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Hydrologic Modelling on the Saint Esprit Watershed

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A thesis submitted to the Faculty of Graduate Studies
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of the requirements for the degree of
Master of Science

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Abstract

A study was undertaken to evaluate the suitability of the SLURP hydrological model for simulating the hydrology of the Saint Esprit watershed (26 km^2) in Quebec. Climatic data and other input were made available through a monitoring program set up in the watershed from 1994 to 1998. GIS was used to store, analyze and export the watershed information into the model. The continuous semi-distributed model SLURP was calibrated using three years of data (1994-1996). Parameter calibration, except that of snowpack melt-rate, was done through an automatic optimization technique. The model was validated using graphical outputs, the Nash/Sutcliffe (R^2) coefficient of performance for daily runoff, and the percent difference of predicted versus computed runoff on a monthly, seasonal and annual basis. Additionally, the evapotranspiration (ET) component of the model was compared with an ET estimated using the Baier & Robertson model (BR) calibrated for the region. The R^2 coefficient of performance was 0.522 after calibration. Model validation performed during 1997 and 1998 yielded R^2 coefficients of 0.659 (acceptable) and 0.483 (poor) respectively. Hydrologic outputs studied were runoff, snowmelt and ET. For all these, model predictions on an annual basis were acceptable as compared to the measured data. Total runoff was simulated within 12.99% and 13.05% of the observed runoff, in 1997 and 1998, respectively. On a seasonal basis, the model predicted well during the non-growing season, where observed runoff deviate by only 0.75% and 0.84% from the recorded runoff in 1997 and 1998, respectively. Predictions over the growing season were poor for both years. In general, runoff was over-predicted, especially when comparisons were made for shorter periods of time. Timing of peak snowmelt-runoff was simulated in most cases within one or two days of the observed peak runoff. No significant differences ($P>0.05$) were found for long term comparisons between SLURP actual ET, and ET_{com} simulated by the Baier & Robertson model. Through this study, crop water requirements (CWR) were estimated in the watershed using the BR model and a soil water-budget computer routine. Irrigation was not needed for any crop during the study period. Overall, results suggest that SLURP could be used for long term estimates of the hydrology of the Saint Esprit watershed.

Résumé

Une étude fut entreprise pour évaluer la convenance du modèle hydrologique SLURP pour simuler l'hydrologie du bassin versant de Saint-Esprit (26 km^2) au Québec. Les données climatiques et autres utilisées dans ces recherches furent rendues disponibles par l'entremise d'un programme de mesure réalisé pour le la bassin pendant cinq ans (1994-98). L'information décrivant le système physique fut stockée, analysée et exportée dans le format du modèle en utilisant un SIG. Le modèle semi-distribué et continu SLURP fut calibré en utilisant trois ans de données (1994-96). La calibration des paramètres, à l'exception de la vitesse de fonte du manteau nival a été effectueé par une technique automatique d'optimisation, . Le modèle fut validé en se basant sur la comparaison des résultats graphiques, sur la valeur du coefficient de performance de Nash/Sutcliffe (R^2) et en comparant l' estimation de l' évapotranspiration (ET) donnée par le modèle à celle du modèle Baier et Robertson (BR), calibré pour la région. Le coefficient R^2 pour la periode de calibration fut de 0.522. Les validations exécutées en 1997 et 1998 ont rapporté des coefficients (R^2) de 0.659 et de 0.483, respectivement. Les variables hydrologiques discutées furent écoulement, fonte des neiges et l' ET. Pour toutes ces variables, l'estimation fournie par le modéle fut acceptable sur une base annuelle. L'écoulement total fut estimé à 12.99% et 13.05% près de l'écoulement observé, en 1997 et 1998, respectivement. Sur une base saisonnière, le modèle décrit bien l'écoulement hors-saison, avec une erreur de 0.75% et 0.84% en 1997 et 1998, respectivement. Par contre, les prédictions pour la période de culture ne furent pas très bonnes. L'écoulement fut surestimé, particulièrement lorsque les comparaisons se firent à une courte echelle de temps. La synchronisation des niveaux maximums de fonte des neiges et d'écoulement fut simulée, dans la plupart des cas à un ou deux jours près de l'écoulement maximal observé. Aucune différence significative ($P>0.05$) ne fut trouvée pour des comparaisons à long terme entre l'ET actuel de SLURP et l'ET_{mais} calculée par le modèle BR. Durant cette étude, la demande en eau des cultures fut estimée par le modèle BR, ainsi qu'avec un logiciel de budget eau-sol. Aucune irrigation ne fut nécessaire pour les cultures durant la période étudiée. Les résultats suggèrent que SLURP pourrait être utilisé pour des estimations à long terme de l'hydrologie du petit basin versant de Saint-Esprit.

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List of symbols and Abbreviations

AGNPS	Agricultural Non-point Source Pollution Model
ANSWER 2000	Areal Non-Point Source Watershed Environment Response Simulation
ARC/Info	The ARC/info GIS ESRI®
ASA	Aggregated simulation area (equivalent to sub-basin in this study)
AV	The ArcView GIS ESRI®
BR	The Baier & Robertson ETp model
c.v	Coefficient of variation
DEM	Digital elevation model
ETc	Crop evapotranspiration
ET_{corn}	Corn evapotranspiration
ETp	Potential evapotranspiration
fc	Weighted averaged field capacity
FC	Field capacity
GCM	General Circulation Model
GIS	Geographic information systems
ha	Hectare
Kc	Crop consumptive use coefficient
kPa	Kilo Pascal
MAPAQ	Ministere de l'agriculture, des pecheries, et de l'alimentation du Québec
MB	Megabyte
NPS	Non-Point Source
P	Probability

PW	Productivity of water
Ra	Extraterrestrial solar radiation
Rsd.	Rain/snow division temperature
R^2	Nash and Sutcliffe coefficient of performance
SCE-UA	Shuffled Complex Evolution-University of Arizona
SLURP	Simple Land Use based Runoff Processes
Sm	Snowmelt
Sp	Snowpack
t_c	Time of concentration
TOPAZ	Topographic Parameterization
$W/m^2/day$	Watts per square meter per day
WSHMS	Watershed Surface Hydrologic Modelling System

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1.0 INTRODUCTION

1.1 Background

As water resources become scarce, there is an increasing need for implementing innovative approaches to better understand and manage drainage basins. The watershed or drainage basin defines the unit of land area that contributes with surface and subsurface runoff to a river system. Watersheds vary in size and their complex hydrological characteristics result from a number of physical, vegetative, climatic and anthropomorphic factors (Viessman, 1989). Over the past twenty years, the watershed has been recognized as the natural unit for water resources management (Heathcote, 1998).

Characterizing watersheds demands a great deal of effort in studying and monitoring of spatially and temporally distributed data. Runoff is probably the most important parameter measured or estimated in watershed systems. Surface runoff is the fraction of the basin water that moves across the land surface until it reaches natural or artificial streams and lakes; therefore, this process plays an important role in maintaining the ecology of the natural system. Before surface runoff occurs, a series of processes described in the hydrological cycle take place. In a typical basin, precipitation or snowmelt represents water inputs. Water interception, evaporation, transpiration, depression storage, infiltration and antecedent soil moisture content, influence the amount of water expressed as surface runoff.

In agricultural watersheds, surface runoff along with groundwater flow are responsible for maintaining the river flow, which in non rain-fed agriculture would constitute the source of water for crop production. In subtropical climates surface runoff is highly correlated to storm events and spring snowmelt. In both cases, an excess of water occurs in the watershed. In natural conditions the water surplus will reach small channels and finally will be incorporated into the main stream or river. Understanding the mechanics of runoff can lead to an increase in water use efficiency at the watershed level, as it can allow one to use the runoff water to satisfy demands from different users , as well as the environment.

In general, studying problems in hydrology requires the evaluation of extensive data and the use of modelling tools to assist water managers in the decision making process. In the last decade, these problems have been addressed by the combined use of data and techniques such as hydrological modelling and geographical information systems (GIS). This approach has gained a wide acceptance among scientists in the field of hydrology. Modelling however, has yet to become commonly available planning and decision making tool for agencies and general users (Arnold, 1998).

In January 1994, the project " Watershed Scale Management of the Waters of the Upper Reaches of the Saint Esprit Creek", was initiated by MAPAQ, Agriculture Canada and with McGill University as a scientific partner (Enright et al., 1995). The main objective of this project was to evaluate and reduce the impact of agricultural activities on the water quality of the basin. The water discharge and water quality at the outlet of the Saint Esprit watershed was monitored for five years. In addition, a digital database containing the watershed physiographic information, including vegetation, soil texture, slope, stream network and socioeconomic data, was developed (Mouzavizadeh, 1998).

Previous work was done to characterize the hydrology of this experimental site (Perrone et al., 1997 and Mouzavizadeh, 1998). However, the contribution of the snowmelt component had not yet been evaluated. Applying a continuous semi-distributed hydrological runoff-snowmelt model will allow us to validate the accuracy of this tool for the experimental site, by comparing historical runoff records measured at the watershed's outlet versus values predicted by model simulations. Eventually, a good agreement between observed and simulated runoff values could allow one to use the model predictively to suggest management strategies, which would take advantage of watershed runoff. One strategy could be the rational utilization to runoff to satisfy seasonal irrigation needs in the watershed. An evapotranspiration model, calibrated for the agro-climatic conditions prevailing in southwestern Quebec was selected and applied in order to estimate crop water requirements in the watershed.

1.2 Objectives

The main objectives of the present study consist of:

1. Applying the SLURP hydrological model to simulate snowmelt-surface runoff in the watershed;
2. Calibrating the model and assessing its performance by comparing the simulated runoff with runoff measured at the watershed outlet;
3. Evaluating the evapotranspiration (ET) component of SLURP by comparing its results with an ET model calibrated for the region;
4. Based on the results of the ET model, estimating seasonal crop water requirements (CWR) for the watershed in order to determine if irrigation is required.

1.3 Scope

Presently, five years of hydrologic and climatic data (1994-1998) have been collected on the Saint Esprit watershed. The scope of this research is to characterize the hydrology of a small agricultural watershed, by making use of a hydrological model, an ET model and an existing GIS database. The most important variables of the hydrologic cycle in the watershed will be quantified, making the first attempt in modelling snowmelt in the watershed and assessing irrigation needs during the period of study.

2.0 LITERATURE REVIEW

2.1 The science of Hydrology

Hydrology is an evolving science, which probably began roughly 3500 BCE in with rudimentary ways of measurements and calculations (Fleming, 1975). In its early stages, advances in hydrology were restricted to the available computational technology. The development of new theories parallel to the development of measurement and calculation techniques have led scientists to reach a better understanding of the hydrologic cycle, allowing them to address the challenges of the present needs in water resources management.

The last 40 years, along with advances in computer technology, have been characterized by great progress in quantitative hydrology. In this era, factors such as the need for integrating different components in hydrological studies (precipitation, runoff, evapotranspiration) and increasing environmental and water management concerns, have led to a rapid development in the science of mathematical modelling as applied to hydrology.

2.2 Modelling concept and classification

Any conceptualization of a natural process in mathematical or visual form is considered a model. By using models we can understand or explain natural phenomena and in some conditions make predictions either in a deterministic or a probabilistic sense.

Models can be categorized as either formal or material. A formal model is a symbolic representation, usually mathematical, of an idealized situation that has important structural properties of a real system. A material model is a physical representation of a complex system, which is assumed to be simpler than the real system, while having similar properties. Formal models are further subdivided into empirical and theoretical models. In watershed hydrology all formal models are mathematical. Woolhiser and Brakensiek (1982) have presented definitions for these systems as follows:

- Empirical models: These models omit the general physical laws and are in reality a mere representation of the data.
- Theoretical models: Include both a set of general laws and theoretical principles and a set of statements of empirical circumstances. Theoretical models simplify the physical system; in consequence, they are imprecise to a certain degree.

2.3 Hydrologic modelling

In general, hydrologic models describe the physical processes involved in the movement of water and pollutants onto, over and through the soil surface (DeCoursey, 1982). One objective of watershed modelling is to gain a better understanding of the hydrologic phenomena occurring in a watershed and how changes in the watershed may affect these phenomena. Models following this approach are generally known as physically based deterministic models. The laws of continuity, energy and momentum generally define the hydrologic phenomena they simulate. Such models have been used for the analysis of individual or continuous rainfall runoff events. On the other hand, watershed modelling is widely used for the generation of synthetic sequences of hydrologic data for forecasting or facility design.

2.4 The snowmelt process

Snowmelt is an important factor affecting the timing and magnitude of runoff in subtropical watershed systems and a major source of streamflow. Snowmelt estimates allow the forecasting of seasonal water yields for diverse purposes. In some watersheds the combination of rainfall and snowmelt runoff are at the origin of annual floods (Viessman, 1989). Snow has received attention as a primary water resource, in the Asia region, Canada, Europe and the northern states of USA (Osborn and Lane, 1982). Harms and Chanasaky (1998) quantified the runoff response from two reclaimed watersheds in central Alberta, for both summer rainfall and spring snowmelt. Snowmelt accounted for 86% and 100% of annual watershed runoff in 1993 and 1994 respectively. Gangbazo et al. (1997) reported that for Southern Quebec, as much as 30 percent of the annual runoff may occur between March 1 and April 15 due to snow melting on frozen soils.

Precipitation in the form of snow is not immediately available to the soil or streamflow. Heat energy from radiation, conduction, convection or a combination of these causes the snow to melt. Snowmelt processes are complex since they depend on variables associated with the snowpack characteristics, the physical characteristics of the watershed and meteorological and geographical conditions occurring in the watershed (Khanjani and Muron, 1982).

In small watersheds snowpack characteristically will be shallow (depth <1 m) (Pomeroy, 1995) have relatively uniform density, and exhibit some degree of redistribution of snow during an after snowfall. The more important snow properties and characteristics used in simulation are snow density or specific gravity, snow water equivalent, snowdepth, optical properties, and areal extent of the snowcover (Osborn and Lane, 1982). The water equivalent of the snowpack (W) is the depth of water contained in the ice and liquid water present in the snowpack. The density (P) is then defined as the mass of water per unit volume of snow (P=W/D; Martinec and Rango, 1981), but is conventionally expressed as a specific gravity and simply measured by weighing a known volume of snow.

Typically, the density increases with time as the pack settles. Density values usually range between 0.15 to 0.45 (150 to 450 mg/m^3) (Pomeroy, 1995) with the lower values during accumulation and after the snowfall and the higher values after a period of partial melting. A generally accepted fact is that the areal density of snow in shallow packs does not vary as much as the depth. Folliot and Thorud (1969) report variations in depth of 9mm ($P > 0.05$), whereas the density variation was only 0.24 ± 0.01 units. Areas with uniform topography and vegetation could thus be measured using a large number of snow stakes and a few density measurements. This also indicates that for much agricultural land, the density could be more accurate modeled than the water equivalent, (McKay, 1968). The areal extent of the snow cover during the melt period is needed to calculate the effective contributing area of melt. Common methods for calculating the snow areal extent are assuming that the area not covered by the snow is a function of time since the last snowfall, or as a function of a percentage of the seasonal runoff.

For small watersheds an estimate of the total melt time is necessary. Usually this time is quite short depending on the snow characteristics: water equivalent, area covered, and watershed physical characteristics such as cover and topography. Gangbazo et al. (1995) report the snow melting period in Southern Quebec occurring between March 25 and April 9 in a spring runoff and water quality experiment conducted from 1992 to 1994. Another important snowpack characteristic for modelling, is the water holding capacity of the snowpack. Any water content above this threshold will be drained from the pack. The amount of water in the snowpack is represented in terms of heat, as the ratio between the amount of heat necessary to produce a given volume of water from the snowpack to that required to produce a similar volume of water from ice. This ratio also represents the fraction of the snowpack that is ice.

2.5 Snowmelt runoff determination

The estimation of the amount of runoff produced by snowmelt can be done following several approaches. Sophisticated methods consider the physical laws involved in the process, while relatively simple techniques completely ignore these laws. Applying either one or another of these techniques depends on data availability.

Some of the most important techniques used to estimate snowmelt runoff are presented in the following section. In fact some of theses techniques have been integrated in several snowmelt runoff models.

The water budget

The water budget method is generally used for areas with short hydro-meteorological records. Introducing the effect or contribution of snowfall to the hydrologic cycle, the general hydrologic budget equation can be rewritten (Viessman, 1989) in depth units as follows:

$$R = P - L - AS \qquad [2.1]$$

where

P = the gross precipitation ;

R = the runoff;

L = the losses; and

ΔS = the change in storage .

Then, for snowmelt estimation the equation is modified to consider components of the gross precipitation. This means the sum of net rainfall P_{rn}, net snowfall P_{sn} and the interception losses for both parameters. Hence:

$$P = P_{rn} + L_{ri} + P_{sn} + L_{si} \qquad [2.2]$$

where

P_{rn} ,P_{sn} = net rainfall and snowfall precipitation, respectively; and

L_{ri}, L_{si} = the rain and snow interception, respectively.

Total losses are represented by:

$$L = L_{ri} + L_{si} + L_e + Q_{sm} \qquad [2.3]$$

Where

L_e = evaporation loss; and

Q_{sm} = change in available soil moisture

The change in storage, ΔS, is represented by:

$$\Delta S = (W_2 - W_1) + Q_g \qquad [2.4]$$

Where

W_2 , W_1 = the final and initial water equivalents of the snowpack, respectively; and

Q_g = the ground and channel storage.

Returning into equation (2.1) and by inserting the new terms for P, L and ΔS; positives and negatives values are canceled, and we get the following equation:

$$R = P_{rn} + P_{sn} + (W_2 - W_1) - Q_{sm} - Q_g - L_e \qquad [2.5]$$

The term $P_{sn} - (W_2 - W_1)$ is equivalent to the amount of snowmelt (M) contributing to runoff, then :

$$R = P_{rn} + M - Q_{sm} - Q_g - L_e \qquad [2.6]$$

Snowmelt indices

Hydrologic indices summarize hydrologic and meteorological variables into a form that is easier to measure and handier than the element it represents (Viessman, 1989). One of the most useful indices used in snowmelt modelling is the degree-day index. This index determines snowmelt by correlating melt with parameters such as degree-days or degree-hours. A degree-day is a temperature index, that defines a day (24 hour) for which the temperature is consistently one degree above the freezing point. The atmospheric temperature is a useful parameter in computation of snowmelt and runoff from snowmelt. Moreover, it is frequently the only meteorological variable available. The reference temperature (datum) in most cases is set to 0 °C. One day with a mean temperature of 5 °C will be assigned an equivalent to 5 degree-days. Howard (1996) discussed the convenience of deriving the degree-day melt factor from the equation of the energy balance presented in the U.S Army Corp component model (USACE,1960).

The following equation based on air temperature is used to compute snowmelt through the degree-day index (Osborn et al.,1982).

$$M = k (T_a - T_b) \qquad [2.7]$$

where

k = degree-day coefficient for melt rate in mm/day/ °C;

T_a= air temperature, generally average daily temperature in °C;

T_b = a base temperature (datum), generally the freezing point of water, 0 °C; and

M = melt, mm/day.

Energy balance models

These types of models consider the thermodynamic nature of the net heat exchange to and from the snowpack. These models attempt to estimate all energy and mass exchange across the boundaries where the exchanges are assumed to take place. In terms of data, these models are more demanding that the indexed models, and in many cases, parameters are not readily available. Necessary data for these model's requirements include net heat transfer from condensation, convective or sensible transfer from the air, latent transfer (evaporation, condensation or sublimation), heat conduction across the soil-snow interface, heat transfer from rain drops and net short and long wave radiation exchange between the snowpack and the environment.

Anderson and Crawford (1964), Fleming (1975), Kuusisto (1980), and Fitzgibon and Dunne (1980) have applied and discussed the energy balance model in snowmelt estimations.

Semi-empirical models (Basin snowmelt equations)

These models estimate the snowmelt rate base on theoretical equations that have been simplified for field use. The equation parameters are correlated to one or more meteorological and watershed parameters (mean air temperature, wind speed, and forest coverage). The US Army Corp of Engineers has proposed snowmelt equations applicable under either rain-free or and rainy conditions (Viessman, 1989). Solar radiation, rainfall intensity, air temperature, wind speed, watershed forest cover and albedo are variables required for this approach.

2.6 Runoff snowmelt models

Stanford watershed model

As the result of a research project at Stanford University, Crawford and Linsley (1964) released a general purpose, continuous and physically based model, which has been applied to simulate a broad variety of catchment regimes throughout the world. When the snowmelt routine is required, a total of 34 parameters are to be considered. When applying the model to watersheds with a number of rainfall stations, the watershed is often divided into sub areas, each containing a rainfall station. Larson (1965) obtained good results when applying the Stanford Model III to a 141-km2 watershed over a 20-year period, using the first five years to fit parameters.

Hydrocomp simulation program

Further developments in the structure of the Stanford watershed model IV, led to the release of the Hydrocomp Simulation Program (HSP). HSP is an advanced conceptual model of the land phase of the hydrologic cycle. The model allows the user to choose to include water quantity and quality, sediment erosion, channel, reservoir routing analysis and data management options. The parameters used by this model are similar to those required by the Stanford model. The input parameters to the channel model are physically based measurements. More than 200 watersheds in different countries have been modeled with HSP. During the 80's, an important part of the HSP code was extended and improved by the U.S EPA to produce the Hydrological Simulation Fortran Program (HSPF), allowing the simulation of hydrologic and water quality processes in natural and artificial water systems (Donigian et al.,1995).

The UBC model

In 1972 Quick and Pipes developed a model to forecast flow in regions where snowmelt is a significant process (Fleming, 1975). The UBC watershed and flow model from the University of British Columbia, is a continuous and conceptual model representing the hydrological cycle. The model considers rainfall, snowmelt, temperature, lake discharge and evaporation, and is able to process one month of data.

Leaf and Brink model

The Leaf and Brink model (1973) was developed to simulate daily snowmelt in a Colorado sub-alpine watershed for all combinations of aspect, slope, elevation, forest cover and density. The model simulates winter snow accumulation, energy balance, snowpack conditions and resultant melt in time and space. The model has been used in the Southwest and Northwest USA.

The SRM model

The Snowmelt Runoff Model (SRM) allows water resources forecasting. This is a simple degree-day model that requires remote sensing input in the form of basin or zonal snow cover extent. It has been successfully tested on over 60 basins worldwide in both simulation and forecast modes. The SRM is designed to simulate and forecast daily stream-flow in mountain basins where snowmelt is a major runoff factor. Martinec developed SRM in small European basins in 1975. Thanks to the progress of satellite remote sensing of snow cover, SRM has been applied to larger and larger basins. Runoff computations by SRM are relatively easily understood.

Kustas et al. (1994) in an effort to improve estimates of snowmelt with SRM, implemented three approaches for computing snowmelt: degree-day, restricted degree-day, and daily energy balance model. These approaches were tested at the local scale by comparing melt rates with lysimeter outflow measurements. The restricted degree-day method yielded melt rates that were in better agreement with the observed lysimeter outflow, respect to the others. However, after a sensitivity analysis a comparison of the actual and synthetic hydrographs for the basin suggested that, a radiation-based snowmelt factor might improve runoff predictions at the basin scale.

For drainage basins in mountainous areas, subdividing the watershed into relatively uniform areas may approximate the snowpack storage effect; commonly elevation zones are used for this purpose (Viessman, 1989). Mitchel et al. (1998) applied SRM for the 1990, 1993 and 1994 snow seasons in a watershed in Pennsylvania. The models predictions for the snowmelt seasons considered, yielded more precise stream flow estimates when using a combination of elevation and land use zones were used than standard elevation zones alone. The use of zones worked best in non rain–on–snow conditions seasons (years 1990 and 1994) where the melt was primarily driven by differences in solar radiation.

CREAMS subroutine for snowmelt

Khanjani and Myron (1982) developed a subroutine to compute snowmelt for the CREAMS model implementing the degree-day approach. The performance of the snowmelt subroutine was tested against two available data sets. Results showed good agreement with the measured data. The aspect (slope direction) in conjugation with a steep slope had a drastic effect on simulated snowmelt. The model was also relatively sensitive to the forest coverage coefficient.

Soil and water assessment tool

SWAT is a conceptual continuous time model, developed by Arnold et al. (1998), to assist water resources managers in assessing water supplies and non-point source pollution in watersheds and large river basins. Major components of the hydrologic balance and their interactions are simulated, this includes: surface runoff, lateral flow in the soil profile, ground water flow, evapotranspiration, channel routing, snowmelt and pond and reservoir storage. Model assumptions are that snow, when present, may melt on days when the second soil layer temperature exceeds 0 °C. Snow melts as a function of the snowpack temperature. A flow validation of the model was conducted by Srinivasan et al. (1998) for a period of 15 years (1970-1984) on the Richland – Chamber's watershed in Texas. Observed and simulated stream flow values at the two stations had a strong linear relationship (r^2 = 0.65 and 0.82).

The HQsim model

HQsim is a hydrological model for runoff simulation in small catchments (Kleindienst, 1998). The model was derived from the water balance model BROOK ver. 2.0 (Fededer and Lash, 1974). This model was used to simulate the daily water balance of a small-forested catchment in east central USA.

HQsim allows computation with variable time steps. With a minimum time step of one day, BROOK was incapable of simulating peak discharge for small watersheds, which led to its revision. The following modules were implemented to allow a shorter time step for calculation:

- Radiation module, computes radiation at a given date and time;

- Snowmelt module, computes snowmelt using a more detailed energy balance equation;
- Channel routing module, simulating the water flow in torrents.

HQsim is a semi-distributed model, meaning that the catchment is subdivided into several sub-areas, each assumed to be homogeneous. HQsim is a storage-based model simulating snowcover, soil layers and ground water body as a reservoir with a specific or unlimited capacity. Each sub-area is represented by the following reservoirs: snow and rain interception, snow cover , unsaturated soil layer and saturated soil layer. HQsim has been applied in four small pre-alpine catchments in Switzerland.

The HBV model

The Swedish Meteorological and Hydrological Institute (SMHI) introduced the HBV model in 1972. Since then a wide range of watershed with different physiographic and climatic conditions, have been simulated by the model around the world. The HBV model has become a standard tool for runoff simulations in Nordic countries and several operational applications has been carried out in Latin America (Häggström et al., 1990 cited by Bergström 1995). A major revision by the SHMI of the structure of the HBV model in 1993 created HBV-96, which is the current version.

The HVB-96 model is classified as a second-generation model, in which an attempt was made to cover the most important runoff generating processes, while keeping as simple and robust a structure as possible. This semi-distributed parameter conceptual model uses sub-basins as primary hydrological units and within these, an area-elevation distribution and a crude land use classification (forest, open and lakes). The main components of the model are subroutines for snow accumulation and melt, soil moisture accounting, and response and river routing. HVB-96 is normally operated at a daily time step. One of the improvements in the present version (HBV-96) is a more sophisticated method for computing areal precipitation and air temperatures. Rather than the use of crude weighting routine and lapse rates, the model introduces an optimal interpolation procedure for these factors based on minimal error estimation. This has been reported to be more accurate in estimating point precipitation than distance interpolation procedures (Johanson, 1994, cited by Lindström et al., 1997).

The standard snowmelt routine of the HBV model is a degree-day approach based on air temperature, and a water holding capacity of snow which delays runoff. This routine controls snow accumulation and melt, and works separately for each elevation and vegetation zone. The precipitation is assumed to accumulate as snow when the air temperature drops below the threshold value. The liquid water holding capacity of snow has to be exceeded before any runoff is generated (usually preset to 10%). A refreezing coefficient, which is used to refreeze water in the snow if snowmelt is interrupted is fixed in the code.

The soil moisture routine determines the runoff coefficient and the actual evaporation. Both are uniquely related to the soil moisture storage, and they increase with increasing soil wetness. There is a maximum capacity (*Fc*) of the soil moisture storage, when this value is reached, each subsequent millimeter of rain contributes to runoff. The ET component in the standard HBV model is based on the Penman formula. Simple interception storage has been introduced, but only for forested areas. Once the water balance is set by the routines of snow and soil moisture, only five parameters in the response function control the dynamics and thus the distribution of the predicted runoff. The upper and lower tanks produce the quick response and base flow, respectively. The routing between sub-basins is described by the Muskingum method or by simple time lags. Lindström et al. (1997) found that the new version, HBV–96, performed better than the original version in a comparative study on eight basins in Sweden.

This more physically realistic model with fewer inconsistencies and better parameterization increased the R^2 index (Nash and Sutcliffe, 1970) from 86% to 89%. However, the authors concluded that these results do not justify increased resolution in time or space, unless more detailed data are to be used as input or for validation. Zhang and Lindström (1996) applied the new model in two watersheds, the Bird Creek in the USA and the Hushile in the central region of the People's Republic of China, obtaining R^2 of 0.86 and 0.83, respectively, for each watershed.

The SLURP model

The Simple Lumped Reservoir Parametric model (SLURP) was originally developed to provide an easy to use alternative to complex hydrological models for Canadian basins (Kite, 1995b). In its latest version (11.2) the Semi-distributed Land Use-based Runoff Processes, has become a conceptual distributed watershed model that simulates the complete hydrological cycle. Parameters are related to land cover/land use characteristics. Although primarily designed to use satellite data for land cover, snow covered area and snow water equivalent, it also operates with in ground measured data. SLURP is a continuous, daily time step model particularly suitable for water balance studies on meso and macro-scale basins (Kite, 1998). However, SLURP has been successfully applied with minor modifications to simulate water level variations in small prairie wetlands (Su et al., 1999). It requires the input of time series of precipitation, air temperature, relative humidity and radiation. Atmospheric general circulation models (GCMs) can provide most of the data for implementing SLURP, otherwise measured data from weather stations and snow courses may be used. SLURP simulates a vertical water balance using four tanks : the canopy storage, the snow storage, the unsaturated soil zone (fast store) and the groundwater zone (slow store).

The major advantage of this "middle ground" model is that its incorporates the necessary physics while retaining simplicity of operation. Kite (1995) has discussed the fact that in practical applications, users of both lumped and physically based fully distributed parameter models may also tend towards this middle ground.

Modelling concept

At a daily time step, calculating an actual infiltration rate (inversely proportional to the current water content in the soil tank) simulates infiltration. Evapotranspiration may be calculated using methods from Morton, Granger or Spittlehouse, depending on data availability. The model divides a watershed into Aggregated Simulation Areas (ASAs) and into areas of different land covers. An ASA is simply a sub-unit of the watershed and may be an individual grid square, a group of grid squares or a sub-basin.

However, each ASA must have known land covers or land uses, a defined river reach and outlet. The number of ASA multiplied by the number of land uses is unlimited.

The size of this matrix allows one to simulate runoff in any river basin. Such watershed division is easily achieved in a GIS environment, where the system allocates areal data from different sources and presents them in a suitable format for the model (Kite, 1995).

The vertical water balance

For each element in the matrix of land cover and ASAs, the model carries out a vertical water balance at each time interval using land cover roughness, infiltration rates and hydraulic conductivity (Figure 2.1; after Kite,1998). A distinctive feature in the SLURP model is that the parameters are related to land covers or land uses representing vegetation types, elevation bands, soil classes, geological characteristics or a combination thereof. This allows physically based parameter estimation over the basin as a whole, and efficient, one step model calibration for all sub-basins.

The following section briefly describes the model operation at a particular time step. These operations will occur within the vertical water balance for a particular land cover and ASA (Kite, 1995):

- Daily precipitation is read and multiplied by a correction factor
- Mean air temperatures for each ASA are derived from a vertical lapse rate. If mean air temperature (T ° C) of the ASA is above a critical value, then the precipitation is assumed to be rainfall and added to the rapid storage tank.
- Percolation from the rapid storage tank to the slow storage tank is governed by the following expression:

$$Inf = \left[1 - (S_l / S_{l\ max}) \right] * Inf_{max} \qquad [2.8]$$

where

Inf = infiltration (mm/day);

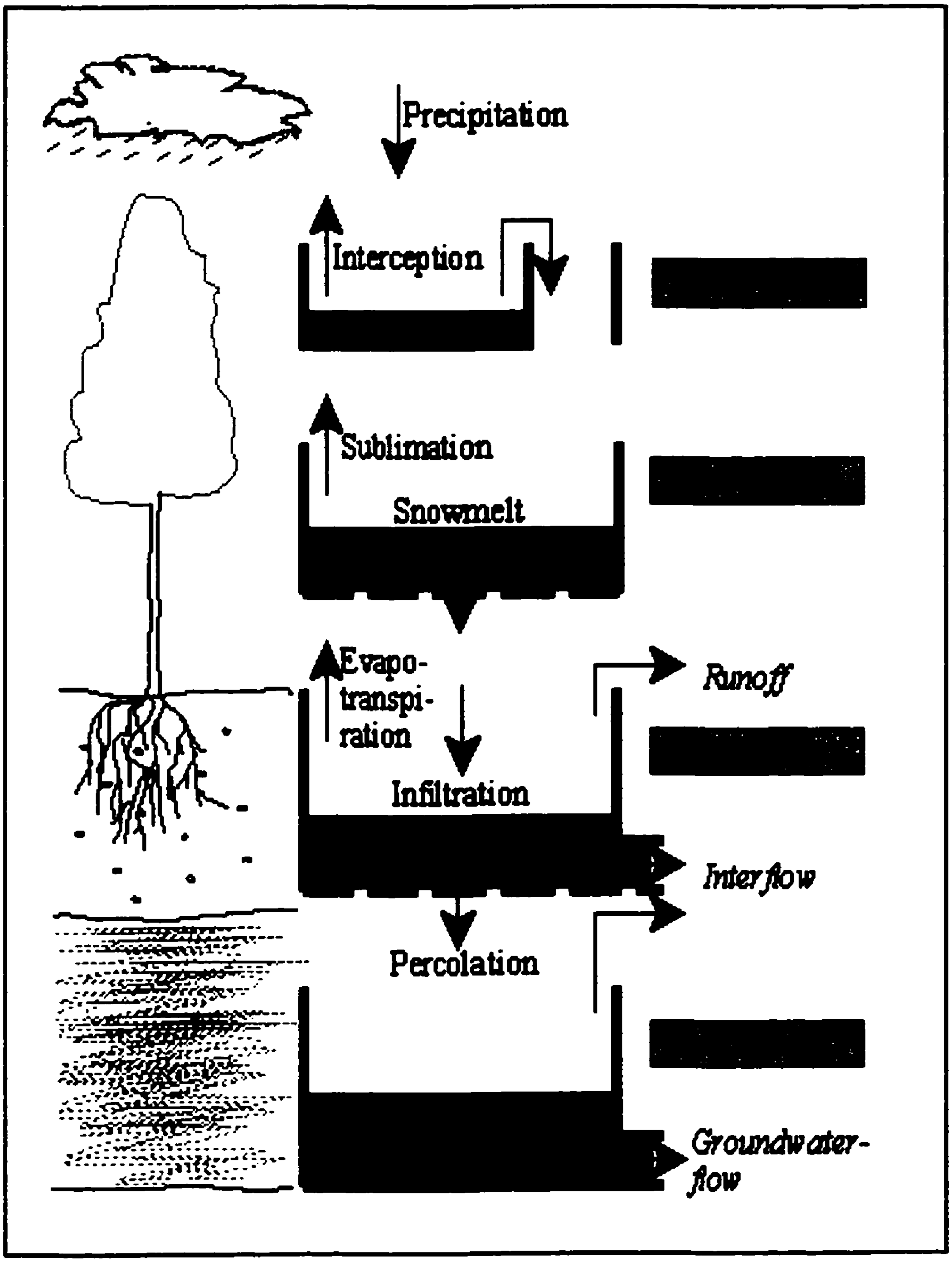


Figure 2.1 The vertical water balance in the SLURP model

S_1 = current content of the rapid store (mm);

$S_{1\,max}$ = maximum capacity of the store (mm); and

Inf_{max} = maximum possible infiltration (mm/day).

If the content of the rapid storage is greater than the infiltration or it is full, then, the excess water is depleted to runoff. The amount of evaporation and transpiration from the fast store depends on the proportion of the percentage of soil and vegetation cover that the model derives from the input LAI. The fast store generates outflow (Q) as:

$$Q = (1 / k_1) \cdot S_1 \qquad [2.9]$$

where

Q = Outflow (mm);

S_1 = Current contents of the rapid store (mm); and

k_1 = Fast storage retention constant (dimensionless).

The outflow then is separated into percolation and interflow using:

$$RP = Q / [(1 + S_2 / S_{s\,max})] \text{ ; since } RP + RI = Q \qquad [2.10]$$

where

RP = percolation (mm);

Q = outflow (mm);

S_2 = current contents of the slow store (mm); and

$S_{s\,max}$ = maximum possible content of the slow store (mm).

Ground water flow (slow store) is represented by:

$$RG = (1 / k_2)^* S_2 \qquad [2.11]$$

where

RG = ground water flow (mm);

S_2 = current contents of the slow store (mm); and

k_2 = slow store retention constant (dimensionless).

- At the same time any snowpack (S_p) (cm), is depleted to snowmelt (S_m) (mm), based on a melt rate (S_{mr}) (mm/day/°C) and the temperature in degrees above the rain/snow division (R_{sd}). This approach makes use of a simple snowmelt factor and temperature index instead of the more physically based energy budget approach. This approach is valid when the main interest is the seasonal depletion of the snowpack;

$$S_m = S_{mr} * S_p (T - R_{sd}) \qquad [2.12]$$

- If on the other hand, the daily temperature is below the critical temperature, then the precipitation is considered as snowfall and added to the snowpack storage, if any. No snowmelt will occur in this case, but the rapid storage would be allowed to infiltrate and to runoff as before;
- Areal evapotranspiration is satisfied first from the snowpack (if existent), then from the rapid storage and finally from the slow store. SLURP uses the complementary relationship areal evaporation (CRAE) described by Morton (1983). The computation of actual evaporation occurs in direct proportion to the potential evaporation. This relationship provides the areal estimates required by the ASA modelling system.

$$E_T = 2E_{TW} - E_{TP} \qquad [2.13]$$

where

E_T = actual areal evapotranspiration (mm/day);

E_{TW} = wet environment evaporation (mm/day); and

E_{TP} = potential evapotranspiration (mm/day).

The CRAE model computes E_{TP} by solving the energy balance and aerodynamics equations at equilibrium temperature using a modified Penman equation, in which the wind function has been replaced with a vapor coefficient (Morton, 1983). E_{WT} is computed from an empirical equation using the slope of saturation vapor pressure and temperature curve, and global radiation (Kite, 1998).

Flow routing within an ASA

A Geographic Information System (GIS) is used to distribute the runoff from each land cover over time. Analyzing the land cover data combined with an ASA streamflow network yields a distribution of distances, both to the nearest stream and then along the stream network to the ASA outlet. Changes in elevation between each point (pixel) of the ASA and the ASA outlet can be calculated, and therefore, an average elevation change for the land cover. In this way, an average velocity for each land cover (*m/s*) is calculated using Manning's equation with a specific coefficient of roughness (*n*). The assumption that the hydraulic radius (*R*) is unity for an infinitely wide shallow channel is adopted.

$$V = (1.0 / n) R^{2/3} (H / L)^{1/2} \qquad [2.14]$$

where

V= Velocity of the flow for each land-cover or land use (m/s);

R= Hydraulic radius of channel (cross-sectional area divided by the wetted perimeter in m);

H= Average change in elevation between a particular land use and the ASA's outlet (m);

L= Average length of the distance from a particular land use to the stream (km); and

n = Manning's roughness coefficient (dimensionless).

From the average velocity and the minimum and maximum distances to the ASA outlet, the minimum and maximum travel times may be calculated. Travel times can then be used in a linear smoothing filter to distribute the runoff from each land cover over time. Then, weighted by the percentage of the ASA covered by a particular land cover, the flow is converted (m^3/s) and added to the total flow of the ASA (Kite, 1995).

Flow routing between ASAs

Once the runoff from different land covers within an ASA have been combined into a ASA streamflow, this flow is routed from one ASA to the next, located down the stream system. In SLURP, the user can select between no routing (no flow delay), the Muskingum method or the more specific Muskingum-Cunge (Cunge, 1969) method for flow routing (Kite, 1998).

Model applications

Kite and Kouwen (1992) compared a lumped version of SLURP with the application of the distributed version, in which the watershed was subdivided for meteorological data input and for the reservoir computation. The author points out that even if the land cover classes are randomly distributed within the watershed boundary, it is still possible to determine the hydrological parameters for each unique land cover class. The advantage of the distributed model approach over the original lumped model was demonstrated in terms of improvements in the calibration and verification statistics.

Kite (1995) investigated the effect of data scale in hydrological simulation using SLURP. The model was applied to Canadian watersheds varying from 200 km^2 to 1,600,000 km^2. Results were used to compare errors due to data input at different scales. Mean errors were computed as the mean of the differences between the observed and simulated flows. The relative errors (mean errors divided by mean recorded flows) were remarkably consistent at about 0.1 for all the watersheds with the exception of one basin suffering from a lack of climatological data. The fact that the SLURP model gave a similar relative error for such a wide range of watershed areas, implies that the ASA concept is a valid method for modelling watersheds.

With minimal modifications SLURP was applied to simulate the hydrology of a small (3 ha) prairie wetland in Saskatchewan, Canada (Su et al., 1999). The model simulated satisfactorily the recorded wetland water level variations during a 28-year period.

Droogers and Kite (1999) applied the SLURP model in the Gediz basin in western Turkey, performing an integrated basin with several modeling tools at three scale levels: the field, the irrigation scheme, and the basin. SLURP was applied at the basin scale. Besides agricultural use of water, water extraction by forest, natural vegetation, urban and industrial water supply, were taken into account. The objective of the study was to assess the productivity of the water (PW) in the basin. Authors pointed out: (i) the importance of a quantitative approach to analyze water resources, (ii) the usefulness of modelling techniques to fulfil the data needs in PW's studies by using readily measured data to feed models, and (iii) the potential for irrigation studies in an integrated environment. In this scenario models use common datasets and transfer information from one scale to another.

2.7 Computer modelling in the Saint Esprit watershed

At present two hydrological models have been applied in the Saint Esprit watershed in Quebec. However, non-of these models considered the effect of snowmelt on simulated runoff, and were thus restricted to simulating the hydrology of the watershed from May to November. Perrone (1997) simulated the runoff and sediment transport on the Saint Esprit watershed using the AGNPS model. After model calibration , average errors of 6.2, 38.9 and 44.3% over the growing season were observed for surface runoff, sediment yield and peak flow, respectively. In general the model over-predicted peak flows. The model performed best for events occurring between June 1 and November 1, but more poorly when complex storms and events occurring in relatively cold climatic conditions were simulated (early spring and fall).

Perrone et al. (1998) investigated different hydrologic relationships within the Saint Esprit watershed and compared the variables and parameters often considered for the runoff and peak flow prediction. All four methods for calculating time of concentration (t_c) under-predicted it. The Soil Conservation Service (SCS) and Airport equations provided the best estimates of t_c at 6.1h and 5.9h, respectively. Lag time and time to peak were found to be variable and related to storm duration. Equations describing the relationship between peak discharge, antecedent flow, total rainfall and surface runoff were developed.

Mouzavizadeh (1998) evaluated the continuous version of the ANSWERS 2000 NPS model in the Saint Esprit watershed. During wetter conditions in years 1996 and 1997, the model predicted total cumulative runoff within 71.1% and 42.4 percent, respectively. The model however, was not able to produce outputs in agreement with the monthly measured values within the period mentioned.

2.8 Evapotranspiration models and crop water requirements.

Evapotranspiration (ET) is a critical component of the hydrologic cycle; therefore, its knowledge is essential in the solution of any problem related to water resource management. Evapotranspiration studies have been carried out in Southern Quebec with different objectives : (i) development or adaptation of new and existing models to local conditions (Baier and Robertson,1965; and Rochette et al., 1990), (ii) model applications to estimate crop water requirements (CWR) Gallichand et al. (1990), and (iii) evaluation of model performance (Barnett et al., 1998).

Baier and Robertson (1965) developed an improved formula to estimate latent evaporation, which is closely correlated with evapotranspiration. In their study they combined readily available climatological factors (maximum temperature and temperature range), extraterrestrial radiation, day length and four additional meteorological variables. These parameters, however, are used in a sound physical sense to approximate results to the more physically based Penman model.

Each of these factors when correlated singly with latent evaporation, yielded statistically significantly coefficients. In example, adding wind speed to the original equation, produced a correlation coefficient of 0.69 between the observed and simulated data. A multiple correlation including six factors yielded a correlation of 0.84, this means that 84% percent of the variation of latent evaporation could be explained by variations in those six factors. The Baier and Robertson equation was one of the firsts to consider the effect of extraterrestrial radiation (*Ra*) on potential evapotranspiration (ETp) as a function of the daily thermal amplitude.

Barnett et al. (1998) carried out a comparative study of five ET models: modified Penman, Jensen-Haise, Baier & Robertson, FAO Blaney-Criddle and SCS Blaney-Criddle. The study used meteorological data collected in the Saint Esprit watershed over a two-year period. Results of the five models we compared with local corrected pan evaporation data. On a seasonal basis, the Baier and Robertson (ETp) equation predicted potential evapotranspiration within 10% of corrected pan evaporation values. Predicted ETP was not significantly different than that calculated from the pan ET data (P>0.05). The other models generated ET values within 10% to 25% of the corrected pan evaporation values, except Jensen–Haise, which showed an average seasonal difference of approximately 50 %.

Rochette et al. (1990) have evaluated the performance of twelve ET models in different locations in the Montreal and Quebec City regions. The authors reported that the Hargraves and Samani model (1985), Baier and Robertson (1965) and Jensen–Haise models most closely estimated the value of ET obtained from the Penman equation (ET_{PEN}) for the Quebec City and Montreal regions. Since the Baier and Robertson equation was calibrated for conditions in Eastern Canada, Rochette et al. (1990) proposed the use of an empirical function (α), for local calibration of the original Baier & Robertson equation. For five stations, this considerably reduced the error accumulated resulting from daily errors in the estimation of (ETp_{PEN}). This version of the Baier & Robertson model ($B\&R_{LAVAL}$) is suitable for estimating ETp in more that 220 stations in southern Quebec. The average water consumption in meridian Quebec for irrigated crops in the period of May to September varies from 456 to 595 mm. During the growing season crops are subjected to frequent water deficits (Rochette et al., 1990).

Gallichand et al. (1990) used the versatile moisture budget (version IV) to simulate irrigation requirements for major crops in South Western Quebec. For crops grown on clay loam and loamy sand soils, water deficits occurred in the first stage (May) of the growing season, as is of the shallow root system existing during this stage. Peak and seasonal irrigation requirements for the median and for the one-in ten dry-year probabilities were developed as a guide for designing irrigation systems and reservoirs.

Singh et al. (1990) followed two approaches for irrigation scheduling: allowable depletion and critical soil moisture content. They reported the need for supplemental end-of-season irrigation for a raspberry crop in Quebec. At least two irrigation events would have been required for the crop on August 24 and 27, regardless the approach implemented.

2.9 Geographic information systems (GIS)

In the last thirty years, the traditional way of representing and analyzing spatial data has evolved from analog methods to digital computerized procedures. Advances in computer-aided design and drafting systems (CADD), relational database management systems (RDMBS) and improvement in hardware performance in term of storage and time of data processing have created the basis for the emerging GIS technologies. A GIS is an information system designed to handle data referenced by spatial or geographic coordinates. Hence, a GIS is both a database system with specific capabilities for spatially referenced data, and a set of operations for working with the data (Star and Estes, 1990).

GIS is a versatile technology. Scientists have found applications in several fields, but especially in the environmental sciences. More recently, hydrological and agricultural problems are being addressed through the use of GIS. Nevertheless, data that is accurate both spatially and in terms of attributes is required to generate meaningful results.

2.10 GIS applications in hydrology

Problems in water resources assessment, water conservation and agricultural system improvement are related to large datasets. Moreover, variability of the data has a strong spatial component (spatial dimension). In such cases a GIS implementation contributes to the management of the project data, facilitating the analysis and in some stages of the decision-making process. In the last decade, GIS's spatial analysis functions (cartographic modelling) have been exploited in research problems in hydrology. At present, several components of the hydrologic cycle have been modeled by the use of GIS. Worthy of mention is the linkage and/or integration of hydrological models (runoff, evapotranspiration, NPS) with a GIS database. Landscape parameterization tools even though they are not inherently fitted into the GIS concept, are playing an important role in the process of extracting physical parameters for most of the current generation of distributed parameters models in hydrology. Tools such as TOPAZ, (Martz and Garbrecht, 1993; Garbretch and Martz, 1993) are examples of this technology.

McDonell (1996), Tim (1996) and Drayton et al. (1992) describe the role of GIS in environmental hydrology as follows:

- GIS provides the tools to collect, store and integrate data from many sources and perform spatial analysis required to better understand hydrological phenomena;
- GIS provides an interactive environment and tools to hydrologic modelling and the integration to physically based models with databases;
- GIS capabilities of visualization and display provide new insights into many hydrological problems.

Today's use of GIS for understanding and modelling complex hydrologic processes is becoming widespread. However, many technical and methodological issues must be recognized. GIS have been developed with a cartographic paradigm, in which data is manipulate in a time-invariant approach (2D space). Unfortunately, problems in environmental hydrology are space and time dependent, often requiring three or four dimensional analysis and display. Furthermore, solutions to hydrologic problems still rely on iterative numerical models (mathematical techniques), data structures and abstractions so far not available in commercial GIS software (Tim, 1997).

Mansoor et al. (1998) implemented GIS and evapotranspiration models to estimate ET, considering spatial and temporal variability of parameters affecting this process. A spatial simulation ET model was used to develop baseline estimates of regional ET, incorporating analytical GIS functions of map algebra and map overlay to calculate the ET for each field management conditions. GIS significantly improved the accuracy of the hydrologic modelling compared to traditional techniques.

Reungsang et al. (1997) fully integrated the Watershed Surface Hydrologic Modelling System (WSHMS) into ARC/Info. Bingner et al. (1997) implemented the integration of GIS, the landscape and topographic parameterization tool (TOPAZ) and the Agricultural Non point Source pollution Model (AGNPS). Such integration automated the development of many of the input parameters necessary to describe the watershed. This technique permitted a better (AGNPS) characterization of the effect of the topographic features on runoff, erosion, and water quality.

Distributed parameter models have opened the opportunity to improve watershed-modelling accuracy. Nevertheless, it has also placed a heavy load on users with respect to the amount of work in parameterization of the watershed and adequately representing the spatial variability (Manguerra and Engel, 1998). Conrad and Kilgore (1997) used IDRISI, a raster based GIS and a flow routine model to develop a synthetic unit hydrograph for an ungauged watershed in Virginia. Based on travel-time mapping of each point in the watershed to its outlet, the cumulative travel-time map of the watershed was used to develop a time-area diagram for generating the synthetic hydrograph. The basic data required by the model included elevation and land use.

When managing raster data, users have to select an adequate grid size to represent the information. Zhang and Montgomery (1994) evaluated the effect of four grid sizes (2, 4, 10 and 90 m) in constructing Digital Elevation Models (DEM) to generate a series of simulated landscapes in two watersheds. Different parameters generated at the given grid scales were further used as input parameters in the O'Loughlin criterion for predicting zones of surface saturation and in TOPMODEL (Beven et al., 1995) to simulate hydrographs. The DEM's grid size significantly affected the computed topographic parameter and hydrographs. The authors concluded that the grid size affected the response of physically-based models on runoff and surface processes, and suggested a 10-m grid size as a rational compromise between increasing resolution and data volume for simulating hydrological processes. Martz and Garbreht (1993) recommended grid areas of no less than 5% of the network reference area (mean area draining directly into the channel links). When testing 19 different resolution grids for the automated delineation of the Wolf Creek watershed using TOPAZ, a 5% grid area reproduced drainage features within an accuracy of 10%.

Mouzavizadeh (1998) evaluated the continuous version of the ANSWER 2000 (NPS model) in the Saint Esprit watershed. The model was integrated into the SPANS GIS user interface. The integrated tool permitted one to select and save watershed information in the model input file format, run the model and visualize the model outputs.

3.0 METHODOLOGY

3.1 The Saint Esprit watershed

3.1.1 Location

The Saint Esprit watershed is located between 45° 55' 00'' and 46° 00' 00'' north latitude and 73° 41' 32'' and 73° 36' 00'' west longitude; approximately 40 km north of the city of Montreal, in the southwestern part of the province of Quebec. The watershed comprises a net area of 26.1 km^2.

3.1.2 Site description

Twenty-one soil series were identified within the watershed. The largest proportion (49.1%) is occupied by light texture soils (very find sands to sandy loam soils). At least 50% of the agricultural land is subsurface drained (Enright et al., 1995).

The watershed is mainly agricultural. During the study period (1994-1998) agricultural land occupied 1678.47 ha (62.71 % of the total watershed area). Agricultural production is based mainly on annual crops such as corn, wheat, soybean and vegetables. The major crop by area is corn with 619.41 ha. A significant increase in the area under vegetable crops has occurred during the last 5 years. Table 3.1 shows the land use in the watershed.

Except in small stony and forested areas where slopes are greater than 5 %, the watershed is characterized by a rolling topography with a land slope varying between 0 to and 3 %. The maximum difference in elevation from the outlet to the top of the watershed is approximately 50 meters. The climate is temperate, with an annual mean temperature of 5.2 °C and 1087 mm of precipitation (Mouzavizadeh, 1998).

Table 3.1 Saint Esprit watershed land use in percentage of the total area

Annual crops	Vegetables	Grassland	Forest	Non agricultural	Urban	Total
40.7	8.5	11.8	23.1	9.5	6.5	100

3.2 Model selection

SLURP was selected for this research, because most of the parameters and time series to implement the model were available, or could be estimated for our experimental site. Another important reason for choosing SLURP was the fact that it simplifies processes by averaging the hydrological response at the land use level. This has an important impact in reducing the number of parameters, compared to more sophisticated distributed parameter models. Finally, SLURP has been designed to easily integrate digital data such as that used in GIS or remote sensing.

3.3.1 Data management and integration using GIS

GIS was used in the implementation of both the SLURP hydrological model and the Baier and Robertson (BR) evapotranspiration model for ET and crop water requirements estimation.

The existing digital information for the watershed on land use, soils texture and the watershed boundaries was used. Non-topological vector files with an arc-node structure (TYDIG .vec and .veh format), were imported into the SPANS EXPLORER GIS. Attribute information in the SPANS native format (.tba) was also imported and further appended to the vector layers. The topology was automatically generated through the import procedure. See Appendix 1 for details on the data integration. Once all the layers were topologically correct, all the information was exported to the Arc view (AV) GIS ver. 3.1, which features modules for easy analysis of vector and raster data formats.

The GIS was helpful in performing the following tasks:

- Data visualization and spatial analysis: mapped data were extensively used in the implementation of the SLURP model and the BR model. The GIS was effective in data visualization, spatial analysis such as map overlay, map reclassification, and parameter estimation from mapped data. A Digital Elevation Model (DEM) was produced with a resolution of 20 m. This was achieved through a grid interpolation tool available in the (AV) Spatial Analyst. The input for this operation was a point data file (x,y,z) obtained from the Photocarthoteque du Quebec. The spline method was used to interpolate the elevation points. This technique is one of the most appropriate for interpolating surfaces from sparse point information in smoothly transitional environments (Burroughs, 1998). The best results were obtained when using information from 12 neighboring points, and 0.1 as the exponent in the polynomial function.

- Rasterization of vector data: The land use data was converted from the AV vector format to raster format. An available rasterization procedure in the AV Spatial Analyst ver. 1.1 was used. The procedure used for data conversion is described in Appendix 2.

- Defining the spatial resolution of the SLURP model: Distributed parameter models generally simulate hydrologic responses using topographically driven algorithms i.e. TOPMODEL, (Beaven et al. 1995), THALES (Grayson, 1992) and SLURP (Kite, 1998). Zhan and Montgomery (1994) have addressed the importance of properly defining the resolution of the grid for constructing elevation models in landscape representation and hydrologic simulation, and recommend a 10-m grid size for hydrological for small watersheds. The Saint Esprit spatial database has a resolution scale of 1:20,000 (except for soil series 1:63,360). A 20-meters (0.04 ha) grid was selected for model implementation, after comparing 100, 50 and 30 m grid resolutions. The 20-m level resulted in a reasonable compromise between the data resolution to accurately depict physiographic characteristics of the watershed, and the need to reduce computational time for parameter generation.

3.4 Input parameters

3.4.1 Parameters required to estimate evapotranspiration (ET) and crop water requirements (CWR)

The Baier-Robertson (BR) potential evapotranspiration model, as proposed by Rochette et al. (1990) was implemented to estimate ETp in the watershed. The description of the model is as follows:

$$ETp = \alpha\,(a_{0i} + a_{1i}\,T_{max} + a_{2i}\,(T_{max} - T_{min}) + a_{3i}\,Ra) \qquad [3.1]$$

where

ETp = Potential evapotranspiration of well - watered grass (mm/day);

$Tmax$ = maximum daily temperature in °C ;

$Tmin$ = minimum daily temperature in °C;

Ra = tabulated upper atmospheric extraterrestrial radiation in $MJ/m^2/day$; and

$a_{0i}....a_{3i}$ = empirical coefficients calibrated for regional wind speed equal to – 1.8216, 0.022074 , 0.12167 and 0.13, respectively (dimensionless).

The α parameter is a dimensionless calibration coefficient to adapt the model to various regions of eastern Canada. Coefficients for the Mirabel region were used, since they approximate the characteristics for wind speed and elevation, of our study area.

$$\alpha = b_0 + b_1 J_M + b_2 J^2_M + b_3 J^3_M + b_4 J^4_M + b_5 J^5_M + b_6 J^6_M + b_7 J^7_M \qquad [3.2]$$

where

J_M = Number of days after 1 May to 30 September (0 to 152 in our study, dimensionless); and

$b_0.....b_7$ = polynomial coefficients for the Mirabel region 0.785, 0.047332, -3.3224 $\times 10^{-3}$, 0.10024 $\times 10^{-3}$, -1.5205 $\times 10^{-6}$, 12.233 $\times 10^{-9}$, -49.991 $\times 10^{-12}$, 81.795 $\times 10^{-15}$ (dimensionless).

The BR ETp model was written using the ANSI C programming language. The program was run for the five years of data (1994-1998) to estimate ETp. Result files provided the estimated ETp as well as the alpha coefficient for each day. ETp was estimated for the whole growing season, which extends from May to September in the watershed.

3.4.1.1 Climatic data

The required climatic data were collected at the Saint Esprit watershed weather station. This station housed a complete set of instruments for measuring air temperature, relative humidity, solar radiation, rainfall, wind speed and wind direction. The climatic data were recorded every 15 minutes.

Five years of meteorological data were used. For estimating ETp, maximum temperature and the difference between maximum and minimum temperature were calculated on a daily basis. Tabulated values for extraterrestrial solar radiation (ASAE, 1990) were interpolated and adapted to the geographical location of the Saint Esprit watershed. A relational database was created using MS ACCESS to store the tabulated data. By querying in this database, an input file for the BR model was generated.

3.4.1.2 Soils data

Perhaps the most popular approach for calculating crop water requirements (CWR) and irrigation scheduling is the soil-moisture budget. This simple model simulates the hydrological cycle, and provides information on timing and quantitative estimation of irrigation. Water inputs (precipitation and irrigation) and water outputs (evapotranspiration and drainage) were computed on a daily time step. The soils data were simplified by reclassifying the soil texture from 14 to 3 classes (light, medium and heavy texture soils). An overlay analysis using GIS, depicted the occurrence of unique combinations of land use and soil texture (See Figure 3.1). This layer was used to derive the parameter used by the soil-moisture budget technique. The next sections describe the method for generation of parameters and the assumptions considered in the estimation of CWR.

Field capacity and permanent wilting point

Mean values for soils field capacities and permanent wilting points were obtained from the literature (Rawls et al., 1982). Although not derived directly from the site, the information obtained from Rawls et al. (1982) comprises the major textural classes defined by the USDA, and was produced from an extensive soil database through out the

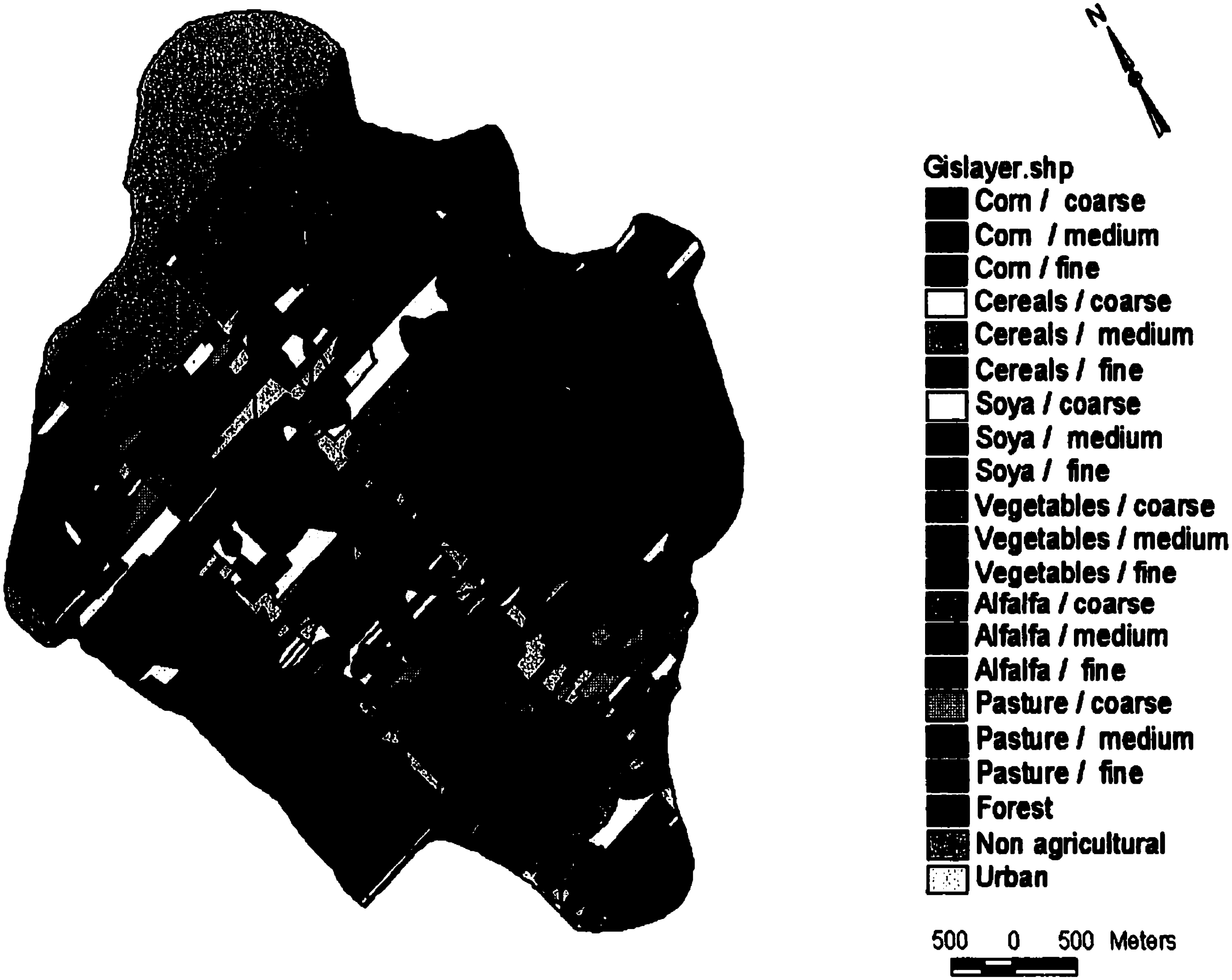


Figure 3.1 Saint Esprit watershed overlaid land use and soil texture layer

United States. The authors recommend the use of mean hydraulics soil properties in applying hydrological modelling of watersheds containing a wide range of soils. The use of this approach may lead to differences in the estimation of soil water parameters of approximately 15% to 20%. However this error can propagate through the estimation of ET by models, and reach 25% to 30% due to spatial variation in soil properties (Leenhardt, 1995). Mean values were assigned to soil groups according to the textural class in the original classification (14 classes). After reclassifying the soil texture layer, a weighted average field capacity (*fc*) and weighted average permanent wilting point (*pwp*) were calculated for each of the three classes using the following expression:

$$fc = [\sum_{i=0}^{i=n} A * fc_i] / TA \qquad [3.3]$$

where

fc = weighted averaged field capacity of the soil class (% vol.);

A = area of each polygon being reclassified into the class (km^2);

fc_i = field capacity of each polygon being reclassified into the class (% vol.); and

TA = sum of the area of all the polygons reclassified into the class (km^2).

The contribution of each polygon, in the characterization of water holding characteristics (*fc* and *pwp*) for a new class, was weighted proportionally to the area that it contributed to the class. Field capacity for each soil polygon class, expressed in millimeters, was calculated as follows:

$$FC = (fc * D_{rz})/10) \qquad [3.4]$$

where

FC = Field capacity of the soil polygon (mm); and

D_{rz} = Depth of the root zone according to land use (cm).

Available water

Available water in millimeters, for each soil class and land use combination, was obtained using the weighted average values of field capacity and permanent wilting point:

$$AW = (D_{rz}*((fc - pwp))/10) \quad [3.5]$$

where

AW = Available water (mm)

Maximum allowable depletion (MAD) is defined as the fraction of the available water depth that can be depleted without causing a detrimental effect on crop development or yield response. This factor reflects climatic, plant and soil relationships and economic considerations. The application of this concept has gained importance in the last two decades, where problems of water availability have in some ways shifted the interest of scientists to evaluate the impact of deficit irrigation schemes on the marginal crop marketable yield response. For the watershed, values of MAD were obtained from tables after Dorenboos and Pruitt (1977).

Ready available water (RAW), the fraction of the available water easily obtained by crops, can be estimated after a depletion factor (MAD) is set. The depth of water at which RAW occurs for a particular soil, is associated with the matric potential of water in the soil profile. RAW was obtained by the following expression :

$$RAW = AW * MAD \quad [3.6]$$

where

RAW = readily available water (mm); and

MAD = maximum allowable depletion factor (dimensionless)

Critical soil moisture content

The critical soil moisture content approach was applied to calculate crop water requirements (CWR). According to this, each soil type should be maintained over its threshold moisture in order to ensure satisfactory crop development, while avoiding undesirable reductions in crop yields and quality. This parameter was obtained by:

$$QC = (FC-RAW) \quad [3.7]$$

where:

QC = critical soil moisture content (mm);

FC = the field capacity of the soil (mm); and

RAW = the readily available water (mm).

3.4.1.3 Land use data

Depth of the root zone

Rooting depth is an important parameter in the estimation of the seasonal CWR and for scheduling crop irrigation. In agricultural soils, texture affects the soil water holding capacity and the development and penetration of the root system through the soil profile (Blanchard et al., 1978, cited by Keppler, 1990; Jones, 1983; and Keppler, 1990).

Background information was used to set typical values of rooting depth reported for agricultural crops grown in southwestern Quebec. Three ranges of root zone penetration, expressed as a restriction to the maximum penetration, were proposed. In this way, one range per class was set with respect to the reclassified soil map of the watershed. The higher rooting depth was then assigned to polygons containing soils classified as coarse (no growth restriction). Heavy-textured soils were assigned to the lower depth of root penetration by restricting by 20% the reported rooting depth. For medium-textured soils an intermediate restriction level (10 %) was assigned. This assumption follows the observations of Tennant (1976) and Jones (1983) on soil texture effects on root development.

Consumptive use coefficient

Consumptive use coefficients were obtained following the procedure described by Doorenbos and Pruitt (1977). Information regarding planting dates, duration of the growing season and the length of the crop development stages was obtained for the watershed (Enright, personal communication).

Crop consumptive use was divided into four stages for seasonal crops: initial, crop development, mid season and maturity. For pasture, a constant *kc* as described by Doorenbos and Pruitt (poor cultural practices) was assumed. In the watershed, alfalfa is grown for hay and harvested 3 times during the growing season. The *kc* for alfalfa was divided into two stages since it is harvested when *kc* is maximum, this means that no mid season or maturity stage was considered.

Initial stage consumptive use (k_{ci}) was calculated for each crop using the relationship between predetermined (ETp) and the average interval of recurrence of significant rain. Mid season *kc* (k_{cs}) and late season (maturity) (k_{cm}), were obtained from tabulated values presented by Doorenbos and Pruitt (1997), using a relative humidity greater than 70% and wind velocity between zero and five kilometers per hour. Values for intermediate stages, i.e. development stage (K_{cd}), were interpolated between the K_{ci} and the K_{cs}, and as well between k_{cd} and k_{cm}. Table 3.2 summarizes the information for *kc* and development stage assumed for crops in the watershed.

Table 3.2 Length of crop development stages and crop coefficients *kc* for agricultural crops in the Saint Esprit watershed

Crop	**Stage of Crop Development**								
	Stage 1		**Stage 2**		**Stage 3**		**Stage 4**		**Duration of Grow. Season**
	Duration[1]	k_{ci}	**Duration**	k_{cd}	**Duration**	k_{cs}	**Duration**	k_{cm}	
Corn	20	0.55	34	int[2]	41	1.05	39	0.55	133
Cereals	14	0.55	24	int	51	1.05	24	0.25	113
Soybean	19	0.55	35	int	40	1.00	24	0.45	118
Vegetables	20	0.55	20	int	30	0.95	11	0.80	81
Hay[3]	15	0.50	31	int	-	-	-	-	138
Pasture[4]	20	0.50	132	0.95	-	-	-	-	152

(1) Duration in days per growth stage

(2) Interpolated value through crop development

(3) Two grow stages considered. Harvested three times (46 days/cycle) during growing season

(4) Permanent, Kc is assumed constant after stage one for pasture growth under poor management

3.4.2 The soil-water budget routine for CWR estimation

All parameters described above were appended to the GIS database. The land use and soil texture layer combination (GIS-layer) was provided with information for estimating crop evapotranspiration (ETc). The routine to perform the water balance for the combinations of crops and soil types was written in ANSI C, and run for five years of data. CWR throughout the growing season was computed from the results of this routine. For every polygon in the combination layer, a daily time series of ETc and CWR was produced. The seasonal ETc and CWR (if required) were then computed using spreadsheets. Appendix 1 describes the operation of the routine, and Table 3.3 summarizes the parameters considered in the calculations.

3.4.3 Parameters required to apply the SLURP hydrological model

SLURP operates by reading a command file (.CMD) which contains not only the parameters characterizing the physical system but also several options for running the model. All parameters describing the physiography of the watershed are measured. These parameters were obtained by landscape analysis using GIS and the spatial database. Alternatively, parameters such as: initial contents of snow store, maximum capacity of the slow store, maximum capacity of the fast store, temperature lapse rate, precipitation lapse rate, albedos (surface, snow), leaf area index, and river geometry (when routing between sub-basins) can be either measured or estimated Kite (1998).

3.4.3.1 Climatic data

Along with the physical parameterization of the watershed, the SLURP model requires several files containing climatic time series. These measurements come from climatic weather stations, snow courses or are estimated from satellite imagery.

Mean temperature, relative humidity and sunshine hours are required by the SLURP model to compute actual evapotranspiration using Morton's (1983) complementary relationship areal evaporation concept (CRAE). Daily data on mean temperature and relative humidity were obtained from the weather station at Saint Esprit. Sunshine hours and percentage of maximum possible hours of sunshine were taken from measurements at the Dorval International Airport weather station, located approximately

40 km from the experimental site. Although this parameter could be estimated by rearranging the equation for solar radiation as recommended by Doorenbos and Pruitt (1977), it was believed that the results would not be any better than the records at the Dorval weather station.

Table No 3.3 Parameters used in the soil-water balance routine

Land use	Soil text	Drz_max (cm)	fc (%)	pwp (%)	MAD	AW (mm)	RAW (mm)	Qc (mm)
Corn	1	60	17.9	8.1	0.65	59.20	38.48	20.72
	2	54	31.0	17.4	0.65	73.34	47.67	25.67
	3	48	37.8	25.2	0.65	60.25	39.16	21.09
Cereal	1	60	17.9	8.1	0.65	59.20	38.48	20.72
	2	54	31.0	17.4	0.65	73.34	47.67	25.67
	3	48	37.8	25.2	0.65	60.25	39.16	21.09
Soya	1	50	17.9	8.1	0.65	49.33	32.07	17.27
	2	45	31.0	17.4	0.65	61.11	39.72	21.39
	3	40	37.8	25.2	0.65	50.21	32.63	17.57
Vegetable	1	40	17.9	8.1	0.5	39.46	19.73	19.73
	2	36	31.0	17.4	0.5	48.89	24.45	24.45
	3	32	37.8	25.2	0.5	40.17	20.08	20.08
Alfalfa (hay)	1	120	17.9	8.1	0.65	118.39	76.96	41.44
	2	108	31.0	17.4	0.65	146.67	95.34	51.34
	3	96	37.8	25.2	0.65	120.50	78.32	42.17
Pasture	1	60	17.9	8.1	0.65	59.20	38.48	20.72
	2	54	31.0	17.4	0.65	73.34	47.67	25.67
	3	48	37.8	25.2	0.65	60.25	39.16	21.09

Soil texture : 1 light, 2 medium, 3 heavy
Drz_max rooting depth according soil type
fc average field capacity of soil class
Pwp average permanent wilting point soil class
MAD maximum moisture allowable depletion
AW difference between fc and pwp
RAW ready available water for crops
Qc critical soil moisture content
fc depth of water at field capacity
Qc depth of water at critical moist. content

Daily precipitation, global radiation and mean air temperature were also obtained from the site station. Global radiation in SLURP version 11.2 must be expressed in $W/m^2/day$. The original units $MJ/m^2/day$ were converted to the required $W/m^2/day$.

Dew point temperature

Some relationships have been proposed for estimating the saturation vapor pressure based on daily records of temperature. Tetens (1930), Bosen (1960) and Murray (1967) had presented simple equations requiring only average daily temperature. The Murray equation was used to calculate the actual saturation vapor pressure in kPa:

$$e^{\circ} = exp\left[[16.78\ T - 116.9\ ] / [T + 237.3]\right] \quad [3.8]$$

where

e° = actual saturation vapor pressure; and

T = average daily temperature (°C).

Saturation vapor pressure at dew-point temperature was estimated from e° and measurements of relativity humidity, using a relationship described by Doorenbos and Pruitt (1977) and Michael (1978):

$$e_d = (e^{\circ} * 100) / rh \quad [3.9]$$

where

e_d = air saturation vapor pressure at dew-point temperature; and

rh = relative humidity (%).

Dew-point temperature was estimated after e_d values were known. Rearranging equation 3.9, the inverse of a version of Teten's equation optimized for dew points in the range of –35 to 50 °C was as follows:

$$T_d = \{[C_3 * (\ln(e_d\ / C_1\ ))] / [C_2 - (\ln(e_d / C_1))]\} \quad [3.10]$$

where

T_d = dew-point temperature.

The best approach to generate parameters not measured at the site, was to obtain them from neighboring stations. Therefore, daily bright sunshine hours was obtained from the Dorval weather station (Environment Canada monthly meteorological summaries, 1994-1998). Cloud cover was estimated from the daily sunshine hour data and the ratio of actual to maximum possible sunshine hours *(n/N)*, as follows:

$$\% \, Cloud\ cover = [((N\text{-}n) * 100)/N] \qquad [3.11]$$

where

N = Maximum possible sunshine (hours); and

$(N\text{-}n)$ = Difference between maximum possible and actual sunshine (hours).

The long term mean annual precipitation (MOR file) was computed from the total annual precipitation in the watershed during the period 1994 to1998.

Since one weather station operates in the watershed, the climatic time series used to calibrate and run the model were common to all the sub-basins (ASAs). SLURP users can assign interpolation weights (weight file) to each ASA according to the relative influence of each weather station to the ASA. In this implementation all sub-basins were assigned a weight equal to one. The model also features user-defined lapse rates for temperature and precipitation change with elevation. These two parameters were set to zero, considering the nature of the topography and the size of the watershed.

Snow-covered area

A linear relationship was assumed between the depth of snow and the areal coverage of snow in the watershed. This simplified solution was assumed because of the lack of distributed snow data (i.e. from snow course) in the watershed.

3.4.3.2 Hydrological data

A gauging station installed at the outlet of the watershed, provided the measured water levels using a DRUCK 950 submersible pressure transducer (0 to 0.35 kg/cm^2 range) buried in the bottom of the stream. An ultrasonic level sensor (UDG01) installed downstream, assessed the change in water level through the control section. A CAMPBELL CR10 data-logger was used to monitor both sensors. An independent secondary flow measurement system (FLOWLOG data-logger) in the control section, measured the flow velocity and depth in the stream. The hydrological data were recorded every 15 minutes.

3.4.3.3 Soils data

Maximum infiltration rate

The infiltration rate affects the land surface processes of the hydrologic cycle. Hydraulic conductivity in the unsaturated zone significantly influence the soil moisture content and the actual evapotranspiration (Refsgaard, 1997). Areal estimates of *Ks* for the three reclassified soil textures could be estimated based on tabulated information (Rawls et al., 1983) and (Jeton and LaRue, 1993) in the PRMS model. However, in SLURP this parameter is defined once for each land use type, regardless of such variability as might occur in the physical properties of the soil, between sub-basins. Therefore, the initial values of maximum infiltration rate for each land use, were set according to the predominant soil type in which the land use existed.

3.4.3.4 Land use data

Leaf area index

The model required beginning of month leaf area index (LAI) for each land use in the watershed. Estimations of this parameter, were based on the linearity between the normalized difference vegetation index (NDVI) and LAI (Wiegand, 1979; Tucker, 1980; Ajai, 1983; Yin and Williams, 1997), and the similarity between the Deering's (1978) corn seasonal curve of NDVI and the Wright (1982) basal consumptive coefficient (k_{cb}).

Daily crop consumptive use values (*kc*) in the watershed, were linearly correlated with maximum and minimum LAI values reported in the literature. Best-fit curves between the estimated LAI and the number of days after planting were used to obtain a close representation of LAI for each crop throughout the growing season. The LAI for forest, was set to values recommended by Kite (1998) in the SLURP manual. Figure 3.2 shows the estimated LAI for corn.

Maximum capacities and retention constants for each land use

Parameters such as maximum capacities and retention constant for the fast and slow store were estimated. Values recommended by Kite (1998) in the SLURP manual, for agricultural and forestland were initially used. The estimated values did not exceed the permissible range designed in the model. Table 3.4 shows the initial parameters values ($P_{(1)}$ to $P_{(10)}$) for different land uses, before calibration.

3.4.3.5 Physiographic parameters

Watershed delineation

The SLURP model requires physiographic data such as: sub-basin areas, distances and elevations (Kite, 1998). Physiographic information can be generated using two different approaches:

1. An approach using GIS and the modular TOPAZ (Topographic Parameterization) for automatic DEM processing and watershed delineation. The procedure automates sub-basins and drainage network delineation. TOPAZ is a public domain terrain-modelling tool, developed by Garbrecht and Marzt (1993);

2. A GIS approach, conducting a series of analyses in which the digitized drainage network (vector file) is converted to a topological network. This allows for distances calculation and flow travel time (cost), from each land use in a sub-basin (ASA) to the nearest stream, and then to the sub-basin outlet (see Figure 3.3).

SLURP structures the watershed in a way that elements such as ASA's outlets, the channel network and terrain elevations are explicitly represented. The existing sub-basin

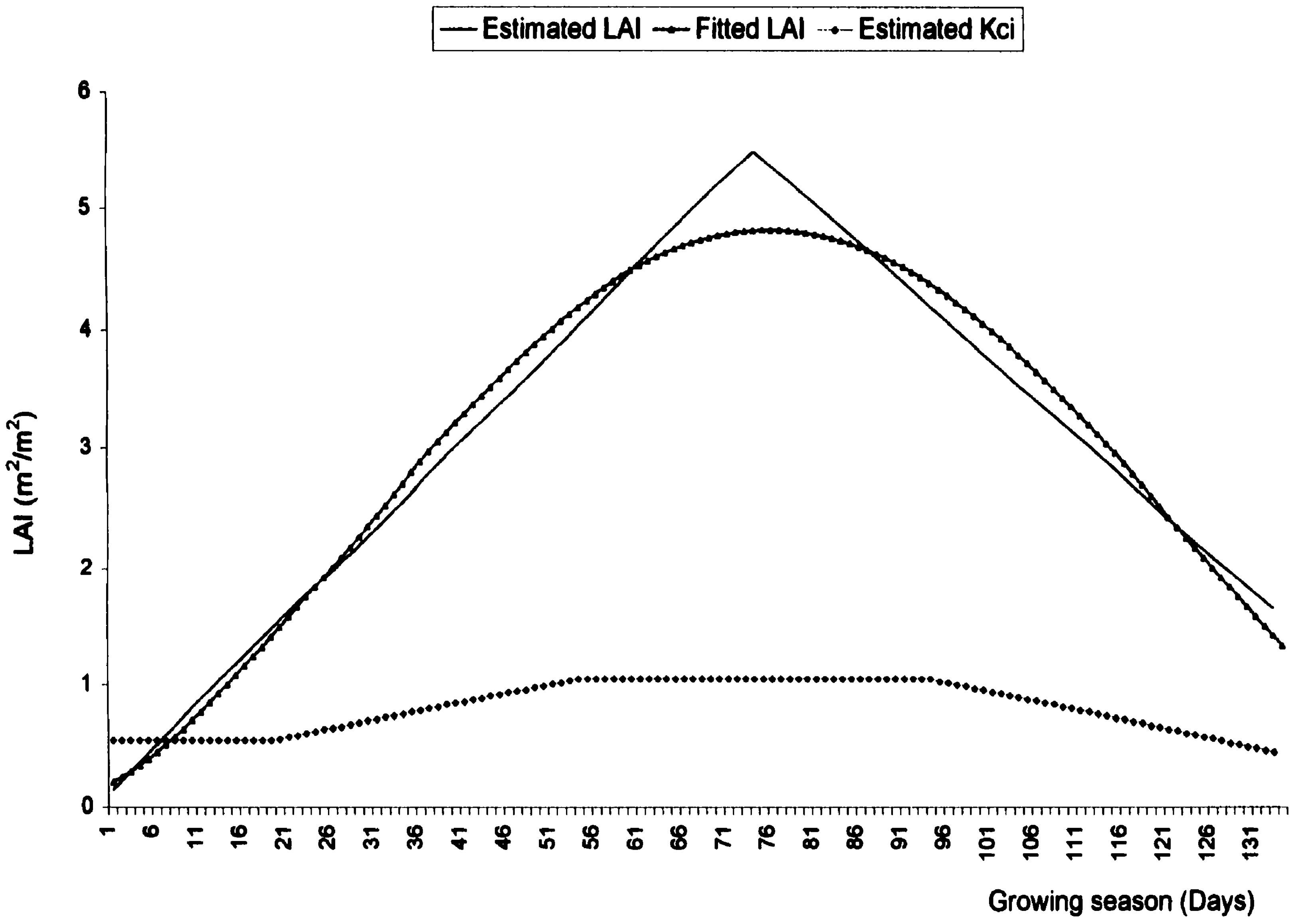


Figure 3.2 Estimated growing season LAI - corn for the SLURP model

Table 3.4 Initial model parameter values before calibration

Parameters P_1 to P_{10} for land-uses									Range Min.	Max.
Corn	**Wheat**	**Soybean**	**Vegetables**	**Alfalfa**	**Pasture**	**Forest**	**Bare**	**Urban**		
	P_1 INITIAL CONTENT OF SNOW STORE (mm)								1.0	1.000
200.0	200.0	200.0	200.0	200.0	200.0	300.0	200.0	10.0		
	P2 INITIAL CONTENT OF SLOW STORE (%)								0.0	100
65.0	60.0	50.0	60.0	60.0	50.0	50.0	50.0	10.0		
	P3 MAXIMUN INFILTRATION RATE (mm/day)								10	100
70.0	65.0	60.0	60.0	70.0	80.0	90.0	50.0	30.0		
	P4 MANNING ROUGHNESS, n								0.0001	0.1
0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001		
	P5 RETENTION CONSTANT FOR FAST STORE (1)								1.0	50
25.0	25.0	20.0	21.0	25.0	20.0	35.0	15.0	12.0		
	P6 MAXIMUM CAPACITY FOR SLOW STORE (mm) (1)								10	500
250.0	250.0	300.0	200.0	225.0	240.0	400.0	200.0	100.0		
	P7 RETENTION CONSTANT FOR SLOW STORE (1)								10	300
180.0	180.0	150.0	150.0	150.0	150.0	220.0	130.0	100.0		
	P8 MAXIMUN CAPACITY FOR SLOW STORE (mm)								10	1000
400.0	400.0	400.0	400.0	400.0	400.0	500.0	400.0	200.0		
	P9 PRECIPITATION FACTOR (1)								0.8	1.5
1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0		
	P10 RAIN/SNOW DIVISION TEMPERATURE (DEG.°C)								-2.0	2.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0		

(1) SLURP model high sensitive parameters (Kite, 1998)

and channel network digital maps, produced by Mouzavizadeh (1998) were used for this purpose. Using approach number one, the GIS assisted in generating parameters required for the model to route the flow inside each sub-basin. The physiographic parameters required by SLURP were the following statistics:

1. Mean and standard deviation of the distances to the nearest stream for each land use;
2. Mean and standard deviation of the distances along the stream to the ASA outlet for each land use;
3. Average change in elevation to the nearest stream;
4. Average change in elevation to the ASA outlet;
5. Average ASA latitude and elevation.

In the semi-distributed approach, the model works with averages and standard deviations of the information obtained by means of the GIS, instead of implementing a more specific watershed grid partitioning such as in the case of completely distributed models. The GIS method led to the generation of two files describing the watershed system. The (.PNT) point file, which is drawn from the digitized channel network and the (.GRD) file, a sampling point file containing information on elevation and land use. The procedure to generate both files is briefly described in Appendix 2.

3.5 Calibration, evaluation and performance of the SLURP model

Model calibration

Although the majority of hydrological models have used manual calibration for matching known hydrological data sets in the past, there has been a move towards the implementation of automatic calibration procedures. This process has been favored by the performance of new computers and also by the need to improve calibration techniques required by more sophisticated models (distributed multi-parameter). When modelling complex systems such as in hydrology, automatic calibration assists modelers

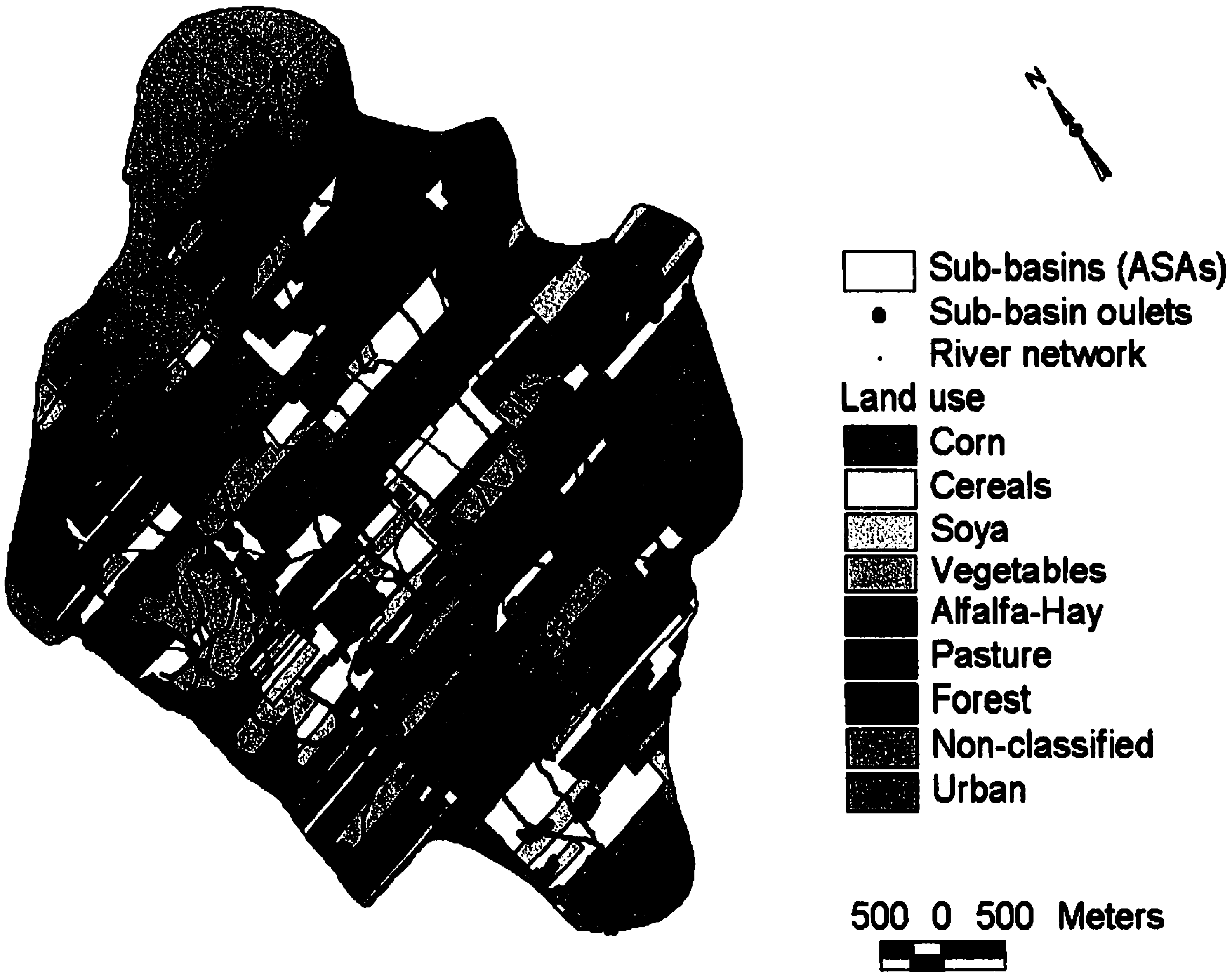


Figure 3.3 Physiographic components of the SLURP watershed model

by finding parameter combinations that minimize the differences between observed and measured runoff. SLURP incorporates the Shuffled Complex Evolution method (SCE-UA; Duan et al., 1994) for automatic calibration. Sorooshian et al. (1993) described the SCE-UA as an efficient optimization method.

The SCE-UA is a global optimization method offering the best features from several earlier optimization techniques. It combines the strength of the Simplex deterministic procedure (Nelder and Mead, 1965; cited by Gan and Biftu, 1995) and the ability of the multiple start simplex (MSX) a probabilistic, global optimization method, which run the Simplex strategy at randomly starting points in the feasible parameter space (Gan and Biftu, 1995). The procedure works dividing the sample of all possible parameter values into a number of communities or complexes, each containing a specified number of points. Each complex is allowed to evolve independently using a modified Simplex process. After a specified number of steps (user defined), the points within the complexes are shuffled to form a new set of complexes each containing a number of points from the previous generation of complexes. In this way the complex shuffling process reduces the risk of optimizing to a local optima that may exist (Duan et al., 1994) and made this calibration method very suited to hydrological models.

The goodness of the points, are based on the sum of squares error of the model, which is evaluated through the (R^2) Nash and Sutcliffe coefficient of performance in the SLURP model (objective function). A large number of complexes and a short duration between reshuffling will search out a wide area, a large number of points per complex will search out smaller areas in greater detail. At each shuffle, the worst point in each complex is changed. First, the centroid is calculated from all the points in a complex except the worst one. The worst point in the complex is then reflected about the centroid and the new set is tried in the model (Kite, 1998). If that does not provide a better result, a point is calculated half way between the worst point and the centroid. If that also does not provide a better result, another point is generated using a random number (mutation) from the computer time system.

Algorithms in the search technique of the SCE-UA use genetic methods for constructing new sets of points (sub-complexes). Sub-complexes are constructed by taking sets of points from the original complex using a trapezoidal probability, such that points with a better function value have a higher chance of being chosen to be in the sub-complex than those points that are not as good (Duan et al., 1994).

The number of parameters in the optimization is dependant upon the number of land covers in the basin as well as the number of ASAs, if routing is to be optimized (muskingum coefficients x, K). The parameters optimized in this study are shown in table 3.4. A set of parameters such as: temperature lapse rates with elevation, precipitation factor, and snow melt temperature can be more easily manually calibrated in case that no direct measurements exist. This is why these parameters are not included in the automatic calibration option.

Based on a total of five years of climatic data, the SLURP model was calibrated using three years of records, April 1994 to December 1996.

Model evaluation

By using the (SCE-UA) calibration method, parameters were adjusted automatically as described above to reproduce (as possible) the observed flow in the watershed. Data from 1997 to 1998 were used for model evaluation. A daily output option with non-external flow routing (between sub-basins) was selected.

Model performance

Besides the simulated graphical hydrograph produced by SLURP, other statistical tools are available to evaluate the goodness of fit of the model's output (Kite, 1998). The Nash and Sutcliffe (1970) R^2 efficiency criterion was selected to evaluate the performance of the model during the simulation period. This method allows for comparison of the observed flow and the simulated flow during the evaluation period, and is given by:

$$F^2 = (F^2_m - F^2_d) / F^2_m \qquad [3.12]$$

where

$$F^2_m = 1/n \sum_{i=1}^{n} (q_i - \bar{q})^2 \qquad [3.13]$$

$$F^2_d = 1/n \sum_{i=1}^{n} (q_i - c_i)^2 \qquad [3.14]$$

where

F^2 = Nash and Sutcliffe efficiency criterion;

F^2_m = sum square of differences between daily observed and mean runoff;

F^2_d = sum square of differences between daily observed and predicted runoff;

q_i = measured flow on day i (mm);

c_i = simulated flow on day i (mm); and

$\bar{q}$ = average measured flow (mm).

Results of the Nash and Sutcliffe (1970) efficiency criterion values can range from zero to one, one being a perfect match between daily observed and daily predicted runoff and zero being a complete mismatch. On the monthly, seasonal and annual basis, a simple percentage deviation of runoff was used to compared the observed versus the predicted runoff.

4.0 RESULTS AND DISCUSSION

4.1 Results of SLURP calibration

The model was calibrated using initial parameters as presented in Table 3.4. The SLURP model has 10 calibrated parameters for which the user inputs values for the initial conditions within a range (maximum and minimum values) internally defined in the model. The rest of the parameters were calculated or estimated.

The calibration was executed by a combination of techniques (Refsgaard and Storm, 1996): (i) using an automatic optimization routine (SCE-UA; Duan et al., 1994) performing 5000 iterations, and (ii) manual adjustment (trial and error) of parameters not included in the automatic optimization. The best combination of parameters found was saved into a new command file to be used during the validation period.

The calibration was run for the period of April 1994 to December 1996. The goodness of fit of the predicted versus observed runoff during this period yielded a Nash/Sutcliffe (R^2) criterion coefficient of 0.522. The percent difference during the same period, between observed and predicted runoff was 17.57 %. The complete water balance of the watershed predicted from this calibration is presented in Table 4.1. Daily-observed runoff as compared to the SLURP predicted runoff during calibration, is shown in figure 3.A, in Appendix 3.

Previous studies using SLURP (Kite, 1995; 1996) have discussed the sensitivity of model performance to changes in parameters (see Table 3.4). All these parameters were included in the automatic optimization routine (Duan et al., 1994). It seemed reasonable that using a large number of iterations in the automatic optimization routine, would increase the opportunities to find an effective combination of parameters. Snowmelt rate (mm/°C/day) a highly sensitive parameter to model output, was calibrated manually. Snowmelt rate can be estimated for specific conditions and land uses in watersheds. Melt-rate is highly variable, and dependent on temperature and climatic conditions such as rain, wind, and seasonal variability (USACE, 1998).

Table 4.1 SLURP predicted water balance over the entire basin after calibration for April 1994 to December 1996

Parameter	(mm)
Mean basin precipitation	2756.00
Mean basin evapotranspiration demand	1687.00
Mean predicted evaporation	562.50
Mean predicted transpiration	842.40
Predicted runoff at basin outlet	1452.00
Predicted runoff still in transit	6.78
Total recorded runoff	*1761.00*

A series of manual optimizations were performed to investigate better melt rate values to be assigned to land uses for January and July, as required by the model. Table 4.2 shows the effect of melt rate on model response. After several runs, it was observed that quantitative variations in runoff caused by different melt rates were almost negligible on an annual basis. However, the Nash/Sutcliffe R^2 coefficient showed that runoff distribution over time (hydrograph) was greatly affected. Small changes in melt-rate values caused proportionally larger differences in the time of arrival between the predicted runoff and the observed runoff at the outlet.

Table 4.2 Sensitivity analysis of melt-rate parameter (mm/°C/day)

January	July	R^2 criterion
0.0	2.0	0.476
0.0	3.0	0.513
0.8	3.3	0.522
0.0	4.0	0.527
1.0	2.0	0.485
1.0	3.0	0.518
1.0	4.0	0.514
2.0	2.0	0.487
2.0	3.0	0.512
2.0	4.0	0.501

4.2 Results on the estimated ET and CWR using the Baier & Robertson model

The Baier and Robertson (BR) ETp model, (Rochette, 1990) was applied to the watershed using the climatic data corresponding to the growing season, for five consecutive years: 1994 -1998. This model had been calibrated for the region and provides good ETp estimates in the watershed (Barnett et al., 1998). Annuals ET estimates are presented in Table 4.3.

Table 4.3 Baier & Robertson model estimated annual ETp in mm

	1994	1995	1996	1997	1998
Annual ETp (mm)	575.4	586.5	563.5	571.9	577.1

Daily values of BR-estimated ETp were used to calculate water crop consumptive use by applying selected crop coefficients according to land use and crop development stage. Figure 4.1 shows BR- estimated long term average daily ETp as compared with the average corn ETc in the watershed. According with the results of the BR model, the maximum ETp value (5.53 mm/day) occurred on June 09 for both 1997 and 1998. SLURP estimated peak ETp on June 08 and 09 in 1997 and 1998, respectively. Both ET models include the effect of solar radiation. The BR model considers extraterrestrial solar radiation (*Ra*), whereas the modified Penman equation in the CRAE method used in SLURP uses net radiation (*Rn*). This response is concurrent with the maximum incidence of radiant energy during this period of the year at the watershed location.

After running the BR- ETp model, parameters needed to implement the soil-water balance routine were calculated as described in Chapter 3. The daily estimated ETp was input into the soil-water balance routine. This routine was run for five years to investigate CWR during the growing season and irrigation requirements at the field level under different agricultural land uses. Irrigation was not required for all combinations of land-use and soil texture. The soil-moisture budget technique was implemented using a water balance routine. During the growing season, even lighter soils in the watershed maintained soil moisture contents above critical levels.

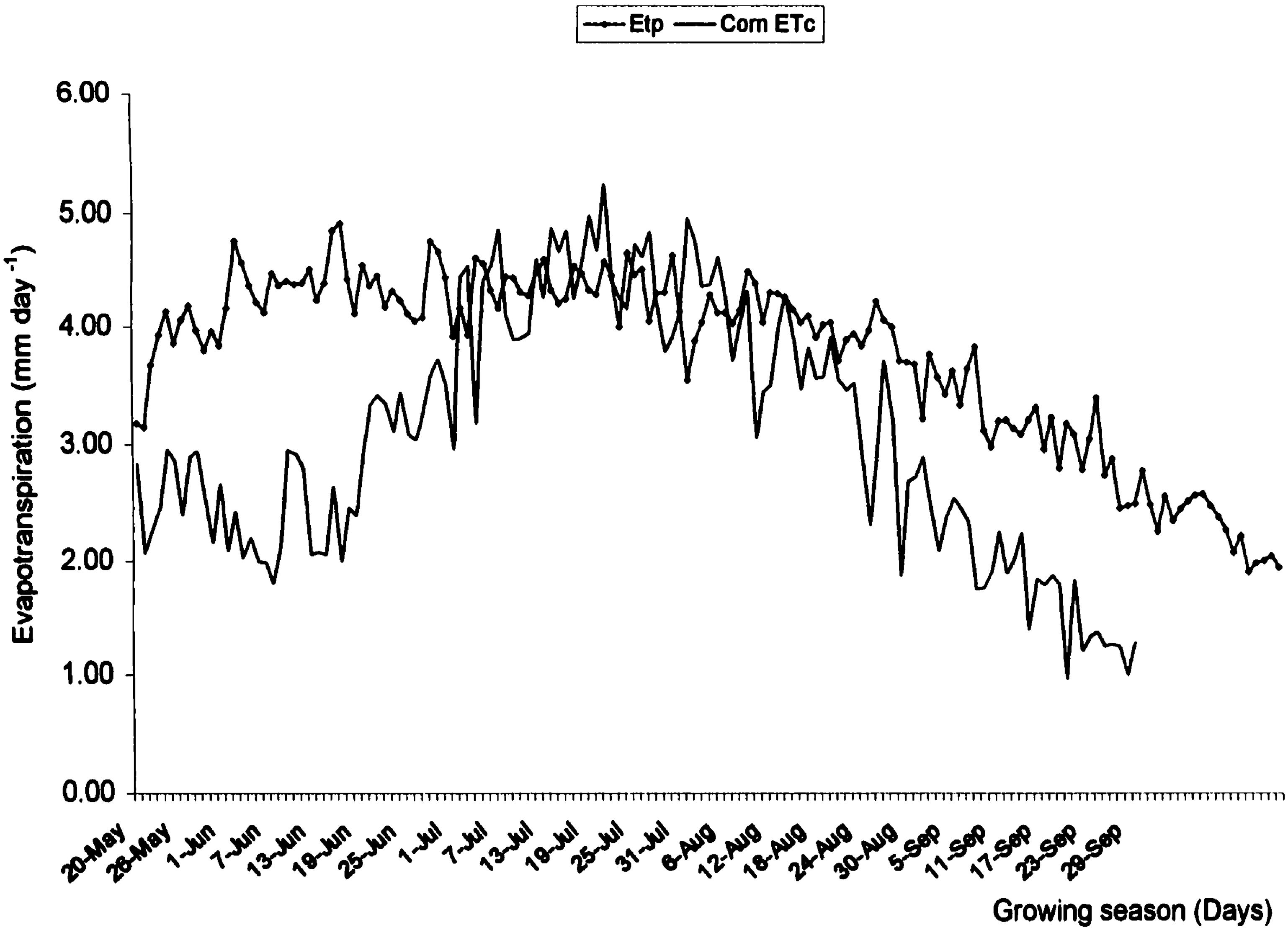


Figure 4.1 Baier and Robertson watershed average ETp versus crop consumptive use ETc

These results are consistent with the use of a rain-fed agricultural system on the watershed. Only for vegetable crops, is some irrigation being practiced in the watershed; However, this irrigation is not generally driven by concerns of water deficits. Rather it is used at transplant time in the spring/summer to attain the desired plant populations, and in the fall to maintain production scheduling (especially in broccoli) for the local processing plant (Enright, personal communication).

All simulations started with soil moisture content at field capacity. Crop development was simulated using dynamic crop consumptive use coefficients and depth of root zone. An example of a simulation used to determine crop water requirements is shown in Figure 4.2. This, combines corn on light soils during the 1998-growing season, and shows the regular pattern for estimated CWR in the watershed. Once crops are established (May), the available water increases steadily following the simulated root zone development pattern. Although atmospheric demands increase throughout the growing season, precipitation (about 36% of total annual during the season) and soil moisture content, are able to meet the seasonal crop water demands without reaching critical conditions for crop development (see Table 3.4). Figure 1.A in Appendix 1, shows seasonal CWR (ETc) in the watershed for the different agricultural land uses. These values agree with those reported by Rochette et al. (1990). However, in contrast to our findings, Rochette et al. (1990) and Singh et al. (1995) reported water deficits during the growing season in southern Quebec.

4.3 Results of SLURP validation

The composite rather than sub-basin level results of the model (evapotranspiration, snowmelt, and runoff) are discussed here. This approach lies in the availability of runoff data only at the watershed outlet for comparison purposes. However, this is sufficient for the objectives proposed in this investigation. The validation period was carried out for two years: January to December for 1997 and 1998. Validation was conducted using parameter values obtained during the calibration process.

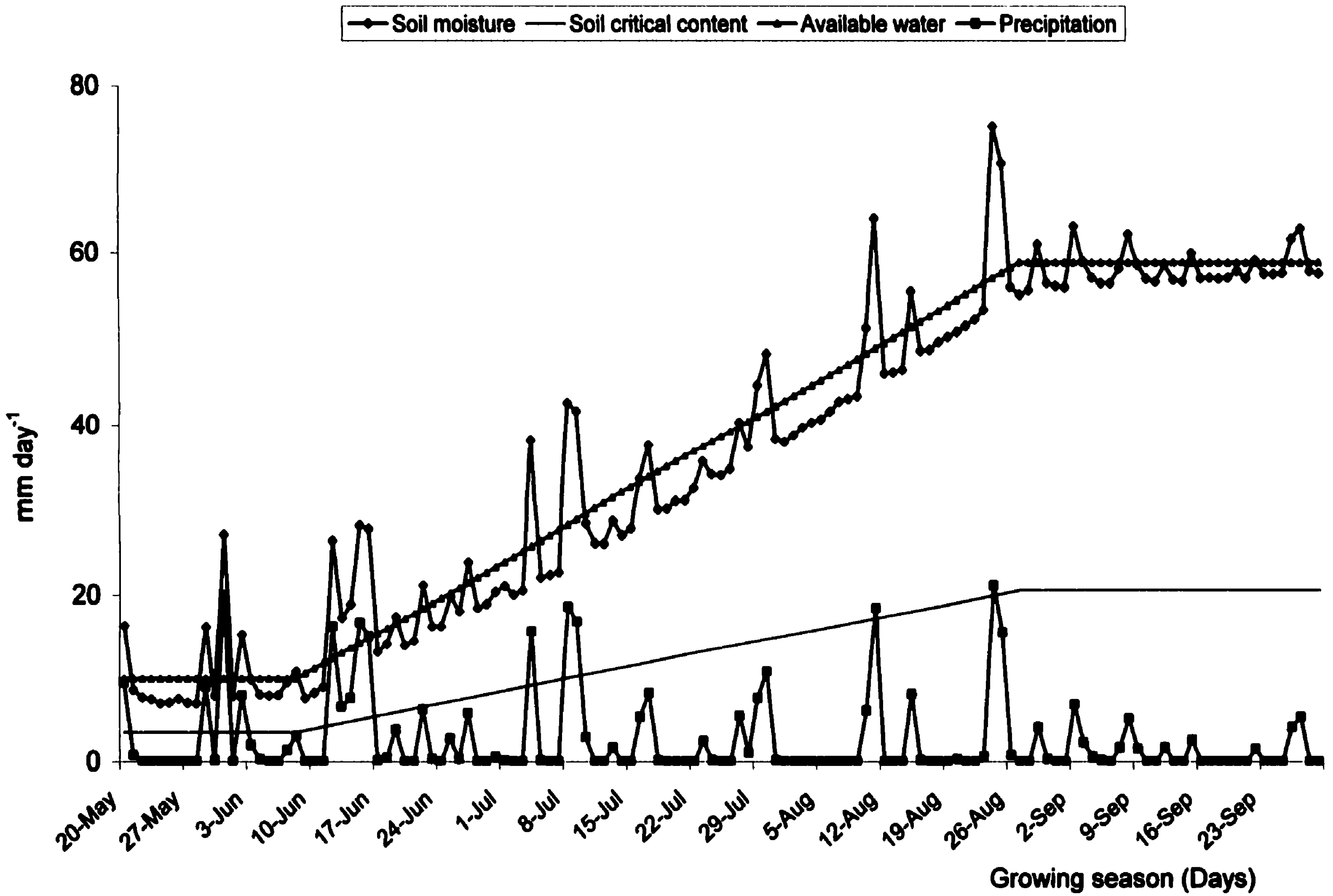


Figure 4.2 Simulation of corn seasonal water requirements on light soils for 1998

4.3.1 Evapotranspiration (ET)

Areal estimates of actual evapotranspiration in a manner similar to other model outputs (runoff, snowmelt) were carried out in a semi-distributed manner. SLURP estimated actual ET over each ASA, using the relationship from potential evapotranspiration and wet environment evaporation described by the Morton (1983) CRAE model. Predicted values of annual ET in 1997 varied from 634.76 mm (ASA 08) to 466.04 mm (ASAs 01 to 03). The basin areal average ET for 1997 was 535.6 mm. This was computed from the predicted annual ET values at 18 ASAs. In 1998 the basin areal ET was 589.1 mm ET values varied from 667.5 mm (ASA 08) to 498.1 mm (ASAs 01 to 03). The model predicted positive evapotranspirative demand from March to November.

Differences in the simulated ET reflected the combined effect of parameters such as LAI, which influenced the canopy storage over time at each ASA. At the same time, LAI defines the duration of the growing season in SLURP. Physiographic factors such as differences in mean ASA elevation causes an internal adjustment in precipitation, dew point temperature and air temperatures when calculating ASA average climatic data using the SLURP option 2.

This could explain why ASAs 01 to 03 (land use bare), assigned lower LAI values throughout the year, yielded lower simulated ET estimates than those of the remaining agricultural ASAs. Table 4.4 summarizes the average predicted monthly ET for 1997 and 1998. The predicted crop transpiration during the non-growing season was computed as zero by the model. Soil evaporation was either zeros or represented a very small quantity. As soon as the growing season began, the soil evaporation and crop transpiration (from agricultural or forestland) rose according to biomass accumulation in the watershed (see Figure 4.3).

4.3.2 Long term comparison between SLURP-predicted and Baier & Robertson predicted evapotranspiration

Given the importance of evapotranspiration in the hydrological cycle, results of ET estimated by the Baier and Robertson model were compared to ET predicted by the

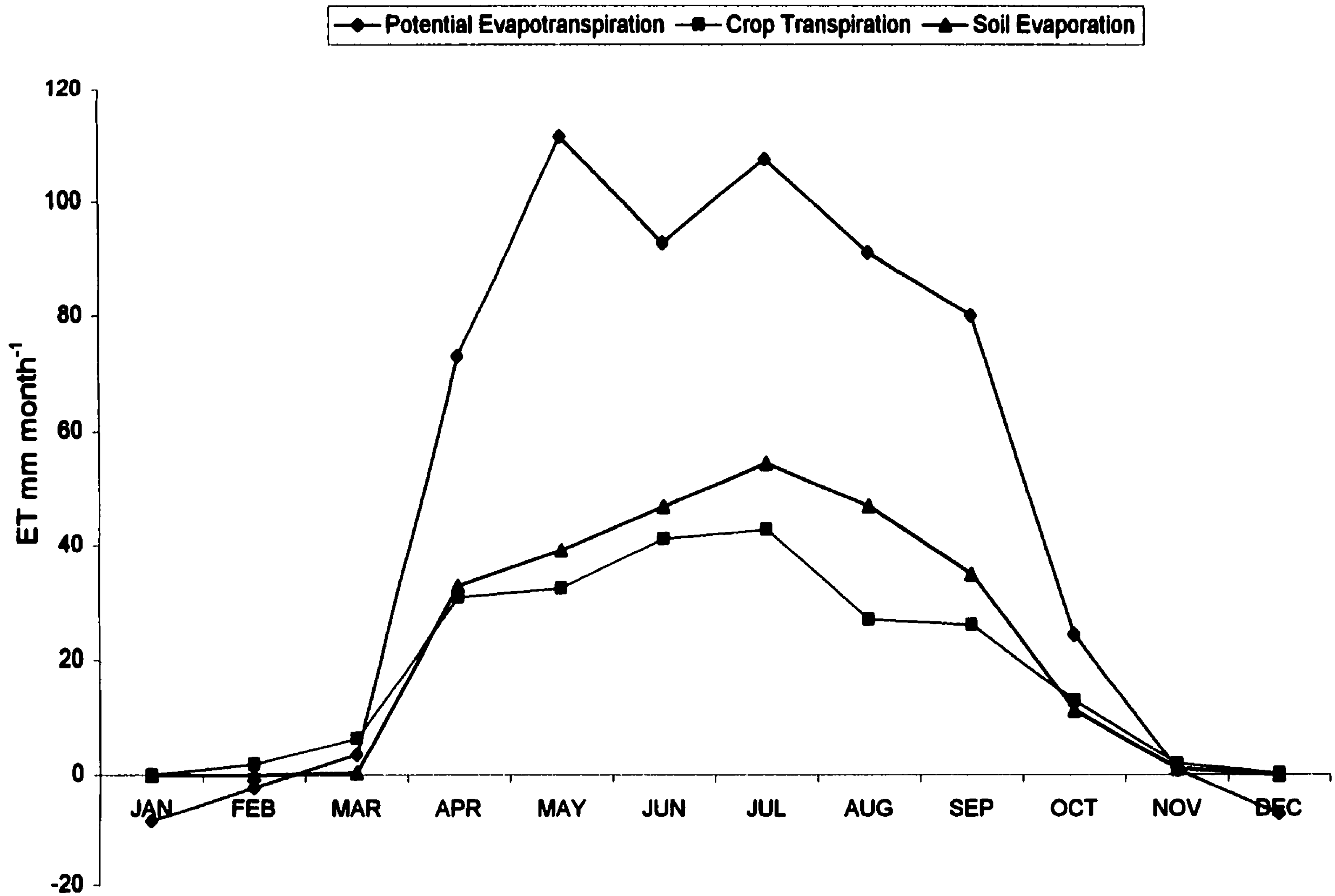


Figure 4.3 SLURP predicted evapotranspiration,crop transpiration and soil evaporation for1998

SLURP model. There is sufficient evidence (as presented in Chapter 2) showing that the B-R model works well at this site, and therefore, provides results accurate enough to be compared or to evaluate the performance of others ET models at Saint Esprit. It is recognized that the best evaluation is to compare the model predictions with ET measured at the site. However, there was no evaporation pan at the site, to compare the measurements with the predictions.

Table 4.4 SLURP predicted average monthly ETp

	ET Demand (1997)	ET Demand (1998)
JAN	0.0	0.0
FEB	0.0	0.0
MAR	2.2	6.1
APR	39.1	72.8
MAY	74.1	111.6
JUN	139.6	92.9
JUL	116.6	107.5
AUG	90.0	91.4
SEP	46.4	80.1
OCT	23.5	24.3
NOV	2.6	2.4
DEC	0.0	0.0

To carry out this evaluation, seasonal average ET data from 1994 to 1998 was used. The SLURP model computes actual ET (equation 2.13) while the BR model estimates potential ET (equation 3.1). For comparison purposes it was necessary to convert the potential ET from the BR model into actual ET, in order to perform a meaningful comparison. A practical way to achieve this, relied on the assumption that we could obtain a representative ET (i.e. the average seasonal ET_{corn}) calculated for CWR purposes using the BR model. This assumption allowed the use of the corn consumptive coefficient (k_c) to convert the potential ET estimates of the BR model, to estimated actual ET values. A statistical analysis using the Student t-test, was applied to verify for differences between the seasonal ET means computed by SLURP and the BR model. The t-test was performed to evaluate the hypothesis that, the average ET for both models was not different over the growing season. The results of the *t*- test are presented in Table 4.5. No significantly differences (P >0.05) were found between the means compared independently for each year. This finding allows us to state that SLURP estimates of actual evapotranspiration in the watershed, are as well as those predicted by the BR model.

Table 4.5 Comparison of seasonal averages of ET (mm) from SLURP and the BR Model, based on Student t-Test

	Mean ET (mm)				
Model	1994	1995	1996	1997	1998
SLURP	3.05	3.32	3.03	3.22	3.12
BR Model	3.09	3.15	3.04	3.12	3.09
P	0.79	0.29	0.95	0.57	0.82

4.3.3 Snowmelt

In southwestern Quebec, approximately 20% of the total precipitation occur in the form of snow. The spring snowmelt is usually the major annual hydrological event in the region. Spring snowmelt was the most important hydrological event on the Saint Esprit watershed in four out of five years of records. Using the SLURP model, simulation of the snowmelt processes and its effect on total runoff were studied.

Maximum snowmelt usually occurs between the last week of March and the first week of April (Gangbazo, 1997) but may vary depending on the conditions of the snowpack and winter temperatures in the region. For two years of validation, the model's prediction of the timing of the snowmelt was accurate. Figures 4.4 and 4.5 show daily snowmelt yields for the entire basin during the validation period. Snowmelt yields averaged 352.5 mm in 1997 and 269.5 mm in 1998 respectively. As SLURP runs in a semi-distributed mode, it predicted daily snowmelt occurring in the matrix of land uses and sub-basins. The snowmelt calculation method was the degree-day approach. The model interpolates the calibrated snowmelt rate between January 01 and July 01 for every land use, using a parabolic interpolation. Although it is not likely in this region to have snow after April, the model has been designed to account for this possibility, as it was initially developed for applications in rangeland watersheds. However, the snowmelt modelling is

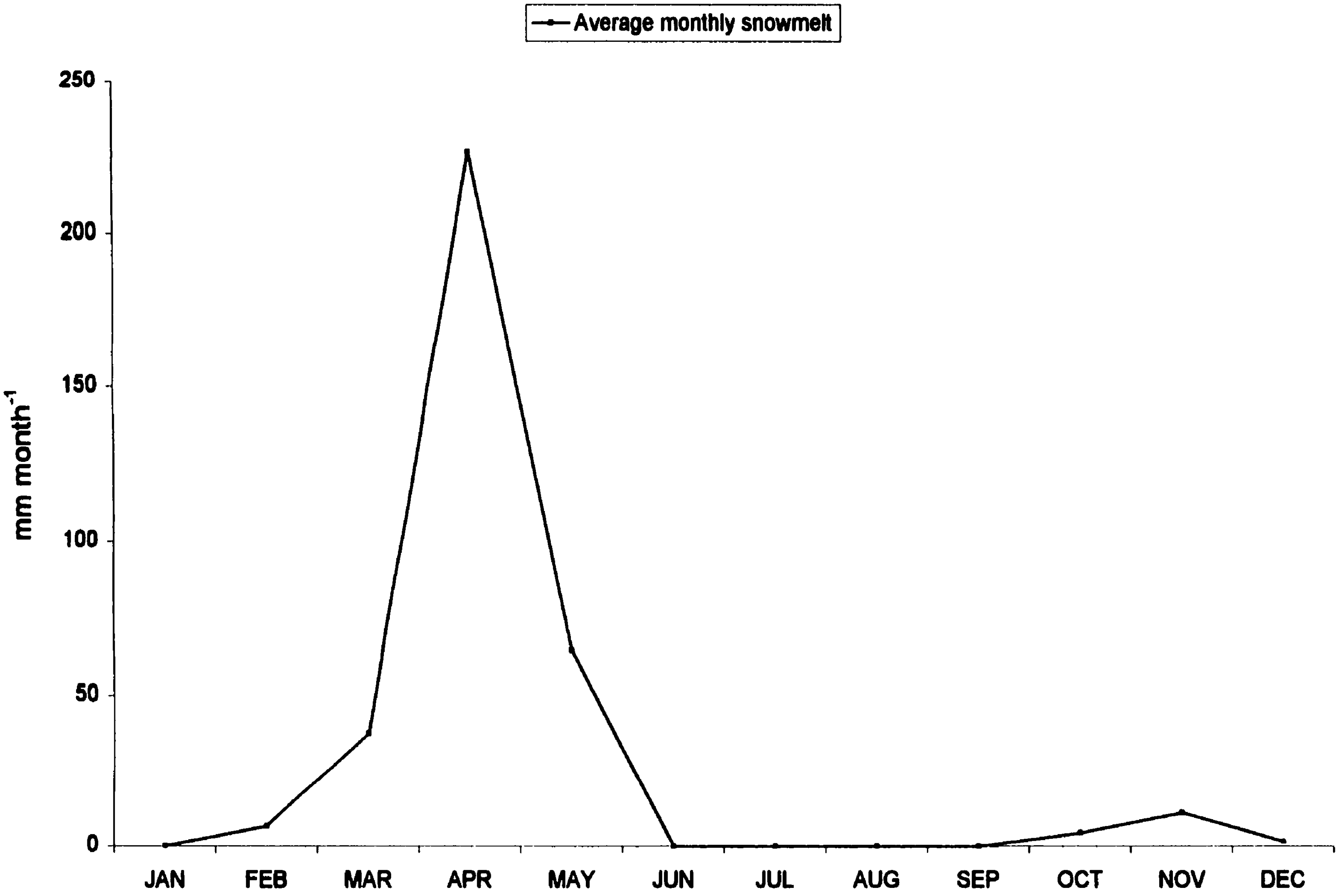
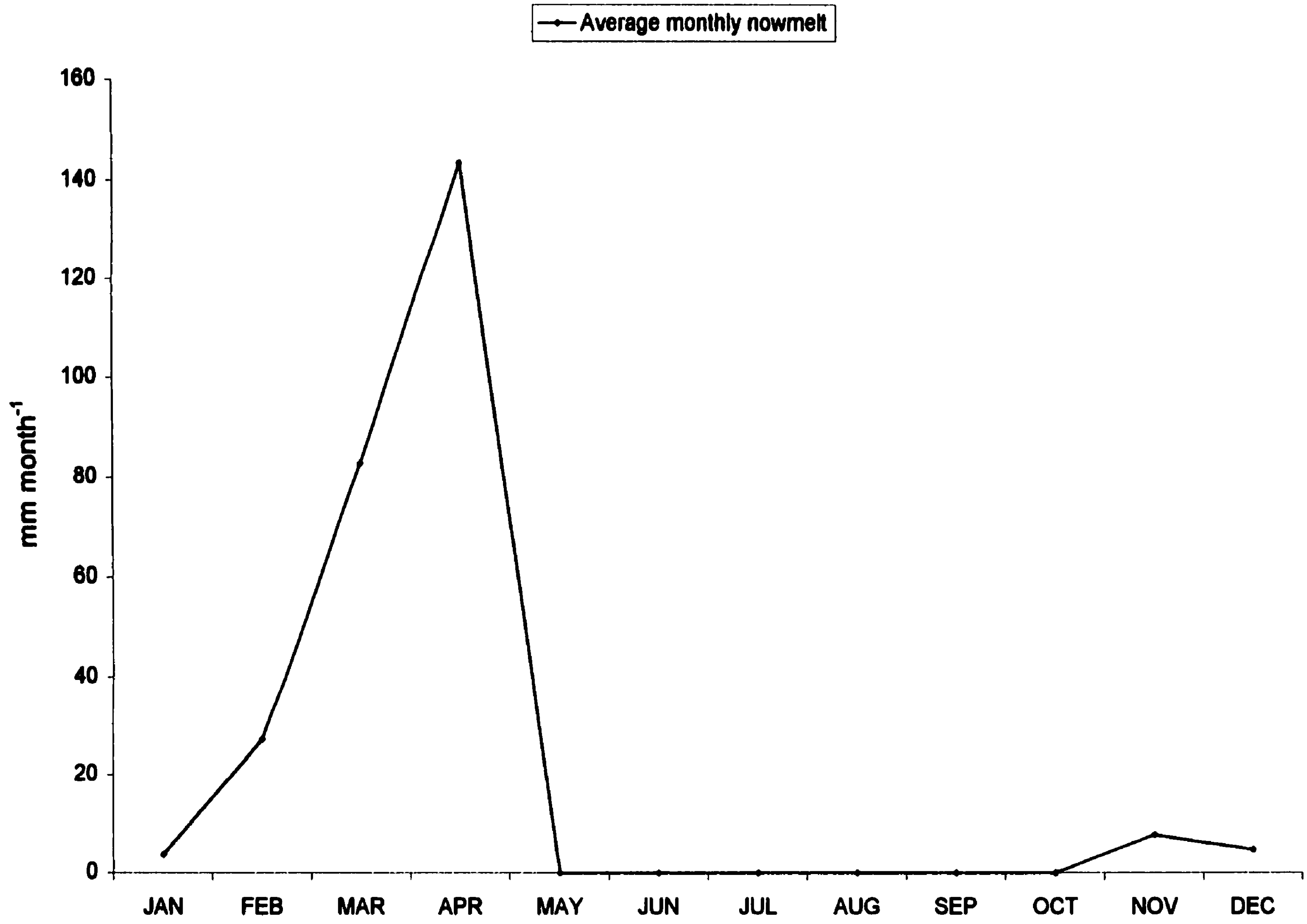


Figure 4.4 Results of monhtly predicted snowmelt for 1997



4.5 Results of monthly predicted snowmelt for 1998

internally governed by the information contained in input files for snow-covered area and temperature.

Considering the size and the relatively flat topography of the watershed, factors such as elevation, slope and aspect, did not seem to play an important role in defining different melt rates for each land use in the Saint Esprit watershed. Therefore, a single calibrated melt rate value was utilized. Melt rates of 0.8 mm/°C/day and 3.3 mm/°C/day were assigned to all land uses for January and July, respectively.

In general, model predictions were in good agreement with regards to the timing of peak snowmelt. Peak snowmelt is associated with the occurrence of the maximum peak runoff in the watershed in late March and early April. In 1997, the predicted snowmelt for all land uses peaked during the last week of April (see Table 4.6). During this year the observed maximum peak runoff (20.4-mm) occurred on April 22. The predicted peak snowmelt which is the average value for all land uses, was predicted to within 1 day in 1997 (April 23, 18.30 mm). In four land uses, snowmelt peaked on April 23, and in the remaining land uses, no later than April 28. The exception to this was the vegetable production land use, for which peak snowmelt occurred on March 29. When looking at land uses, it was found that the predicted peak snowmelt for the bare and soybean land uses, occurred a few days later than the remainder of land uses. Also, total depletion of the snowpack for these land uses was completed very late on May 16 and 17, respectively. This looks unrealistic for this watershed, since by these dates most of the agricultural fields have been planted.

The model predicted the timing of peak snowmelt well in 1998. The observed maximum peak runoff occurred on March 31 (26.9 mm). Table 4.7 shows the predicted snowmelt peak for each land use in 1998. In six land uses, snowmelt was within 2 days of the observed maximum peak runoff and in the three remaining (bare, pasture and soybean) within seven days. The average predicted peak snowmelt occurred on March 29 (17.90 mm). In 1998 peak snowmelt was distributed between March and April.

Table 4.6 SLURP -predicted monthly snowmelt in (mm) by land use, 1997

	Bare	Urban	Wheat	Vegetables	Alfalfa	Forest	Corn	Pasture	Soya	Monthly mean
JAN	0	0	1	0	1	0	0	0	0	0
FEB	2	8	5	13	5	13	3	9	2	7
MAR	11	47	30	70	29	70	16	55	11	38
APR	229	283	170	178	149	249	175	378	229	227
MAY	301	0	0	0	0	0	0	0	275	64
JUN	0	0	0	0	0	0	0	0	0	0
JUL	0	0	0	0	0	0	0	0	0	0
AUG	0	0	0	0	0	0	0	0	0	0
SEP	0	0	0	0	0	0	0	0	0	0
OCT	11	0	2	0	2	0	14	0	11	4
NOV	25	8	2	12	2	11	6	8	26	11
DEC	0	2	0	6	0	6	0	2	0	2
Annual	579	349	210	278	187	348	214	452	555	352*

* Basin average snowmelt on annual basis

Table 4.7 SLURP -predicted monthly snowmelt in (mm) by land use, 1998

	Bare	Urban	Wheat	Vegetables	Alfalfa	Forest	Corn	Pasture	Soya	Monthly mean
JAN	1	5	3	7	3	7	2	5	1	4
FEB	4	33	15	61	14	61	7	44	4	27
MAR	46	97	70	112	69	138	53	114	46	83
APR	427	110	50	0	34	48	78	149	396	144
MAY	0	0	0	0	0	0	0	0	0	0
JUN	0	0	0	0	0	0	0	0	0	0
JUL	0	0	0	0	0	0	0	0	0	0
AUG	0	0	0	0	0	0	0	0	0	0
SEP	0	0	0	0	0	0	0	0	0	0
OCT	0	0	0	0	0	0	0	0	0	0
NOV	26	1	3	1	3	0	9	1	26	8
DEC	10	1	3	1	3	0	13	1	10	5
Annual	514	245	145	181	126	254	163	314	483	269*

*Basin average snowmelt on annual basis

However, 49.29% of the total snowmelt yield of the basin was concentrated in April. Again in 1998, the soybean and the bare land uses showed an extension of the snowmelt processes until April 30 and 29 respectively, at which point the snowpack was depleted. This response suggests that after the automatic calibration, values for the initial content of the snow store could have been too high for both land uses. For the rest of land uses, the snowpack was depleted no later than April 12.

Measurements of snow depth at the automated weather station located in the middle of the watershed, showed that the snowpack disappeared on April 12 in 1997. In 1998, these records showed that snow depletion occurred about one week earlier than predicted by the model (April 6). It is recognized that point data of snowmelt are not good estimates of snowmelt in a watershed (Kite, 1998).

The automated weather station is located in the middle of intense agricultural areas. It is known that the snowpack in the upper parts of the watershed, which have slightly higher elevations (10 to 20 m) and more wooded areas, tend to persist longer (Enright, personal communication). It was difficult to establish a direct comparison between the observed snow depth, measured at the weather station at Saint Esprit and the areal predicted snowmelt by the model. SLURP predicted daily snowmelt for each land use. The amount of snowmelt predicted for the season depends greatly on the initial conditions (i.e. initial content of the snowpack) set for each land use during the calibration period.

An average daily snowmelt was computed using daily results from nine land uses in the watershed. These average values were summed up during the spring snowmelt (March 29 to April 27 in 1997, and March 27 to April 30 in 1998). Table 4.8 compares the results of both the total observed and total predicted runoff with total predicted snowmelt during the spring snowmelt period. This information seems to support the conclusion that, for some land uses the calibrated parameter "initial content of snow" was unrealistically high, and therefore snowmelt might have been over-estimated in the watershed. For both years the amounts of predicted snowmelt were greater than the predicted runoff during the spring snowmelt. The differences observed between the predicted snowmelt and the predicted runoff are mainly due to water retention in the slow store and evapotranspiration. SLURP adds all the snowmelt from the snowpack immediately to the fast store on a daily basis. Infiltration and deep percolation depend both on parameters such as infiltration rate, storage capacities and retention constants in both the fast and slow store (Kite, 1998).

Table 4.8 Comparison between observed runoff, predicted runoff and average predicted snowmelt during the snowmelt period

Year	Observed runoff (mm)	Predicted runoff (mm)	Predicted snowmelt (mm)
1997	254.15	175.74	229.22
1998	287.33	132.33	209.35

4.3.4 Runoff

Performance of runoff simulation on an annual basis

Although SLURP over-predicted runoff, in general, the model performed well in both years. In 1997 the model over-predicted the observed runoff by 12.99%. In 1998, runoff was over-predicted by 13.05%. The observed and predicted runoffs were 464.8 mm and 525.5 mm, respectively. These results indicate that, even though the SLURP model was designed for hydrological studies in rangeland basins (meso-and macroscale level) it could also be used to estimate the long-term water balance in small agricultural watersheds, such as Saint Esprit.

During the calibration period, only 1995 was somewhat of a dry year. 1994 was wet and 1996 was exceptionally wet. The validation period occurred during the years 1997 (exceptionally dry) and 1998 (somewhat dry). It seems that calibration during an overall wet period did not greatly affect the results obtained from the model on an annual basis. This however, may have introduced some bias in the calibrated parameters, leading in general, to over-estimation of runoff during the dry years of the validation period. This issue will be presented further in the discussion of seasonal and monthly-predicted runoff.

Performance of runoff simulation on a seasonal basis

Two main seasons were analyzed: the growing season, (May to September), and the non-growing season (October to April), comprising the fall and winter seasons. Most of the runoff in the watershed occurred during the non-growing season because (i) the non-growing season is longer than the growing season, (ii) during the non-growing season, events such as winter snowpack accumulation and spring snowmelt occur.

In 1997 the non-growing season accounted for 405.35 mm out of 479.4 mm of total observed runoff. SLURP estimated 408.41mm for the same period, a difference of only 0.75%. During the growing season, 74.02 mm of runoff were observed. The model predicted 133.21 mm over this period, which meant a seasonal difference with respect to the observed runoff of 79.96%.

During 1998, the observed runoff recorded during the non-growing season was 417 mm, out of 464.8 mm of total runoff. Predicted runoff during the same period was 420 mm, a difference of only 0.84% from the observed value. However, observed and predicted runoffs during the growing season were of 47.8 mm and 105 mm, respectively. This showed a deviation of the predicted runoff with respect to the observed runoff of 119.58%.

On a seasonal basis the model showed a distinct pattern, characterized by over-prediction during the growing season and accurately predicting during the non-growing season. Again it seems that, the effect of wet years in the calibration (especially 1994) with high growing season runoff after significant snowmelt yields, could have played an important role in shaping the model response on a seasonal basis. Gan and Biftu (1996) state that models calibrated with high flow rates tend to over-simulate low flows and vice versa.

Performance of runoff simulation on a monthly basis

Monthly values of observed versus predicted runoff are presented in Figure 4.6 for 1997 and Figure 4.7 for 1998. In 1997 the model over-predicted observed runoff in 11 of 12 months, April being the only exception. Similarly in 1998 only in March and April was

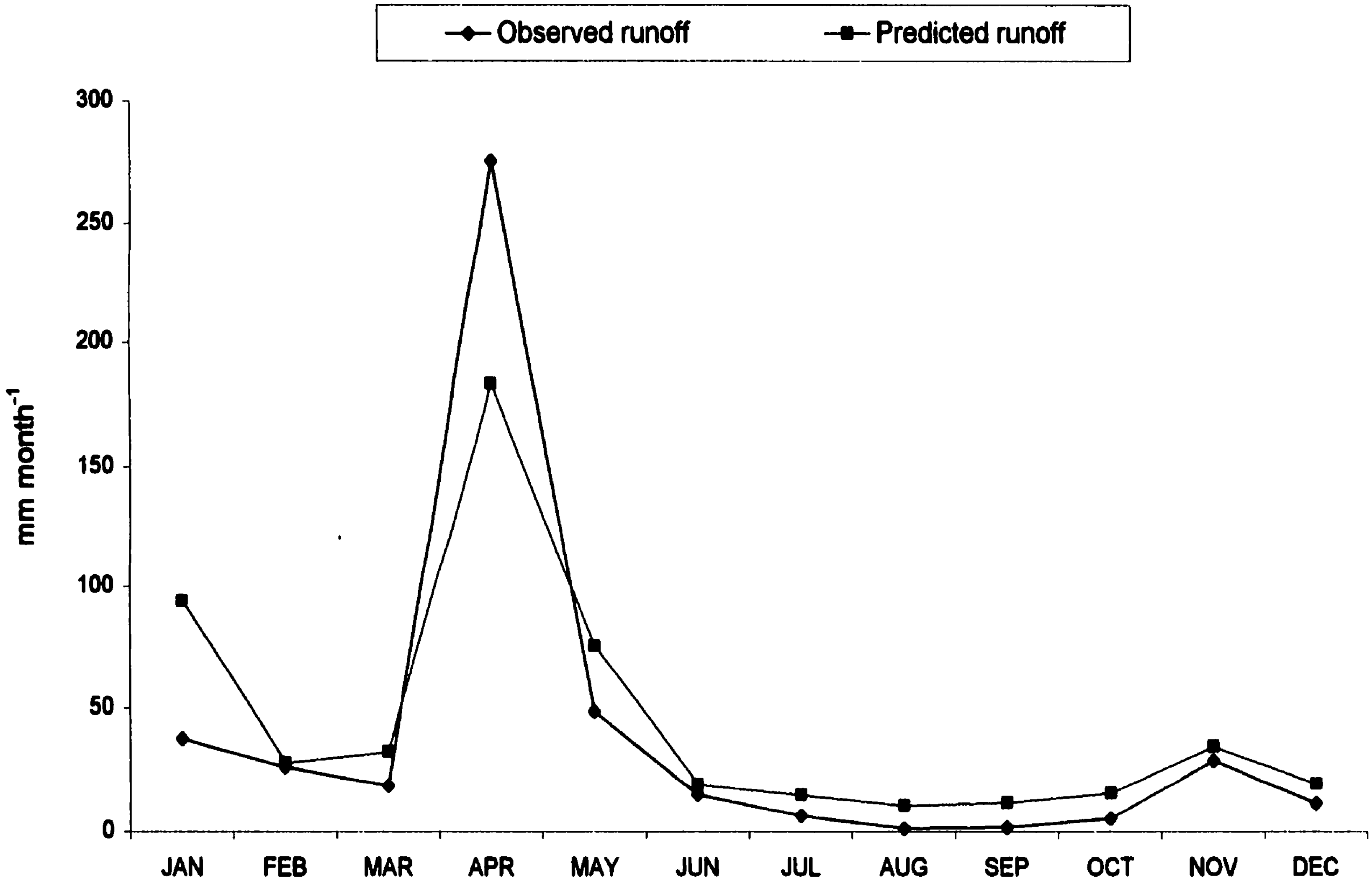


Figure 4.6 Results of monthly observed versus SLURP predicted runoff for 1997

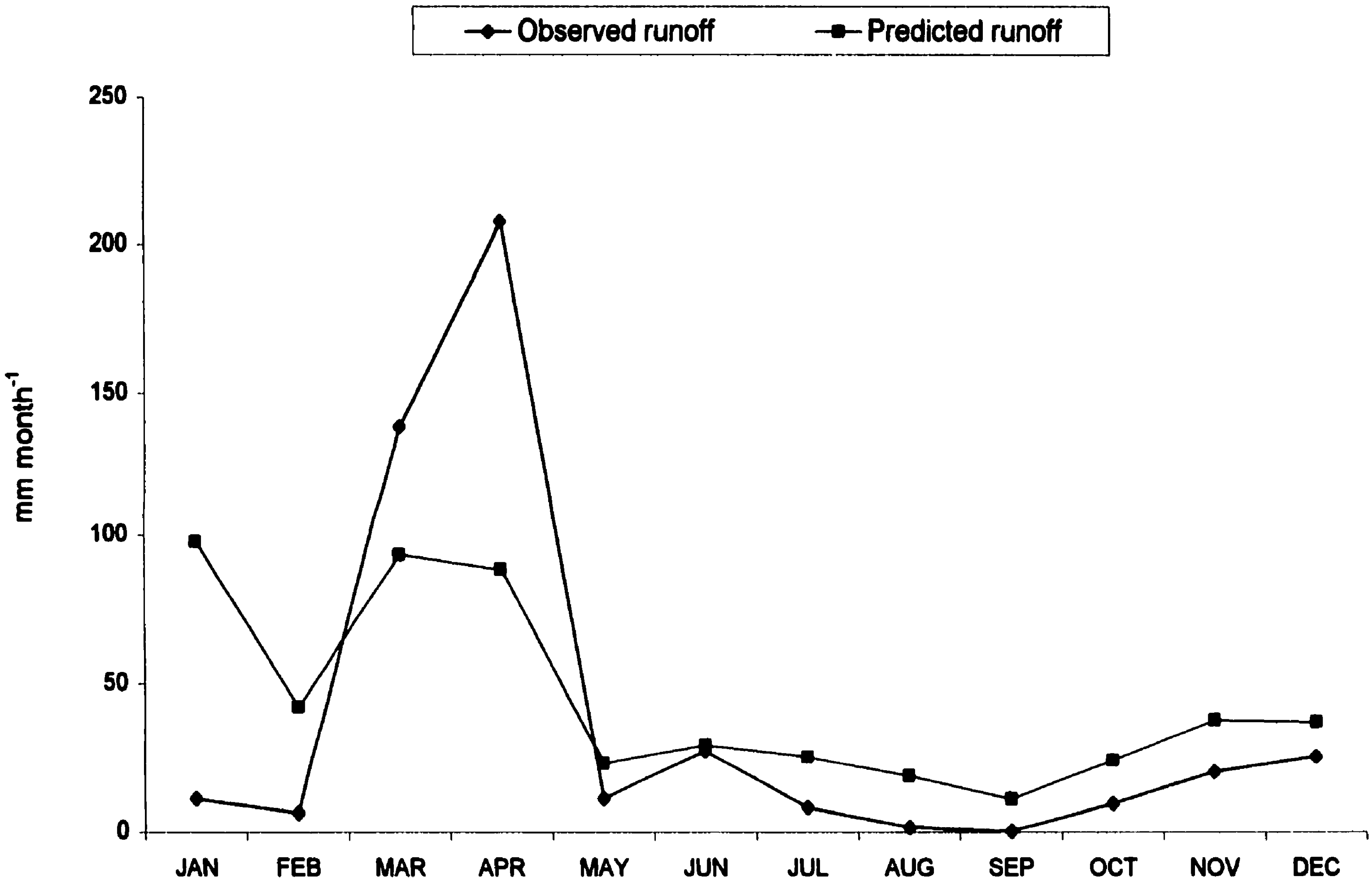


Figure 4.7 Results of monthly observed versus SLURP predicted runoff for 1998

the runoff accurately predicted, whereas for the other months the observed runoff was greater than the predicted runoff. This response represents a clear consequence of the effect that peak snowmelt has on the watershed hydrograph, as discussed in the previous section. It is important to highlight that SLURP predicted the maximum peak runoff within one day for both years of the validation. Thus, maximum observed runoff for 1997 occurred on April 22, while the maximum predicted runoff was on April 23. In 1998 the maximum observed runoff was recorded on March 31. SLURP predicted this event to occur on March 30.

However, most of the time the model over-predicted runoff. Annual differences, which might seem acceptable (i.e. 12.99 % in 1997 and 13.05 % in 1998), increased markedly when the period of comparison was shortened i.e. to a monthly basis. In 1997, the best prediction on a monthly basis occurred in February, when the difference between observed and predicted runoff was 6.23 %. The least monthly percent difference in 1998 was 8.18 %, in June. In general, monthly differences during both years tended to be quite high, with the largest differences (worst predictions) occurring during months in which particularly small flows were recorded at the outlet, such as during August and September. This caused that differences between the observed and predicted runoff reached 669% in August 1997, and 2780% in September 1998.

Results on monthly basis are similar to those reported by Mouzavizadeh (1998) using the ANSWERS 2000 model at this watershed. It seems reasonable that, good predictions during the non-growing season show a compensatory effect occurring on a relatively long-term period (7 months) when compared with poor results obtained on a monthly basis.

Performance of runoff simulation on daily basis

Model performance was acceptable for 1997. On the other hand for 1998 it might be considered poor. The Nash/Sutcliffe R^2 coefficients were 0.659 and 0.483 for 1997 and 1998, respectively. Kite (1992,1995) has reported R^2 for validation of up to 0.91 and 0.94, respectively. This means that SLURP did not fully describe the daily runoff produced in the watershed. The Nash/Sutcliffe coefficient criterion (see equation 3.12) explains the variation observed in the daily runoff, by computing square differences between measured and predicted runoff. Then, even though in 1998 the annual performance of the model yielded a percent difference of 13.05 % (not very different from 1997), on a daily basis the R^2 coefficient showed that the model performed poorly when compared to the preceding year. For hydrological problems such as water balance studies, in which the objectives are to assess seasonal or annual runoff, it is less important for the predicted runoff to match daily observed runoff. However some other studies i.e. hydrologic design for peak flows or irrigation water availability, require a much higher correspondence between observed and predicted flows.

The calibration process is essential in assessing model's performance. There are many reasons that could have influenced the low performance (R^2 0.522) obtained in this implementation. The possibility that the calibration was trapped by the existence of local optima in the data, is not a likely situation to occur when using the SCE-UA calibration method. Instead, problems associated to limitations of the use of point data (i.e. precipitation), lack of identification of more realistic initial conditions, data measurement errors (i.e. runoff), and errors inherent to the downscaling of the SLURP model to the scale of the Saint Esprit database may have had a more direct impact on the model performance.

The SCE-UA method has an "embedded" purpose to achieve global optima convergence (best set of parameter combination over the entire solution surface) during the calibration. Even though powerful optimization methods search for parameter sets which best fulfill the objective function, in doing so, these sets might reflect a better curve fitting while parameter values loose physical meaning (Gan and Biftu, 1995). An example of this was the calibrated initial snow depth for some land uses in our study. The poor fitting of the objective function (R^2) seems therefore related to the problems described above.

In this implementation the system was discretized using a grid cell size of 20 m., which produced a high level of resolution for land use definition, and the generation of physiographic parameters such as distances, changes in elevation, and percentage of land use per sub-basin. However, in an attempt to simplify the system, the model structure defines parameters related to land-use regardless of possible spatial variations, occurring for example in the same land-use class but at a different location of the watershed. Then, the high level of data resolution, might have not impact significantly on the results.

Particular conditions such as the existence of sub-surface drained land in approximately 50% of the agricultural land (Enright et al., 1995), affects the response to runoff of a large area in this watershed. This might lead to an increased infiltration capacity of the soils before runoff occurs, but drains water out of the 0-1 m profile more rapidly, once it has infiltrated. This generally results in some attenuation of the hydrograph, as compared to what would be observed on undrained agricultural soils. Therefore, it is possible that runoff differences observed on a daily and monthly basis might be a response to this condition, which modifies the underground water movement of the watershed.

5.0 SUMMARY AND CONCLUSIONS

5.1 Summary

The continuous semi-distributed hydrological model SLURP, was applied to study the hydrology of the Saint Esprit watershed in southwestern Quebec. The model was parameterized using GIS for physiographic parameters. Five years of climatic data were collected at the experimental site between 1994 and 1999, and streamflow was measured at the outlet of the watershed. Most of the input parameters were derived from the Saint Esprit field database produced by Mouzavizadeh (1998), and the rest were estimated.

The model was calibrated using a combination of both automatic optimization techniques and manual parameter adjustment. Climatic data and runoff measurements from three years (1994 to 1996), were used for calibration purposes. Following calibration, the model was validated for two years, 1997 and 1998. The hydrologic outputs of the model studied were: evapotranspiration (ET), runoff and snowmelt. Model efficiency was assessed graphically, by the use of the Nash/Sutcliffe (1970) coefficient of efficiency (R^2) for daily simulations and the percentage difference between observed and computed runoff on a monthly, seasonal and annual basis.

The snowmelt component of the model was used to simulate the annual snowmelt for each land use. Snowmelt was averaged throughout the different land uses to obtain a representative value for the watershed on an annual basis. Characteristics such as timing of peak snowmelt and the relative amount of spring snowmelt to the total yearly runoff were studied.

The Baier & Robertson (BR) ETp model (Rochette, 1990) calibrated for southwestern Quebec conditions, was used for three purposes: (i) estimating potential ET in the watershed, (ii) investigating crop water requirements and irrigation needs according to land use, and (iii) comparing estimated ET with those produced by the CRAE method (Morton, 1983) built into the SLURP model.

5.2 Conclusions

The philosophy on which spatially distributed hydrological models are developed, is to provide the best possible understanding of the watershed system, in order to solve water quantity or quality problems. This relies however, on fully using data and knowledge about the system studied.

Predictions of evapotranspiration were in good agreement with previous estimates carried out in the watershed. Average computed annual ET was 535.6 mm in 1997 and 589.1 mm in 1998. Long term seasonal mean of the predicted actual ET from the SLURP model, compared well to the seasonal means actual ET for corn (ET_{corn}) estimated by using the watershed potential evapotranspiration calculated from the Baier and Robertson (BR) model. Using the Student *t*-test, no significant differences ($P>0.05$) were detected between these data series. BR-potential evapotranspiration was input into a routine to estimate crop water requirements (CWR) and irrigation needs for six agricultural land uses in the watershed. Irrigation was not necessary for any land use during the study period. This result is consistent with the current rain-fed agricultural system practiced in the watershed.

Snowmelt in the watershed was studied for first time using modelling techniques. The model performed well in reproducing the timing of peak snowmelt and consequently the timing of maximum peak runoff. For most land uses, predictions of peak snowmelt were within 1 and 2 days from the observed peak runoff in 1997 and 1998, respectively. On the other hand, peak runoff was predicted within one day for both years of validation. However, results in both years, showed the tendency of the model to extend the snowmelt period for some of the land uses. This seemed to be related to high initial values set for these land uses for the parameter "initial content of the snowpack", after performing an automatic calibration.

Runoff predictions by the SLURP model in the watershed were acceptable for long term prediction such as on an annual basis. SLURP predicted annual runoff within 12.99% and 13.05% of the observed runoff in 1997 and 1998, respectively. For both years the model over-predicted observed runoff. Seasonal predictions showed an alternate pattern of poor and good performance for the growing and non-growing season, respectively. During the validation period, the model over-predicted runoff during the growing season by 79.96% in 1997 and by 119.58 % in 1998. Predicted runoff over the non-growing season were in good agreement with the observed runoff; for both 1997 and 1998 runoff deviation from the observed data was only 0.75% an 0.84%, respectively. These results in particular demonstrated that SLURP has a good potential to be used in water balance studies at Saint Esprit.

In general, model predictions on a monthly basis were not good. The model over-predicted runoff in 11 out 12 months during 1997 and in 10 out of 12 months in 1998. Percent differences between observed and computed runoff were greater than 50% in 8 of 12 months in 1997 and 10 of 12 months in 1998. Differences tended to increase during months in which the observed runoff was very small. Runoff predictions on a daily basis were more difficult to achieve, as model predictions for monthly scale were not good, for the daily scale predictions may deteriorate if compared to the monthly scale. The model yielded Nash/Sutcliffe coefficients R^2 of 0.659 for 1997 and R^2 of 0.483 for 1998. However, on a daily basis the model worked better during the 1997 validation, when comparing its R^2 (0.659) with the one obtained during the calibration (0.522).

6.0 RECOMMENDATIONS FOR FUTURE RESEARCH

The effort to characterize the hydrology of the Saint Esprit watershed so far has produced a valuable source of information, not only in terms of the database achieved, but also in terms of the information gained from modelling exercises. This research aimed to produce a contribution to the understanding of the system studied. Considerations presented in this section are focused on the opportunity for improving future works using distributed hydrological modelling in the Saint Esprit watershed.

1. The lack of distributed precipitation data is maybe the most important constraint when applying distributed models. Even in small basins like Saint Esprit, this leads to a significant source of errors, which cannot be assessed. We believe that increasing the amount of rain gages in the watershed or implementing precipitation estimates by the use of radar techniques, will allow us to improve the accuracy of rainfall input into the models. It will also permit us to asses the real impact of using the distributed data. Similarly, since snowfall represents a significant part of the total precipitation in southwestern Quebec, then, snow should be measured in a distributed manner. Implementing snow course measurements would give more realistic estimates of the snow distribution and other physical characteristics of the snowpack. These considerations have to be balanced in light of cost constraints.

2. In this research we tested the SLURP model, and used it mainly for system characterization. There are, however different possibilities that can be accomplished using this tool. This model is suitable to investigate how changes in land use pattern could affect the hydrological response of the watershed. Using historical data or simply by constructing change scenarios (i.e. diminishing forest land) it would be interesting to simulate the effect of changes on total runoff. Another possibility might be in the direction of integrated watershed management, by simulating interventions

in the water balance, such as those occurring when sectoral demand for water use increases in agricultural-animal production, population or industrial-related activities in the watershed.

3. New modelling techniques and data collection technology are available to study hydrological components in a separate or integrated way. In particular remote sensing techniques could be used in order to keep an updated database on the time-variant factors i.e. land use and snow. Since Saint Esprit is a small watershed, this limits the number of current satellite platforms by which one could obtain parameters required by hydrological models to those having higher data resolution. Therefore, these data are more expensive. However, some satellite operators have started to deliver images for small areas (<10MB) free of charges over the internet.

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APPENDIX 1
Estimating ETp and crop water requirements (CWR) in the watershed

1.1 Data management and integration into the GIS

The procedure described used existing digital information for the watershed produced by Mousavizadeh (1998):

- Before importing the information into SPANS EXPLORER GIS, the data was organized in two separate layers, vector layers (lines and polygons) containing the graphical information and point layers containing the attributes associated to the features. Information pertaining to land-use and soil texture was used.

- Non topological vector files with an arc-node structure (TYDIG .vec and .veh format), were imported into the SPANS using import vector function. Attributes information in the SPANS native format (.tba) were also imported, and further appended to the vector layers using the analysis/point inside function. The topology was created in the GIS environment through the import procedure. This allow one to calculate areas and perimeters for polygons and length for arcs. In consequence it permitted further spatial analysis to prepare parameters for the model.

- Assembling the database, implied appending the point layers to the vector layers, either for the lines or for the polygons. The geographic data was imported into the study area prior to the attributive data. Attributes were appended to geographic features.

- The original vector files for the land-use and the soil texture, comprised two contiguous watersheds, Saint Esprit and Deroscher. A spatial analysis to clip out the information correspondent to the Saint Esprit watershed was performed. This was achieved through the functions analysis/overlay/vectors and file/save_as/layer in SPANS. The Saint Esprit watershed boundary layer was used as input layer1 and the soil layer as input layer2.

1.2 Reclassifying the soil texture layer

After obtaining polygon layers for land-use and soil texture, an overlay of this information would have resulted in a very large number of polygons. To perform a simplified analysis and improve the interpretation of the data, a re-coding operation was carried out. Adjacent polygons being classified into the same class received the same code, then, their boundaries were dissolved. Thus, the soil texture layer containing fourteen different classes was reclassified into three classes. This approach allowed grouping these polygons into: fine, medium and light (coarse) texture class soils.

A table from the original soil database layer was developed to associate the texture type of each soil polygon, with physical parameters related to the soil water holding capacity as reported in the literature by James (1982), ASAE (1980) and Jones (1978).

SPANS do not allow deleting polygons; therefore, the edition work was performed transforming the original soil map from an area layer into a line layer (tool/transform/ area to lines). Arcs dividing soil polygons in the same class were deleted to generalize the information, once completed this edition; the new reclassified layer was transformed back into a polygon layer (tool/transform/lines to areas). A new attribute (soil type) for the reclassified soil map was added using the function model/attribute/calculate. This function allowed not only to add new fields to the GIS database, but also to calculate values for specific records through simple user defined Boolean expressions using existing information in the database fields. After processing the data layers, land-use for the Saint Esprit database resulted in a 296 polygon layer and the reclassified soil texture layer in a 31 polygon layer.

1.3 The unique land-use/soil texture layer combination.

The next step in the analysis was to perform an overlay between the land-use layer and the reclassified soil texture layer. This overlay produced a polygon layer showing unique combinations of land-use (agricultural crops and other uses) and soil texture type. The unique layer combination, allowed to spatially investigate the occurrence of factors affecting crop evapotranspiration. The soil texture reclassification procedure reduced significantly the number of polygons. The overlaid between land-use and soil type layer (GIS-layer) produced 714 polygons (see Figure 3.1). The GIS database of this layer was used to feed parameters required by the computer routine for estimating CWR (ETc) and irrigation needs in the watershed. Non agricultural, forested and urban areas were neglected in the CWR estimation.

1.4 Adding new attributes to the GIS database for CWR estimation

The land-use and soil texture layer combination (GIS-layer) provided with the basic information for CWR estimation. For each polygon a code combination "concatenated field" was assigned; this field joined in a single database field the land-use code and the soil texture code. Estimated values for the parameters describing the soil water holding capacity and crop characteristics were added to the database. New fields aggregated to the database are mentioned as follow: concatenated field code, field capacity (mm), soil critical moisture content (mm), length of the growing season for each crop (days) , initial crop consumptive use (*Kci*) , date of planting (days elapse after may 20) and initial rooting depth (*Drzi*). Calculations were done using a spreadsheet and further added to the GIS database through the SPANS's function model/attribute/calculate.

1.5 The soil-water budget routine

The intention to perform CWR estimations in the watershed using the GIS, was to take advantage of the GIS as a data management platform in the spatial context. Programming irrigation scheduling which results in varying water applications and intervals over the growing season for a large irrigation scheme with different crops, soils and planting dates have been recognized as a problem (Smith, 1984). Although a GIS, surely facilitates the theoretical solution, in practice the implementation of irrigation scheduling is only possible in cases where farmers independently can manage water supply and irrigation.

A brief description of the soil-water budget routine is presented as follows:

Selected fields of the final GIS-layer database were exported from the GIS as ASCII file (plain text file) using the function file/export/attributes. This file was read for an ANSI C routine to perform the calculations into the CWR routine, as follows:

- The soil water-balance routine was programmed to read the assigned polygon identifier of the GIS database , this permitted to keep track of the relation between land-use/soil texture type an their new estimated attributes.

- Integer parameters were used to define the size of two arrays; the first array of size 153 for the number of days in the season (1 may to 30 September). A second array of 715 to allocate the number of polygons (equal number of records in the ASCII file) contained in the overlaid land-use and soil texture layer 'GIS-layer'.

- Arrays of global variables in the program were defined for : the unique polygon identifier *ID[]*, the concatenated field *concfld[]*, the initial crop consumptive coefficient *Kci[]*, the soil moisture content *soilmoist[]*, the evapotranspiration values *et[]*, the crop evapotranspiration *etc[]* , the effective precipitation *pe[]*, the duration of the growing season for each crop *gs[]*, the irrigation requirements *irrig[]*, the field capacity *% fc[]* and permanent wilting point of each soil polygon *% pwp[]*, the initial rooting depth *Drzi[]*, the amount of deep percolation *deep[]* and the soil critical moisture content *qc[]*.

- The structure of the program was divided in one main function and seven sub-functions which managed the calculations for each crop (land-use). In the main function all the sub-functions were prototyped; further, the file containing five years of average *ETp* and *Pe* is read and stored in memory. The GIS-layer database (ASCII file) is read, a decision block utilizing the concatenated field is used to pass data from the main function to the appropriate crop sub-function, in which a complete time series database is calculate for the growing season of a particular crop being grown in a determined soil type.

- Daily *ETc* and irrigation (if required) was estimated and written in six result files, containing crop information for: corn, soybean, wheat, vegetables, alfalfa and pasture. The information from polygons containing land-uses such as urban, forest and non-agricultural was passed to a sub-function (default) which ignored ETc estimation for these land-uses.

- Every record in the GIS database contained the information resulting for the overlay of land-use and soil type. Calculations for each polygon were performed according with values estimated from the maps. The *Kci* factor was read from the GIS, and updated inside the crop sub-function according to the crop development stage, using an interpolation function.

- Soil moisture content was simulated during the growing season, and irrigation events were computed when the soil moisture content was equal or under the critical soil moisture content (*qc[]*) defined for each soil type in the reclassified soil texture map.

- An initial rooting depth was assumed for the first 20 days. The root system develops between the end of the initial stage and the end of the third stage or mid season. Hence, the root zone development is simulated using a slightly modified interpolation function described in ASAE, (1990).

$$Drz = Drzi + (Drzmax-Drzi)/(Gs-Y)$$

where

Drz = the current rooting depth;
Drzi = the initial rooting depth;
Drzmax = the maximum rooting depth;
Gs = the duration of the growing season; and
Y = the number of days comprised between the end of the growth stage 1 and the end of growth stage 3 of the crop. Assumed as the effective period for roots to grow.

- The strategy for calculating CWR assumed a hundred percent of application efficiency . Water losses occurring by deep percolation were computed daily.

1.6 Data visualization and presentation

For every polygon (crop/soil type combination) a time series of ETc and irrigation during the growing season was calculated. Seasonal ETc and CWR were computed in a spreadsheet. The concatenated field was helpful to perform seasonal computation of the data, and further, to relate it back to the GIS.

Using the SPANS export utility all GIS layers were after exported into the ArcView (shapefile) format to perform final calculations using existent fields of the database. The compiled database of ETc and CWR was exported into the dbase (.dbf) format, and then imported into the ArcView project, a collection of digital files represented by maps, tables, terrain models and scripts in avenue code for the study area. The .dbf file containing the information in mm for the growing season was joined to the existing GIS-layer database.

Additional information such as dates of occurrence of maximum ET , maximum ETc, was also linked to the GIS database in the ArcView project.

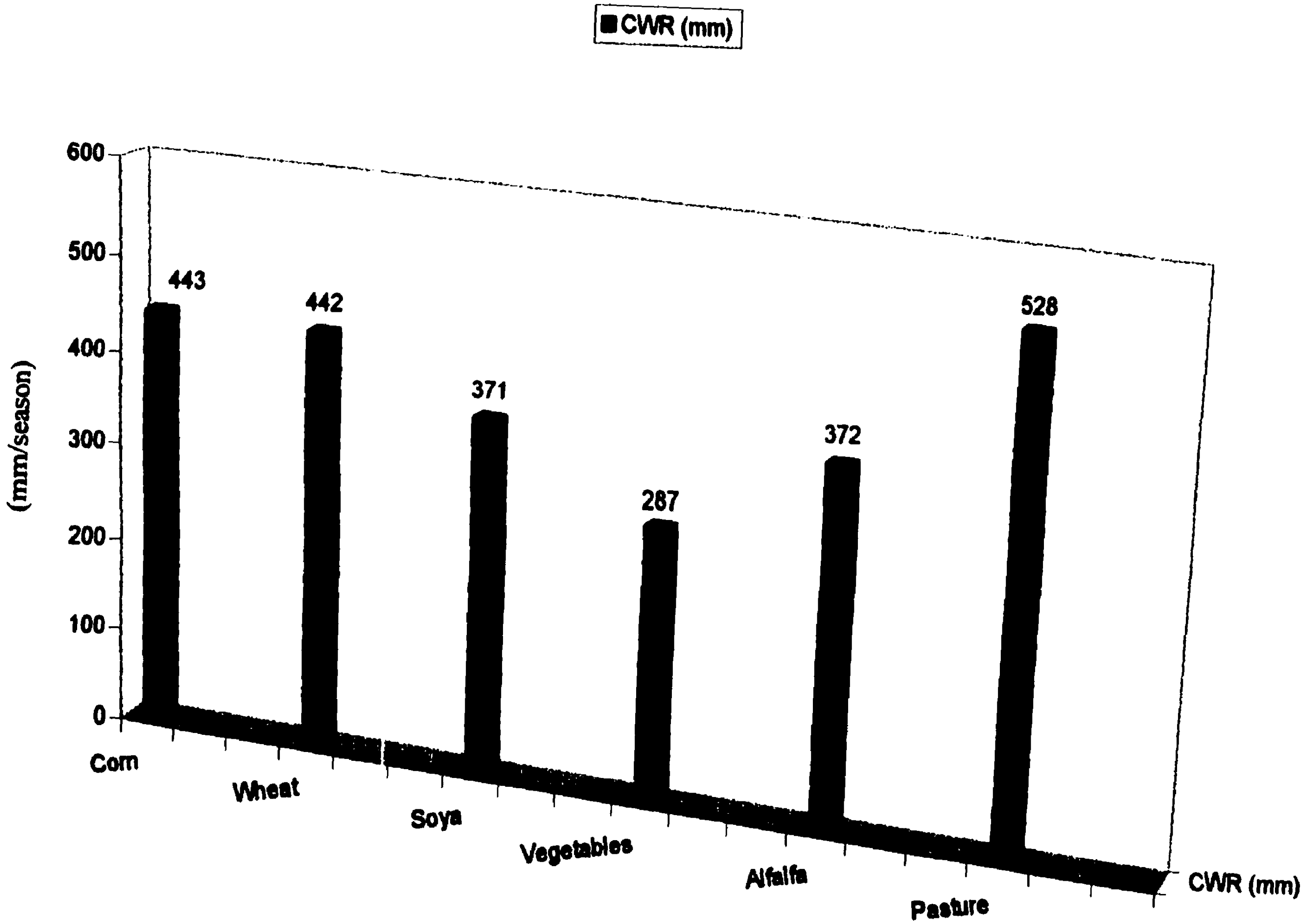

Figure 1.A Average seasonal crop water requirements at the Saint Esprit watershed, based on Baier & Robertson model estimated ETp

APPENDIX 2
Rasterization of the data and estimation of physiographic parameters for the SLURP model

3.1 Grid data generation from vector layers

All the necessary layers describing the physical characteristics of the watershed were converted from the vector format (Arc View shape file) to the grid format. For this purpose, an available rasterization procedure in the Spatial Analyst extension of the Arc View GIS version 1.1 was used.

- A 20 m. raster resolution was selected, by input parameters required for this level of resolution into the analysis property windows of the project file.

- The watershed boundary was used to mask (areal clip) the output grids.

3.2 SLURP watershed physiographic parameterization using GIS techniques.

Instead of implementing a specific watershed partitioning, such as in the case of completely distributed models, the semi-distributed approach of the SLURP model works with averages and standard deviations of the physiographic information described by the means of the GIS. The following statistics are required:

- Mean and standard deviation of the distances to the nearest stream for each land use.
- Mean and standard deviation of the distances along the stream to the ASA outlet for each land-use.
- Average change in elevation to the nearest stream
- Average change in elevation to the ASA outlet
- Average ASA latitude and elevation

The GIS method led to the generation of two files describing the watershed system. The (.PNT) point file which is drawn from the digitized channel network and the (.GRD), a sampling point file containing information on elevation and land-use.

3.3 Generating the network point (.PNT) file:

- Using the river (channel) layer, a network topology was created. This means performing an arc-node topology on the river network. Each ASA outlet must be coincident with a node in the river network. The latter was ensured by intersecting the sub basin layer with the river layer. Nodes were created every 20 m all over the river network by splitting the original channel network using the DENSIFY command of ARC/Info.

- The first procedure generated two tables, the arc table and the node table. The first table contained a field distance that was joined to the node table to create a cost table. The cost concept is in term of distance. The distance for the water to flow into the network, or the distance from each node of the network to the ASA outlet. The resultant point network produced 2684 nodes.

- A best route analysis (minimum cost), from each node of the river network to the watershed outlet was calculated using the ArcView Network Analyst v.1.0 .

- Information regarding ASA number and elevation was appended to the points of the network. The point file was converted in a 3D-point file using the watershed's digital elevation model (DEM). The sub-basin code was appended by a function assigning data by spatial location (i.e. points falling into polygons).

- For every network point, the UTM coordinates were calculated using a suitable script

3.4 Generating a random sampling grid point (.GRD) file:

- A random function routine for automatic point generation was used to digitize 5000 points inside the watershed. To ensure a complete distribution of points, a 50 meters distance threshold (minimum distance between points) was selected. The USGC (1998) public domain animal movement program ver.2.0 for Arc View, was used for this purpose.

- The land-use information was appended to the randomly generated points, by spatially assigning data to the points.

- Elevation information (from a DEM) was appended to the point file. The point file was converted to a 3D-point file using the DEM surface.

- For every random point the UTM coordinates were calculated using a suitable script

3.5 Calculating the statistics of the physiographic data:

Files (.PNT) and (.GRD) contained the basic data to calculate the statistics required by the model. For data simplification the watershed was separated in its component sub-basins. The following steps summarize, how the calculations for distances and changes in elevation were carried out for each sub-basin, using ArcView and spreadsheet analysis.

- The digitized basin file was separated in its 18 component sub-basins

- Sub-basin files were used to clip the information pertaining to the .PNT and the .GRD files

- A distance routine (avenue script) was used to calculate the distance from each point of the .GRD file to each point of the .PNT file. The routine uses the UTM coordinates of the database to calculate the linear distance between the point pairs

- The exported database was analyzed using spreadsheets, the file was sorted by land-use. The distance to the nearest stream (shortest distance value) for each point in the .GRD file was queried. Average and standard deviation from these values was calculated in the spreadsheet

- The distances along the stream for those points in the (.PNT) file being closest to the points in the GRD file were determine. This uses the information from the best route analysis table. Average and standard deviation from this information was calculated in the spreadsheet

- The average change in elevation to the nearest stream, was calculated by averaging the elevation of each land-use, and calculating the difference between this value and the elevation of the nearest point in the stream

- The average change in elevation along the stream, was calculated by subtracting the averaged elevation of the points along the stream, from the elevation at the ASA outlet

APPENDIX 3
Daily observed runoff as compared to the SLURP predicted runoff during calibration

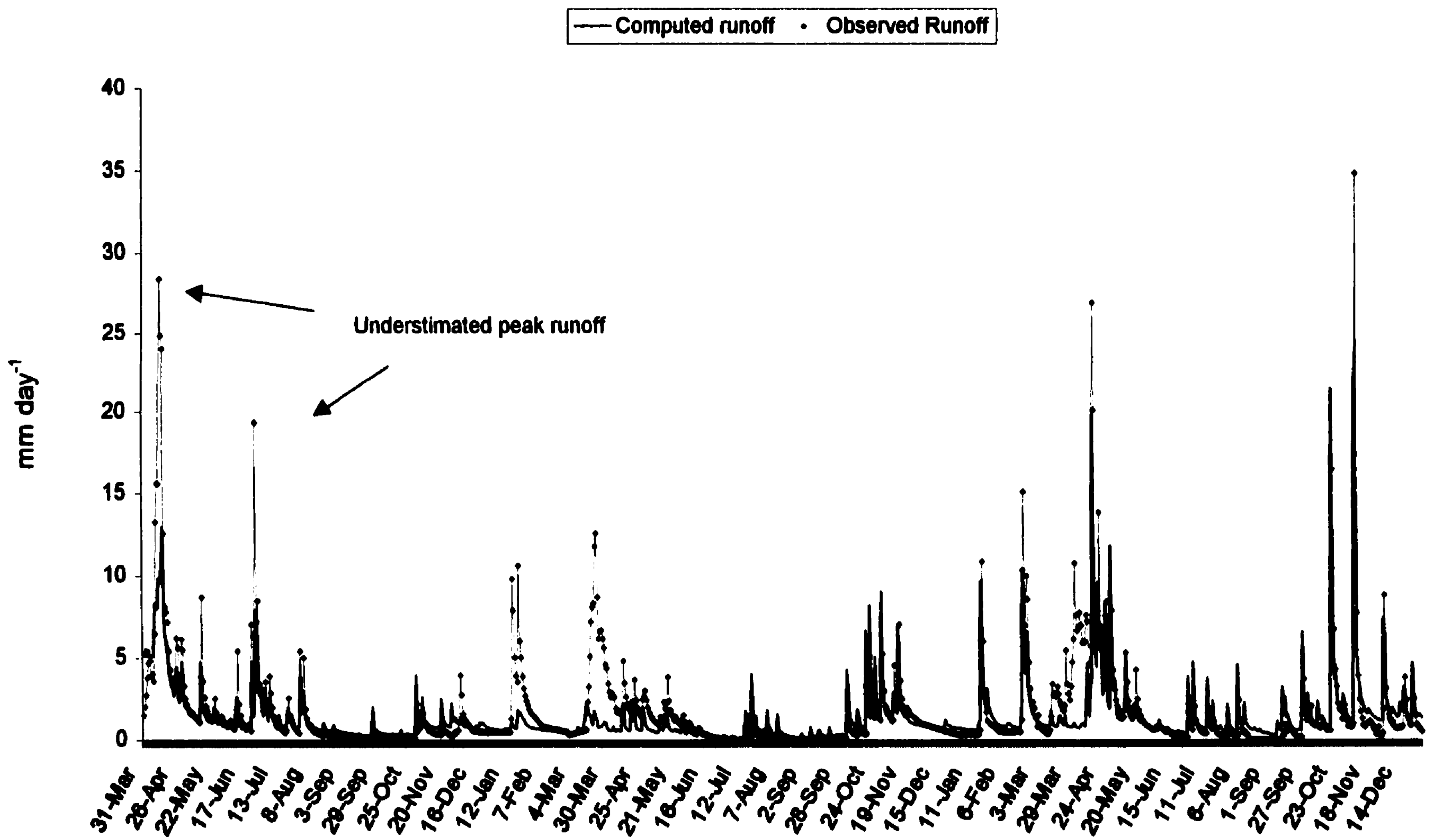

Figure 3A Predicted versus observed runoff after model calibration 1994 to 1996