microsoft Corporation. 1996. What is ActiveX? Microsoft Developer Network, Library-Visual Studio 97. MK:@ivt:backint/D1/S977.HTM. 3 pages.

Mitchell, J.K, B.A. Engel, R. Srinivasan, and S.S. Y. Wang. 1993. Validation of AGNPS for small watersheds using an integrated AGNPS/GIS system. Water Resources Bulletin. 29(5).

Mockus, V. 1964. SCS National Engineering Handbook. Section 4, Hydrology. U.S. Soil Conservation Service, 548 pp.

Moeller, R.A. 1991. Application of a geographic information system to hydrologic medalling using HEC-1. In *Civil Engineering Applications of Remote Sensing and Geographic Information Systems*, ed. D.B. Stafford. New York: ASCE.

Montas, H.J., and C.A. Madramootoo. 1991. Using the ANSWERS model to predict runoff and soil loss in southeastern Quebec. Transactions of the ASAE 34(4):1754-1762.

Montas, H.J., and C.A. Madramootoo. 1992. A Decision Support System for soil conservation planning. Computers and Electronics in Agriculture. 7:187-202.

Muchovej, R. M.C. and J.K. Rechcigl. 1994. Impact of Nitrogen Fertilizer Of Pastures and Turfgrasses on Water Quality. In *Advances in soil science, soil processes and water quality*, eds. Lal, R. and B.A. Stewart. London: Lewis publisher.

Muhr, T., H. Auernhammer, M. Demmel, and K. Wild. 1994. Inventory of fields and soils with DGPS and GIS for precision farming. ASAE Paper No. 94-1583. ASAE, St-Joseph, Mich.: ASAE.

Needham, S., and B.E. Vieux. 1989. A GIS for AGNPS parameter input and mapping output. ASAE Paper No. 89-2673. ASAE, St-Joseph, Mich.: ASAE.

Negahban, B., C.B. Moss, J.W. Jones, J. Zhang, W.D. Boggess, and K.L Campbell. 1994. Optimal field management for regional water quality planning. ASAE Paper No. 94-3553. ASAE, St-Joseph, Mich.: ASAE.

Novotny, V. 1986. A review of hydrologic and water quality models used for simulating agricultural pollution. In *Agricultural Nonpoint Source Pollution, Model Selection and Application*, eds. A. Giorgini, and F. Zingales. New York: Elsevier.

Novotny, V. and H. Olem 1993. *Water quality: prevention, identification, and management of diffuse pollution.* New York: Van Nostrand Reinhold.

Oiu, W., G.A. Watkins, C.J. Sobolik, and S.A. Shearer. 1995. A Feasibility Study of Direct Injection for Variable Rate Herbicide Application. ASAE Paper No. 95-1567. ASAE, St-Joseph, Mich.: ASAE.

Panuska, J.C. and L.D. Moore. 1988. AGNPS Terrain: Development and preliminary testing. ASAE Paper No. 88-2655. ASAE, St-Joseph, Mich.: ASAE.

Papineau, F., et P. Enright. 1997a. Gestion Del'eau Dans le Bassin Versant de la Partie Superieure du Ruisseau St-Esprit. Caracterisation de la problematique environnementale, Projet 61-13008.

Papineau, F., et P. Enright. 1997b. Gestion Del'eau Dans le Bassin Versant de la Partie Superieure du Ruisseau St-Esprit. Rapport d'etape no. 3 – Campagne d'echantillonnage 1995, Periode du 1er avril 1995 au 31 mars 1996, Projet 61-13008.

Park, S.W. and J.T. Kim. 1995. Validating AGNPS model with complex topography in central Korea. ASAE Paper No. 95-2502. ASAE, St-Joseph, Mich.: ASAE.

Park, S.W., J.K. Mitchell, and J.N. Scarborough. 1982. Soil erosion simulation on small watersheds: a modified ANSWERS model. Transactions of the ASAE 25(6):1581-1588.

Perrone, J., C.A. Madramootoo, P. Enright, F. Papineau. 1997. Hydrologic modeling of and agricultural watershed in Quebec using AGNPS. CSAE Paper no. 97-101. Saskatoon, Canada: CSAE.

Philip, J.R. 1954. An infiltration equation with physical significance. Soil Sci. 77:153-157.

Pokrzywka, S. and M. Yitayew. 1993. A GIS based erosion estimation using RUSLE. ASAE Paper No. 93-3557. ASAE, St-Joseph, Mich.: ASAE.

Razavian, D. 1990. Hydrologic response of an agricultural watershed to various hydrologic and management conditions. Water Resources Bulletin. 26(5):777-785.

Rewerts, C.C. 1992. ANSWERS on GRASS: Integrating a watershed simulation with a Geographic Information System. Ph.D. dissertation, Purdue University, W. Lafayette, In.

Richards, C.J., H. Roaza, and R.M. Roaza. 1993. Integrating geographic information systems and MODFLOW for aground water resource assessments. Water Resources Bulletin, 29(5):847-853.

Richie, J.T. 1972. A model for predicting evapotranspiration from a row crop with incomplete cover. Water Resources Research 8(5):1204-1213.

Ridley, H.M., P.M. Atkinson, P. Arpin, J-P Muller and I. Dowman, 1997. Evaluating the potential of the Forthcoming Commercial U.S. High-Resolution Satellite Sensor Imagery at the Ordnance Survey. Photogrammetric Engineering & Remote Sensing. Vol. 63, No. 8, August, 1997, pp.997-1005.

Ritter, J.B. 1992. Application of field infiltration data to hydrologic model parameterization: An example drainage basins disturbed by surface mining. J. of Hydrology, 134(1-4):173-202.

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, 41:11-30.

Runyon, J. 1994. Environmental management solutions for agriculture: Integrating field inspections, GIS, GPS, and aerial photography. Geo Info Systems magazine. May 31: 42-44.

Samet, H. 1990. *Design and Analysis of Spatial Data Structures*. Readin Mass: Assison and Wesley.

Sample, V.A. (ed.). 1994. *Remote Sensing and GIS in Ecosystem Management*. Washingtin, D.C.: Iskand Press.

Scott, H.D., P.A. Smith, A. Mauromoustakos, M.J. Cochran, and W.F. Limp. 1991. Using a GIS for nitrate water quality analysis. ASAE Paper No. 91-2532. ASAE, St-Joseph, Mich.: ASAE.

Searing, M.L., A. Shirmohammadi, T. Ifft, and W.L. Magette. 1995. Utilizing GLEAMS models to prescribe best management practices for critical areas of a watershed identified using GIS. ASAE Paper No. 95-3248. ASAE, St-Joseph, Mich.: ASAE.

Shanholtz, V.O., C.J. Desai, N. Zhang, J.W. Kleene, C.D. Metz, and J.M. Flagg. 1990. Hydrologic/water quality medalling in a GIS environment. ASAE Paper No. 90-3033. ASAE, St-Joseph, Mich.: ASAE.

Shichani, A.S. 1982. Modelling phosphorus transport in surface runoff from agricultural watersheds. Ph.D. dissertation, Purdue University, W. Lafayette, In.

Simoneau M. 1996. Qualité des eaux du bassin du la rivière Chateauguay, 1979 à 1994. Direction des écosystèmes aquatiques, MFE. October 1996.

Simoneau M., et Y. Grimard. 1989. Qualité des eaux du bassin du la rivière L'Assomption 1976-1987. Direction des écosystèmes aquatiques, Ministère de l'Environnement, rapport EMA88-31. 178p + 8 annexes.

Srinivasan, R. 1992. Spatial decision support system for assessing agricultural nonpoint source pollution using GIS. Ph.D. Dissertation, Purdue University, W. Lafayette, In, 193 p.

Srinivasan, R., B.A. Engel. 1991. GIS estimation of runoff using the CN technique. ASAE Paper No. 91-7044. ASAE, St-Joseph, Mich.: ASAE.

Srinivasan, R., B.A. Engel. 1992. GIS: A Tool for sensitivity analysis of nonpoint source pollution models. ASAE Paper No. 92-7062. ASAE, St-Joseph, Mich.: ASAE.

Srinivasan, M.S., J.M. Hamlet, and R.L. Day. 1995. Hydrologic transport medalling in lake Wallenpaupack, Pennssylvania. ASAE Paper No. 95-3245. ASAE, St-Joseph, Mich.: ASAE.

Star, J. and J. Estes. 1990. *Geographic Information Systems: An Introduction.* Englewood Cliffs, N.J.: Prentice Hall.

Statistics Canada, 1992. Agricultural profile of Quebec, part 1 and part 2. Catalogue No. 95-335 and 95-336. Ottawa, Canada: Statistics Canada.

Stempvoort, D., L. Ewert, and L. Wassenaar. 1993. Aquifer Vulnerability Index: A GIS - Compatible Method for Groundwater Vulnerability Mapping. Canadian Water Resources Journal, 18(1): 25-37.

Ston, K.C., P.G. Hunt and M.H. Johnson. 1994. Groundwater monitoring and modeling of spatially distributed management systems on a demonstration watershed. ASAE Paper No. 94-2618. ASAE, St-Joseph, Mich.: ASAE.

Storm, D.E., T.A. Dillaha, S. Mostaghimi, and V.O. Shanholtz. 1988. Medalling phosphorus transport in surface runoff. Transaction of the ASEA 31:117-127.

Stuebe, M.M., and D.M. Johnston. 1990. Runoff volume estimation using GIS techniques. Water Resource Bulletin 26(4), pp:611-620.

Summer, R.M., C.V. Alonso, and R.A. Young. 1990. Medalling linked watershed and lake processes for water quality management decisions. J. of Environ. Qual. American Society of Agronomy, 19(3):421-427.

Telmer, K. 1995. Evaporative losses in the Ottawa River Basin: and isotopic constraints. Proceeding of the 1995 International SPANS workshop. Ottawa, Canada: TYDAC.

Tim, U.S. 1995. Emerging issues in hydrologic and water quality medalling research. In *The International Symposium on Water Quality Medalling*, Proceedings of the International Symposium. April 2-5, 1995, Orlando, Florida. Heatwole, C. (ed.). Sponsored by ASAE. St Joseph, MI.: ASAE

Tim, U.S., S. Mostaghimi, V.O. Shanholtz, and N. Zhang. 1991. Identification of critical nonpoint pollution source area using geographic information systems and simulation modelling. ASAE Paper No. 91-2114. ASAE, St-Joseph, Mich.: ASAE.

Tomlinson, R.F. and M.A.G. Toomey. 1995. GIS and LIS in Canada. Unpublished paper. Proceeding of the 1995 International SPANS workshop. Ottawa, Canada: TYDAC.

TYDAC Technologies Inc. "SPANS", Spatial Analysis System, Version 5.3. 1992. Nepean, Canada: TYDAC.

USACERL, 1988. GRASS reference manual. U.S. Army CERL, Champaign, IL.

USEPA, 1993. Guidance specifying management measures for sources of nonpoint pollution in coastal waters. U.S. Environmental Protection Agency, Office of Water, Washington, DC. EPA/840-B-92-002.

Von Eu, E.L., V.F. Bralts, and L.J. Segerlind. 1998. Hydrologic modeling using the finite element method and geographic information systems. ASAE paper no. 88-2090. ASAE, St-Joseph, MI. USA.

Wagenet, R.J., and J.L. Huston. 1989. LEACHM: Leaching Estimation and Chemistry Model, a process based model of water and solute movement, transformations, plant uptake and chemical reaction in the unsaturated zone. Continuum Vol. 2. Water Resource Ins., Cornell University, Ithaca, NY.

Williams, J.R. 1983. EPIC, The Erosion Productivity Impact Calculator. Agricultural Research Service, U.S. Department of Agriculture, Washington, D.C.

Wischmeier, W.H. and D.D. Smith. 1965. *Predicting rainfall-erosion losses from cropland east of Rocky Mountains-guide for selection of practices for soil and water conservation.* Agriculture Handbook No. 282. Washington, D.C.: U.S. Department of Agriculture.

Wolfe, M.L., W.D. Batchelor, T.A. Dillaha, S. Mostaghimi, and C.D. Heatwole. 1995. A Farmscale water quality planning system for evaluating best management practices. In *The International Symposium on Water Quality Medalling*, Proceedings of the International Symposium. April 2-5, 1995, Orlando, Florida. Heatwole, C. (ed.). Sponsored by ASAE. St Joseph, MI.: ASAE.

Woolhiser, D.A. and D.L. Brakensiek. 1982. Hydrologic system synthesis. In Hydrologic medalling of small watershed, pp. 3-16, Monograph No 5, American Society of Agricultural Engineers, St Joseph, MI.

Wu, T.H., J.A. Hall, and J.V. Bonta. 1993. Evaluation of runoff and erosion models. J. Irrig. and Drin. Eng. American Society of Civil Engineers, 119(2):364-382.

Yagow, E.R., V.O. Shanholtz. 1992. Agricultural NPS Model Application with PC-Based GIS. ASAE Paper No. 92-2013. ASAE, St-Joseph, Mich.: ASAE.

Yalin, Y.S. 1963. An expression of bed-load transportation. Journal of the Hydraulic Division, ASCE 89(HY3):221-250.

Yoon, K.S., and W.J. Rawls. 1995. Application of the ANSWERS model on mixed land use watershed. ASAE Paper No. 95-2402. ASAE, St-Joseph, Mich.: ASAE.

Young, R.A., C.A. Onstad, D.D. Bosch and W.P. Anderson. 1985. AGNPS: Agricultural Nonpoint Source Pollution Model AGNPS I and II. Model documentation. Minnesota Pollution Control Agency, St. Pual, MI, and Agricultural Research Service, U.S. Department of Agriculture, Washington, D.C.

Young, R.A., C.A. Onstad, D.D. Bosch and W.P. Anderson. 1987. AGNPS: Agricultural Nonpoint Source Pollution Model; a large watershed analysis tool.

Agricultural Research Service, U.S. Department of Agriculture, Report 35, Washington, D.C., pp. 77.

Young, R.A., C.A. Onstad, D.D. Bosch and W.P. Anderson. 1989. AGNPS: A nonpoint source pollution model for evaluating agricultural watersheds. J. of Soil and Water Conservation 44(2):168-173.

Zahradka, N.R., M.L. Wolfe, and W.D. Batchelor. 1994. A knowledge based system to estimate input parameters for the ANSWERS model. ASAE Paper No. 94-2615. ASAE, St-Joseph, Mich.: ASAE.

Zhang, N., M.D. Schrock, J.L. Havlin, and G.J. Kluitenberg. 1994. Development of a field-scale GIS database for spatially-variable nitrogen management. ASAE Paper No. 94-3550. ASAE, St-Joseph, Mich.: ASAE.

Zhang, H., D. Nofziger, and C.T. Haan. 1990. Interfacing a root-zone transport model with GIS. ASAE Paper No. 90-3034. ASAE, St-Joseph, Mich.: ASAE.

APPENDIX A

Table A1 Hydrologic and NPS model overview

Model aspects/Model name			ACTMO	AGNPS	ANSWERS	ANSWERS 2000	ARM	CREAMS	EPIC
Model criteria	Scale	Field	N	N	N	N	N	Y	Y
		Watershed	Y	Y	Y	Y	Y	N	N
	Simulation Period	Event	N	Y	Y	N	N	N	N
		Continuous	Y	N	N	Y	Y	Y	Y
	Aerial distribution of parameter	Distributed	N	Y	Y	Y	N	N	N
		Lumped	Y	N	N	N	Y	N	Y
	GIS integration potential		N	Y	Y	Y	N	N	N
Hydrologic parameters	Water quantity	Surface	Y	Y	Y	Y	Y	Y	Y
		Subsurface	N	N	N	N	?	N	N
	Snowcover variation and melt		N	N	N	N	Y	Y	N
	Soil moisture		Y	?	Y	Y	?	?	?
Nonpoint source pollution	N		Y	Y	N	Y	Y	Y	Y
	P		Y	Y	N	Y	Y	Y	Y
	K		Y	N	N	N	Y	Y	Y
	Pesticides		Y	N	N	N	Y	Y	N
	Sediment		Y	Y	Y	Y	Y	Y	N

Y=yes N=no ?=no information found

Table A1 Hydrologic and NPS model overview (continue)

Model aspects/Model name			FESHM	GAMES	GLEAMS	HSPF	HYDROTEL	LEACHM
Model criteria	Scale	Field	N	N	Y	N	N	Y
		Watershed	Y	Y	N	Y	Y	N
	Simulation Period	Event	Y	Y	N	N	N	N
		Continuous	N	N	Y	Y	Y	Y
	Aerial distribution of parameter	Distributed	Y	N	N	N	Y	N
		Lumped	N	Y	Y	Y	N	Y
	GIS integration potential		Y	N	N	Y	Y	N
Hydrologic parameters	Water quantity	Surface	Y	Y	N	Y	Y	N
		Subsurface	N	N	Y	?	N	Y
	Snowcover variation and melt		N	N	N	N	Y	?
	Soil moisture		?	?	?	Y	N	?
Nonpoint source pollution	N		N	N	Y	Y	N	Y
	P		N	N	Y	Y	N	N
	K		N	N	?	?	N	N
	Pesticides		N	N	Y	Y	N	Y
	Sediment		N	Y	N	Y	N	N

Y=yes N=no ?=no information found

Table A1 Hydrologic and NPS model overview (continue)

Model aspects/Model name			PERFECT	PESTFAD	PRZM	SWERRB	TOPMODL	WEPP
Model criteria	Scale	Field	Y	Y	Y	N	N	N
		Watershed	N	N	N	Y	Y	Y
	Simulation Period	Event	N	N	N	N	N	N
		Continuous	Y	Y	Y	Y	Y	Y
	Aerial distribution of parameter	Distributed	N	N	N	N	N	Y
		Lumped	Y	Y	Y	Y	Y	N
	GIS integration potential		N	N	N	N	Y	Y
Hydrologic parameters	Water quantity	Surface	Y	Y	Y	Y	Y	Y
		Subsurface	N	Y	Y	Y	Y	Y
	Snowcover variation and melt		N	N	Y	N	?	Y
	Soil moisture		?	Y	?	?	Y	Y
Nonpoint Source pollution	N		Y	N	N	Y	N	N
	P		Y	N	N	Y	N	N
	K		Y	N	N	Y	N	N
	Pesticides		Y	Y	Y	Y	N	N
	Sediment		Y	Y	Y	Y	N	Y

Y=yes N=no ?=no information found

APPENDIX B

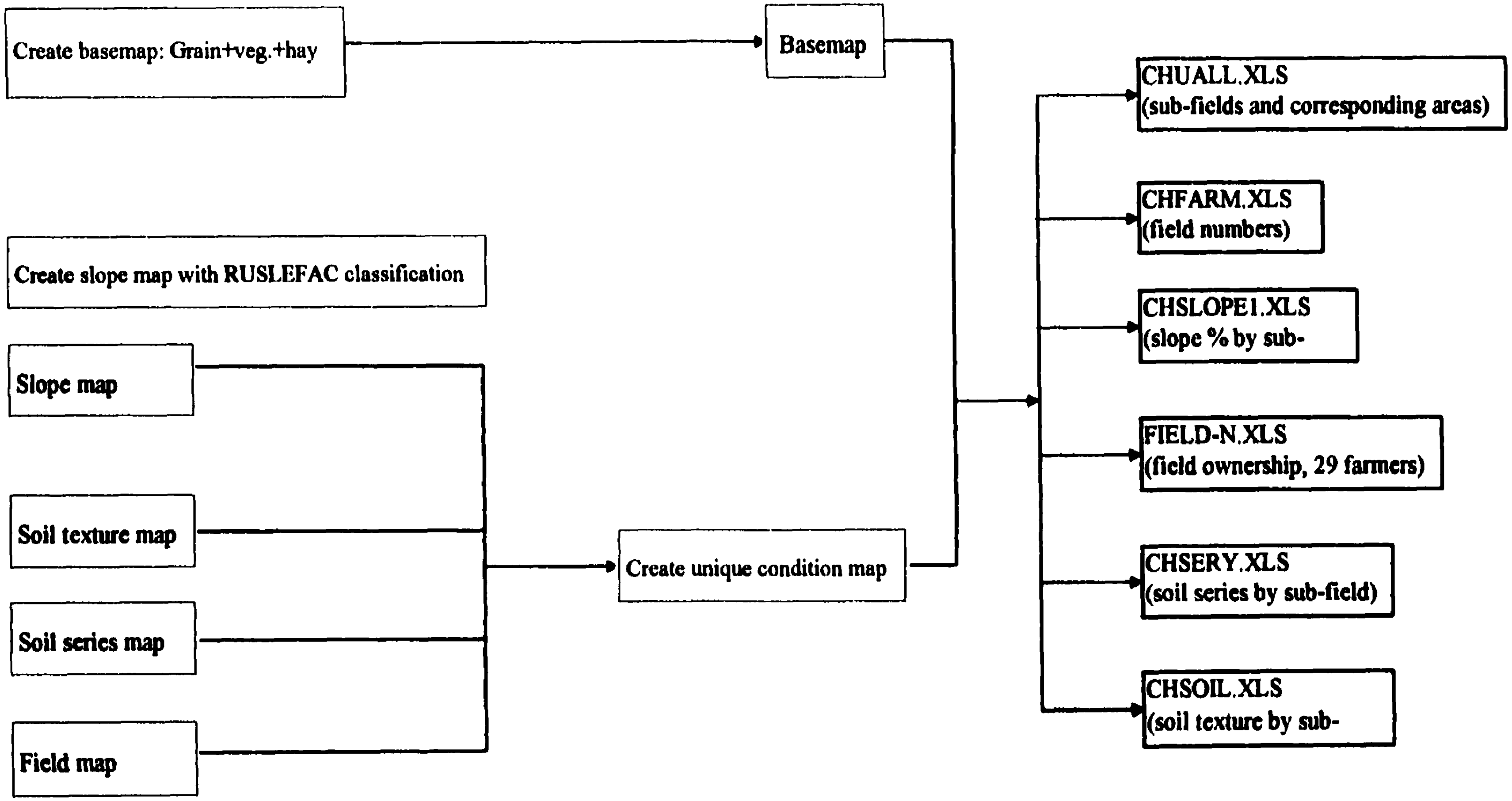


Figure B1 Flow chart for developing the required database from the Saint Esprit spatial database to build the RUSLEFAC factors

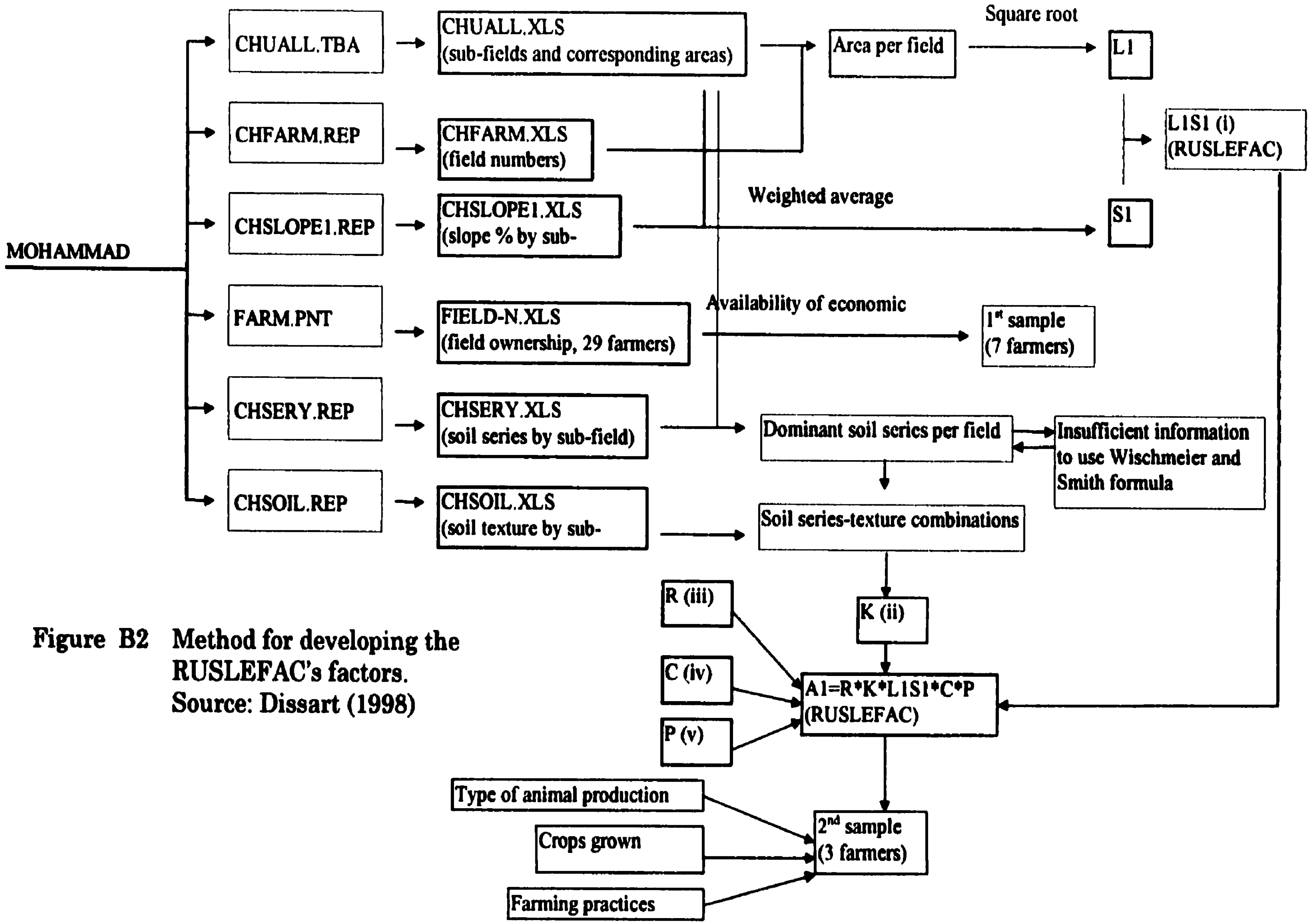


Figure B2 Method for developing the RUSLEFAC's factors.
Source: Dissart (1998)

Table B1 Total N and P_2O_5 content in manure applications in the Saint Esprit watershed

	1994				1995				1996			
Map legend	**N**		**P_2O_5**		**N**		**P_2O_5**		**N**		**P_2O_5**	
Dose (kg/ha)	%	ha	%	ha	%	ha	%	ha	%	ha	%	ha
5-10	----	-----	----	-----	0.46	11.95	----	------	----	-----	0.06	1.46
10-25	----	-----	----	-----	----	-----	----	------	----	-----	1.25	32.57
25-50	----	-----	1.04	27.19	----	-----	0.72	18.81	----	-----	0.20	5.34
50-75	----	-----	0.94	24.49	1.36	35.53	1.18	30.75	0.06	1.46	1.27	33.23
75-100	0.38	9.94	2.27	59.25	0.49	12.90	1.49	38.91	0.43	11.24	----	------
100-125	0.11	2.83	1.34	34.83	0.09	2.30	0.75	19.51	1.72	44.90	2.07	54.03
125-150	3.29	85.72	0.91	23.63	1.10	28.61	0.62	16.22	1.06	27.54	2.14	55.77
150-175	1.25	32.56	0.34	8.85	0.70	18.28	0.72	18.80	1.76	45.98	----	------
175-200	0.34	8.85	1.24	32.28	0.97	25.24	1.55	40.32	0.33	8.71	0.85	22.24
200-225	2.69	70.11	----	-----	1.93	50.23	0.03	0.71	1.47	38.33	----	------
225-250	----	-----	0.48	12.53	0.20	5.23	0.40	10.50	1.05	27.38	0.84	21.87
250-275	----	-----	----	-----	----	-----	----	------	0.14	3.62	0.14	3.62
275-300	0.28	7.25	----	-----	0.65	16.97	----	------	0.42	11.06	0.69	17.99
300-325	----	-----	----	-----	----	-----	----	------	0.69	17.99	----	------
325-350	----	-----	----	-----	----	-----	0.33	8.52	----	-----	----	------
375-400	0.22	5.80	----	-----	0.30	7.76	----	------	0.38	9.90	----	------
400-425	----	-----	----	-----	----	-----	----	------	----	-----	0.04	1.11
825-850	----	-----	----	-----	----	-----	----	------	0.04	1.11	----	------
no appl.	23.56	614.45	23.56	614.45	32.02	834.96	32.02	834.96	30.78	802.69	30.78	802.69
no data	31.66	825.72	31.66	825.72	23.53	613.61	23.99	625.56	23.57	614.84	23.5	1555.31
not cult.	36.22	944.61	36.22	944.61	36.21	944.27	36.21	944.27	36.09	941.11	36.09	941.11
Total	100.00	2607.85	100.00	2607.85	100.00	2607.85	100.00	2607.85	100.00	2607.85	100.00	2607.85

TABLE B 2 Percent of landuse and soil texture in the Saint Esprit sub-watersheds

Sampling Point	Sub-Watershed	Area (ha)	Soils			% Agri.	LAND USE - 1994				LAND USE - 1995				LAND USE - 1996			
			Light	Medium	Heavy		corn	cereal	veg	forage	corn	cereal	veg	forage	corn	cereal	veg	forage
B24	1	38.8	0%	39%	61%	86%	27%	17%	23%	20%	36%	3%	14%	33%	33%	8%	22%	24%
B17	2,3,4	410.3	45%	3%	52%	60%	6%	22%	19%	13%	12%	10%	19%	18%	13%	16%	13%	18%
B17-50	3,4	163.7	62%	0%	38%	48%	2%	19%	20%	7%	8%	14%	22%	5%	18%	16%	12%	2%
B17-51	4	102.4	75%	0%	25%	39%	1%	13%	13%	11%	6%	10%	15%	8%	17%	8%	12%	3%
B14	5	83.1	89%	0%	11%	41%	9%	17%	6%	9%	18%	6%	7%	11%	25%	3%	12%	2%
B13	6	93.6	100%	0%	0%	21%	11%	0%	1%	8%	8%	0%	0%	12%	13%	0%	4%	4%
BRE-GL	7,9,16,8,17	1018.0	49%	7%	44%	59%	30%	12%	4%	12%	26%	19%	3%	11%	31%	15%	4%	9%
BRE-333	9,16,17	424.7	71%	6%	22%	43%	16%	14%	3%	10%	16%	14%	5%	8%	19%	9%	6%	9%
B3	8	477.1	34%	4%	61%	66%	40%	12%	2%	13%	34%	22%	0%	11%	34%	23%	3%	6%
B10-340	10,1314,15	289.7	59%	0%	41%	60%	16%	18%	8%	16%	14%	23%	5%	17%	20%	13%	6%	21%
B10-356	13,14,15	174.9	76%	0%	24%	42%	9%	8%	6%	17%	10%	10%	4%	19%	11%	6%	2%	23%
B10-GUY	14,15	111.0	92%	0%	8%	28%	1%	1%	4%	21%	1%	3%	1%	23%	0%	1%	0%	26%
B12-GL	11,12,5,6	456.1	81%	0%	19%	58%	23%	14%	11%	11%	24%	13%	8%	14%	22%	13%	12%	10%
B12-BUR	12,5,6	381.7	85%	0%	15%	54%	20%	11%	11%	11%	21%	11%	9%	12%	20%	10%	14%	9%
RC-10	15	31.0	100%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
RC-B1	16	34.9	100%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
RC-BRE	17	45.5	100%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
...	18	392.2	23%	20%	58%	89%	33%	26%	4%	26%	32%	17%	14%	26%	37%	16%	9%	26%

Source: Enright et al., 1998