Modelling the hydrology of an agricultural watershed in Quebec using SLURP

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Romero, D., Madramootoo, C.A. and Enright, P. 2002. **Modelling the hydrology of an agricultural watershed in Quebec using SLURP.** Canadian Biosystems Engineering/Le génie des biosystèmes au Canada **44**:1.11-1.20. Five years (1994-1998) of climatic and hydrologic data recorded on the small Ruisseau Saint Esprit agricultural watershed, located 50 km north of Montreal, Quebec, served to calibrate and validate the SLURP hydrological model. A Geographical Information System was used to store, analyze, and export the watershed information to the model. SLURP was calibrated with data recorded from 1994 to 1996 using an automatic calibration technique. The Nash/Sutcliffe coefficient of performance obtained through the automatic calibration feature of SLURP was 0.522 for daily runoff. Model validation was carried out by comparing predicted and measured daily, monthly, seasonal, and annual runoff using data from 1997 and 1998. Model validation using daily data yielded Nash/Sutcliffe coefficients of 0.659 (acceptable) and 0.483 (low) for 1997 and 1998, respectively. Hydrologic outputs predicted by the model on an annual basis (evapotranspiration, snowmelt and runoff) were acceptable, but runoff was over-predicted. On a seasonal basis, the model predicted runoff well during the non-growing season, but poorly over the growing season. SLURP-predicted actual ET compared well with the ET_{corn} predicted by the Baier and Robertson model. Timing of peak snowmelt-runoff was in most cases simulated within one or two days of the observed peak runoff, but runoff from snowmelt was greatly underpredicted by SLURP. This may be in part related to the lack of on-watershed spatially distributed measures of snow pack depth and snow-water equivalence, but also may be related to the inflexibility of the model to parameter tweaking after the autocalibration. Overall, the present study suggests that, with additional data, SLURP could be used for long-term estimates of the hydrology of the Saint Esprit watershed.

Cinq ans (1994-1998) de données climatiques et hydrologiques enregistrées sur le petit bassin versant du Ruisseau Saint Esprit, 50 km au nord de Montréal, Québec, servirent à calibrer et valider le modèle hydrologique SLURP. L'information décrivant le bassin versant fut stockée, analysée et exportée au modèle en utilisant un SIG. Le modèle fut calibré par une technique d'optimisation automatique, utilisant trois ans de données (1994-96). Le coefficient de performance Nash/Sutcliffe (R^2) d'après calibration fut de 0.522. Le modèle fut validé en comparant l'écoulement observé et l'écoulement simulé pour les années 1997 et 1998, sur une base annuelle, saisonnière, mensuelle et quotidienne. Pour 1997 et 1998, sur une base quotidienne, des coefficients (R^2) de 0.659 (acceptable) et de 0.483 (bas), respectivement, furent obtenus. Les variables hydrologiques étudiées furent: l'ET, la fonte des neiges et l'écoulement. L'ET simulé par SLURP et l' ET_{mais} simulé par le modèle Baier et Robertson ne furent pas sensiblement différents. Pour l'ET et la fonte les prédictions furent acceptables, mais l'écoulement fut largement surestimé. Sur une base saisonnière, le modèle performa bien hors-saison, mais mal durant la saison de culture. La synchronisation des niveaux maximums de fonte des neiges et d'écoulement furent simulés, dans la plupart des cas à un ou deux jours près de l'écoulement maximal observé. Cependant l'écoulement provenant de la fonte fut fortement sous-estimé. Cette erreur pourrait être reliée en partie au manque d'une distribution spatiale de données d'épaisseur du manteau nival et d'équivalence neige-eau sur le bassin versant. Cette erreur pourrait aussi être reliée à l'inflexibilité du modèle aux ajustements des paramètres après l'autocalibration. Nos résultats suggèrent qu'avec des données additionnelles, SLURP pourrait servir à l'estimation à long terme de l'hydrologie du petit basin versant de Saint-Esprit.

INTRODUCTION

Management of water resources is a key issue for environmental conservation. Hydrological modelling is an effective technique to assist managers and decision-makers in the assessment and protection of water quantity and quality. Watersheds have been recognized as natural units for water resources management (Heathcote 1998). Hydrological models are tools intended to realistically represent the watershed's complex system (Kite 1995) in which hydrological characteristics result from a number of physical, vegetative, climatic, and anthropomorphic factors (Viessman et al. 1989). Understanding runoff generation through modelling techniques can lead to an increase in water use efficiency in the watershed. Models are used to simulate water management strategies which satisfy demands of different users, while mitigating deleterious effects on riparian ecosystems.

Spatially distributed hydrological models were first developed in the 1960s, but a new generation of models, including: SLURP (Kite 1998), HBV (Lindström et al. 1997), COSSEM (Burney and Edwards 1996), AGNPS (Young et al. 1995), THALES (Grayson 1992), and SHE (Abbot et al. 1986) have recently been developed. Spatially-distributed watershed models demand a great deal of effort in collecting and organizing the input data which varies both spatially and temporally. This problem has been addressed by improved data collection techniques, and the use of geographical information systems (GIS) (Arnold et al. 1998). In addition, extensive sets of monitoring data are required to adequately validate the models.

In this study, the discharge at the outlet of the Saint Esprit watershed was monitored for five years (1994-1998). In addition, a digital database containing physiographic information including: land use, soil texture, and stream network data was developed for the watershed (Mouzavizadeh

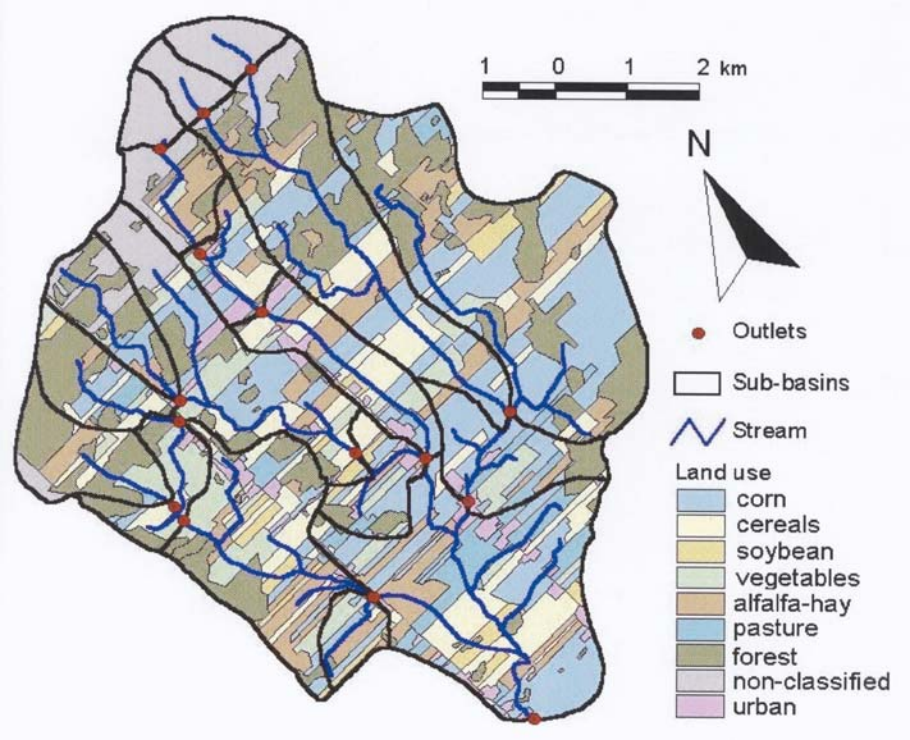

Fig. 1. The St. Esprit watershed.

1998). Previous hydrological studies have been carried out at this site (Perrone 1997; Mouzavizadeh 1998). However, the contribution of the snowmelt component has not yet been evaluated through modelling.

SLURP was selected for this study because of its ability to predict snowmelt (Kite 1998), normally the major hydrological event of the year in this region of Quebec. Most of the parameters required to run the model were measured at the site or could be estimated. The model was applied *a posteriori* to data from a watershed water quality monitoring project, as opposed to a project designed specifically to gather all the data necessary to calibrating and validating the SLURP model. Consequently, snowpack density and depth distribution over the watershed as well as the snow-water equivalence for the region were not collected. Snowpack depth was obtained from a single meteorological station on the watershed; the other factors from the closest sites from which such data were available. Other required parameters were measured at the site after the fact or estimated from literature. The model, applied in a semi-distributed form, offers a reasonable compromise on the amount of data required, while retaining the necessary physics describing hydrological processes (Kite 1998).

The objectives of this research were: (i) to apply the continuous and spatially-distributed hydrological model SLURP on the Saint Esprit watershed; (ii) to calibrate and validate the model for the watershed using five years of data; (iii) to test the accuracy of the SLURP evapotranspiration (ET_a) predictions; and (iv) to evaluate the ability of the model to accurately predict the timing and quantity of snowmelt.

METHODOLOGY

Site description and field data

Situated in southwestern Quebec, some 50 km north of the city of Montreal, the Ruisseau Saint Esprit watershed, a subwatershed of the L'Assomption river, is mainly devoted to agriculture. Located between 45°55'00'' and 46°00'00'' N, and 73°41'32'' and 73°36'00'' W, the Saint Esprit watershed comprises a net drainage area of 26.1 km^2 (Fig. 1). During the study period (1994-1998), agricultural land occupied 1678 ha (62% of the total watershed area). The remaining surface (933 ha) was occupied by forested, bare, and residential lands. Agricultural production was based on annual crops such as corn (*Zea mays* L.), small grain crops, including wheat (*Triticum aestivum* L.), soybean (*Glycine max* L.), and various vegetable crops. Forage accounted for about 25% of agricultural lands. The major crop by area was corn, occupying 620 ha.

The watershed boundary, streams, roads, and elevation information were obtained from 1:20,000 cadastral maps (Ministère de l'agriculture du Québec 1993; Ministère de l'énergie et des ressources du Québec 1993), as were lot boundaries (Ministère de l'agriculture du Québec 1975). These maps, along with 1:63360 soils maps (Canada Department of Agriculture 1962), 1:15000 field-level aerial photography, and information provided by the producers (Enright et al. 1995) identified 21 soil series, and nine different land use categories (Table 1).

In general, the largest proportion of the watershed is occupied by coarse textured soils (50%), followed by fine texture soils (41%). At least 50% of the agricultural land is tile drained (Enright et al. 1995). Except in small stony and forested areas (<15% by area), the watershed is characterized by a rolling topography with a land slope varying between 0 and 3%. The maximum difference in elevation from the outlet to the highest point of the watershed is about 50 m. The principal watercourse is 9 km long, and there are a total of 60.3 km of watercourses on the watershed. The climate is temperate, with a mean annual precipitation of 998 mm, mean potential evapotranspiration of 572 mm and mean temperature of 5.2°C (MEFQ 1995). The watershed contains a total of 28 farms and a human population of roughly 700, but no village or town.

Model input parameters

SLURP operates on a daily basis and requires information on climate, land use, and physiography. A weather station was installed centrally on the watershed (77° 39' 43" W, 45° 55' 37" N) to measure meteorological parameters. The "St. Esprit" station was based on a Campbell CR10 datalogger programmed according to the Environment Canada (1992) Guidelines for Co-operative Autostations. For the parameters of air temperature, relative humidity, wind speed and direction, soil temperature,

Table 1. Calibrated parameter values according to land use for the SLURP model.

Parameter		Cover								Range	
No.	Description	Corn	Wheat	Soybean	Vegetable	Alfalfa	Pasture	Forest	Bare	Urban	Min	Max
1	Initial content of snow store (mm)	192.0	58.2	200.0	135.7	34.5	259.3	208.0	250.0	202.3	1	1000
2	Initial content of the slow store (%)	14.3	36.6	73.4	22.7	87.1	58.9	21.6	93.6	0.0	0	100
3	Maximum infiltration rate (mm/d)	63.4	144.5	10.5	99.8	72.8	21.3	75.7	148.5	170.7	10	100
4	Manning roughness, n	0.09	0.06	0.01	0.10	0.10	0.10	0.0001	0.0001	0.0001	0.0001	0.1
5	Retention constant for fast store	1.0	1.0	50.0	50.0	50.0	1.0	4.2	5.0	5.0	1	50
6	Maximum capacity for fast store (mm)	352.8	438.5	415.5	153.1	77.8	420.8	360.6	396.0	60.0	10	500
7	Retention constant for slow store	185.7	52.1	200.1	91.7	19.9	27.3	121.7	274.8	225.1	10	300
8	Maximum capacity for slow store (mm)	304.5	52.1	208.8	512.6	901.2	595.7	37.6	428.0	262.2	10	1000
9	Precipitation factor	0.8	0.8	1.5	0.8	0.8	1.0	0.8	1.42	0.8	0.8	1.5
10	Rain/snow division temperature (°C)	1.5	0.5	2.0	-2.0	0.6	-1.1	-2.0	2.0	-1.2	-2.0	2.0

solar radiation, rainfall and snowfall intensity, and snow depth, readings were taken every 5 s then averaged over 15 or 60 min intervals. Daily bright sunshine hours, unavailable locally, was obtained from the Dorval International Airport station, located approximately 55 km SSW of the watershed. These data were used to estimate percent cloud cover. Given that SLURP was only applied to the St. Esprit runoff data *a posteriori* no spatially distributed measures had been made of percent snow-cover, snow water equivalent, or snow depth, nor were winter aerial photographs of the watershed of sufficient resolution available. Snow-covered area was estimated by linearly simulating percent coverage throughout the winter season, based on the single observations of snow depth made at the St. Esprit weather station. Snow water equivalent was estimated by using the snow depth data and snow density measurements on a snow course network located in Joliette, 18 km ENE from the study site (MEFQ 1994).

A control section was identified at the outlet of the St. Esprit watershed (77° 39' 01" W, 45° 54' 51") and a gauging station installed. Water level in the control section formed by a bridge was measured using a Druck (Druck Limited, Groby, Leicester, UK) 950 submersible pressure transducer (0-34.5 kPa range), buried in the bottom of the stream. An ultrasonic level sensor (UDG01) was installed downstream to assess the change in water level through the control section and serve as a backup for the pressure transducer. Both sensors were monitored with a Campbell CR10 datalogger. A rating curve relating discharge to water level elevation was developed for the section by measuring velocities in the section using a velocity meter.

An additional secondary flow measurement system was also installed in the control section. The FLOWLOG datalogger (FLOWLOG, Aberdeen, UK) measured velocity and depth in the stream and served as a backup. During the winter period (December to March), with ice over on the channel, discharge varied little. Hydrological data were measured at 5 s intervals and stored as means over a 15 min period. Full details of the hydrologic measurements are given in Enright et al. (1995).

The 21 soil texture series were reclassified into 3 classes: light, medium, and heavy. Hydraulic conductivity (K) values were assigned to the value of the predominant soil class in each land use based on an areal weighing estimate (Rawls et al. 1982).

Land use data were used to estimate leaf area index (LAI) through a two step process. A number of works have shown a significant and generally linear relationship between combinations of the red [R] and infrared [IR] reflectance of various major field crops and ground cover or LAI: barley (*Hordeum vulgare* L.; Peñuelas et al. 1997); maize (Walburg et al. 1982); potatoes (*Solanum tuberosum* L.; Bouman et al. 1992); soybean (Holben et al. 1983); sugar beet (*Beta vulgaris* L.; Clevers 1997); durum wheat [*Triticum aestivum* L. subsp. *durum* (Desf.) Husn.; Aparicio et al. 2000]; and conventional wheat (Mahey et al. 1991). A number of reflectance indices have been derived, the best of which are the simple ratio (SR) of IR/R and a weighted difference or normalized difference vegetation index (NDVI; Rouse et al. 1973, 1974; Tucker 1979):

$$NDVI = \frac{IR - R}{IR + R} \quad (1)$$

Bausch (1993) described how the relationship between the corn seasonal curve of NDVI and the basal consumptive coefficient (k_{cb} ; Wright 1982) for corn is linear. A similar approach was used for corn and the other crops in the watershed. This approach entailed using estimated crop coefficients (k_c ; Doorenbos and Pruitt 1977) throughout the growing season, which were used to calculate NDVI and subsequently LAI values (minimum and maximum according to the variation in NDVI) for the land uses described in this study (Fig. 2). The assumption was that $k_c \cong k_{cb}$ though it does neglect the effect of evaporation from the soil surface (k_e) which occurs during the initial stage of crop development, when the expanding canopy does not yet cover the ground.

Finally, best-fit curves between the estimated LAI and the number of days after planting were used to simulate LAI for each crop throughout the growing season. The fitted data were inputted into the SLURP model as "beginning of month LAI" (January to December); the model interpolated daily values for each land use.

Other parameters such as maximum capacities and retention constants for the fast storage (upper soil layer) and the slow storage (groundwater) were initialized according to land use following Kite's (1992) approach. Lower values were assigned to bare ground, intermediate values to crops and grass, and the highest values to wooded areas.

Since SLURP is a distributed parameter model, it requires a physiographic description of the watershed. The following information was therefore required: sub-basin areas, percentage of the sub-basin under each land use, distances and change in elevation from each land use to the stream, and from each land use to the sub-basin outlet (Kite 1998). Existing sub-basin and channel network digital maps produced by Mouzavizadeh (1998) were used for this purpose. A digital terrain model (DTM) was produced using the spline interpolation method and digital point elevation data provided in 1999 by the Quebec Cartographic Centre. The stream network digital file was converted to a network topology by placing nodes at 20 m intervals. Further analysis of the spatial data to calculate the 'to stream', and the 'to sub-basin outlet' distances from each land use and the respective changes in elevation was done using GIS and spreadsheets. All spatial analyses were performed using Arc View (AV) version 3.1 and Spatial Analyst extension for AV 1.1 (Romero 2000). The model was run using a daily output option with non-external (between sub-basins) flow routing. The physiographic components of the model are shown in Fig. 1.

The SLURP watershed model

The Semi-distributed Land Use Runoff Processes (SLURP) model is a continuous, spatially-distributed watershed model that uses parameters associated with land cover or land use characteristics to simulate the hydrology of a watershed. It carries out a vertical water balance for each element of the matrix represented by the number of sub-basins and land uses occurring in each sub-basin. The vertical water balance includes interception, snowmelt, infiltration, surface runoff, and percolation (groundwater flow). Runoff is optionally routed within and between the subbasins using the Muskingum method developed by McCarthy in 1938 (cited in Viessman et al**.** 1989).

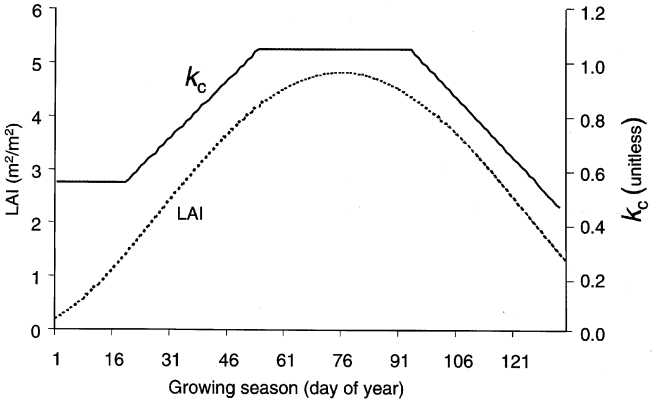

Fig. 2. Leaf area index (LAI) and crop consumptive use coefficient (k_c) for corn through the growing season.

In this application a non-external routing (between subbasins) was selected, based on the size of the watershed and the model daily time step. The model describes processes such as actual evapotranspiration, snow storage and melt, infiltration, runoff, and groundwater flow over each identified land use within each sub-basin or Aggregated Simulation Area (ASA) of the watershed. Weighted by the precentage of the ASA covered by a particular land use, the flow was converted to m^3/s and added to the total flow of the ASA. Specific land class designations for drained or undrained lands were not created as any information on subsurface drainage systems was available on a land parcel basis and accurately integrating a number of such parcels into a larger grid system would have been difficult and time consuming. Furthermore, while on a short term basis (day or week) not taking subsurface drainage into account might lead to misprediction of the runoff/infiltration ratio, and consequently of peak flow extent and timing, on a seasonal basis such short-term differences should not significantly alter total seasonal runoff.

A modification of the Penman ET equation is used to estimate potential evapotranspiration by solving the energy balance and aerodynamic equations. The daily net radiation (R_d) required in the Penman equation is estimated within SLURP from either the measured global solar radiation (RF1 standard) or from recorded hours of bright sunshine. Then, actual evapotranspiration (ET_a) is estimated by applying the Complementary Relationship Areal Evapotranspiration method (CRAE) by Morton (1983).

$$ET_a = 2E_w - E_p \quad (2)$$

where:

ET_a = actual evapotranspiration (mm)
E_w = wet environment evaporation (mm), and
E_p = Penman potential evapotranspiration (mm).

The snowpack is depleted to snowmelt based on a melt rate (mm d^{-1} $°C^{-1}$) and an arbitrary threshold snowpack melt temperature equal to the rain/snow threshold temperature. In SLURP the snowmelt rate on any day is calculated using a quadratic curve fit to values assigned to each land use on January 1 and July 1.

Deriving parameters for a set of land covers could be helpful in transferring the model to a similar watershed (containing the same land covers) without the need for new calibration (Kite 1992). The present model has been used for several different purposes in watersheds varying in size from a few hectares (Su et al. 2000) to 17 000 to 57 000 km^2 (Droogers and Kite 1999; Sanjay et al. 1998) to macroscale basins of 1.6 million km^2 (Kite 1995).

Model calibration and evaluation

Ten model parameters were calibrated using the Shuffled Complex Evolution method, an automatic calibration technique incorporated into SLURP (SCE-UA; Duan et al. 1994). The melt rate parameter (mm d^{-1} °C^{-1}) was manually calibrated. The best combination of values was found when setting the range at 0.8 mm d^{-1} °C^{-1} for January and 3.0 mm d^{-1} °C^{-1} for July.

Almost three years (April 1994 to December 1996) of records were used for calibration. Data from 1997 and 1998 were used to validate the model. SLURP performance was assessed by the Nash and Sutcliffe (1970) coefficient of performance (Eq. 1).

$$R^2 = \frac{\sum_{i=1}^{i=n}\left(O_i - \overline{O}\right)^2 - \sum_{i=1}^{i=n}\left(S_i - O_i\right)^2}{\sum_{i=1}^{i=n}\left(O_i - \overline{O}\right)^2} \qquad (3)$$

where:

O_i = individual observed value,
S_i = individual simulated value,
$\overline{O}$ = mean observed value, and
n = number of paired observed-simulated values.

The R^2 evaluates the error relative to the natural variation in the observed values. An R^2 of 1.0 represents a perfect prediction, while a value of 0.0 represents a prediction no better than simply taking the mean observed value, increasingly negative values indicate increasingly poorer predictions. On a monthly, seasonal or annual basis, a simple percent difference between observed and predicted runoff was used. These two approaches for model validation are built into SLURP.

Computing ET

The Baier and Robertson potential evapotranspiration model (BR), as proposed by Rochette et al. (1990), was used to estimate potential ET (ET_p) in the watershed. The model is:

$$ET_p = \alpha\left[a_{0i} + a_{1i}T_{\max} + a_{2i}\left(T_{mas} - T_{\min}\right) + a_{3i}R_d\right] \qquad (4)$$

where:

ET_p = potential evapotranspiration of well - watered grass (mm/d),
T_{max} = maximum daily temperature (°C) ,
T_{min} = minimum daily temperature (°C),
R_d = daily net radiation (MJ m^{-2} d^{-1}),
α = calibration coefficient (dimensionless), and
a_{0i}….a_{3i} = empirical coefficients calibrated for regional wind speed (182.1 x 10^{-2}, 220.7x10^{-4}, 121.6 x 10^{-3} and 0.13, respectively (dimensionless).

The α parameter, a dimensionless calibration coefficient to adapt the model to various regions of eastern Canada, was proposed by Rochette et al. (1990). Following the approach adopted by Perrone et al. (1998), the coefficients for the Mirabel region (50 km west of the watershed) were used. These coefficients approximate the characteristics for wind speed and elevation of the study area.

$$\alpha = b_0 + b_1 J_M + b_2 J_M^2 + b_3 J_M^3 + b_4 J_M^4 + b_5 J_M^5 \qquad (5)$$

where:

J_M = number of days after 1 May to 30 September (0 to 152 in our study, dimensionless), and
b_0…b_5 = polynomial coefficients for the Mirabel region 0.785, 0.047, -3.322 × 10^{-3} , 0.100 × 10^{-3}, -1.520 × 10^{-6}, 12.233 × 10^{-9} (dimensionless).

The BR ET_p model (Eq. 4) was written using the ANSI C programming language to automate input parameters reading and results writing. Daily ET_p in the watershed was estimated by running the program with five years of data (1994-1998) from May to September. Temperature data required for the model were measured at the watershed; solar extraterrestrial radiation (R_d) was obtained from tabulated values according to site latitude (ASCE 1990).

RESULTS and DISCUSSION

Model calibration

An automatic optimization of the parameters shown in Table I was performed using SCE-UA (Duan et al. 1994) allowing up to 5000 iterations. The goodness of fit of the predicted versus observed runoff during the calibration period (1994-1996) yielded a Nash/Sutcliffe criterion coefficient of 0.522, and the percent difference between total observed and predicted runoff was -17.5 %, indicating that total runoff was under-predicted during this period. Daily observed and SLURP-predicted runoff over the calibration period are shown in Fig. 3.

Model validation

Using parameters obtained in the calibration, the model was validated during 1997 and 1998. Daily ET_a, as well as snowmelt and runoff at the outlet of the entire watershed are discussed as measurements were not made at the sub-basin level. However, this was sufficient to meet the objectives proposed in this investigation.

Evapotranspiration The BR model predicted a maximum ET_p value (5.53 mm/d) on June 9 for both 1997 and 1998. SLURP estimated peak ET_a on June 8 (6.03 mm) and May 24 (5.63 mm) in 1997 and 1998, respectively.

Areal estimates of actual evapotranspiration ET_a in a manner similar to other model outputs (runoff, snowmelt), were carried out in a spatially-distributed manner. SLURP estimated basin areal average ET_a for 1997 as 535.6 mm. This was computed from the predicted annual ET_a values for 18 sub-basins. In 1998 the basin areal ET_a was 589.1 mm. The model predicted evapotranspirative demand from March to November. The mean predicted monthly ET_a for 1997 and 1998, are given in Table 2.

To assess the accuracy of the SLURP-predicted ET_a, simulated results were compared to those estimated by the BR

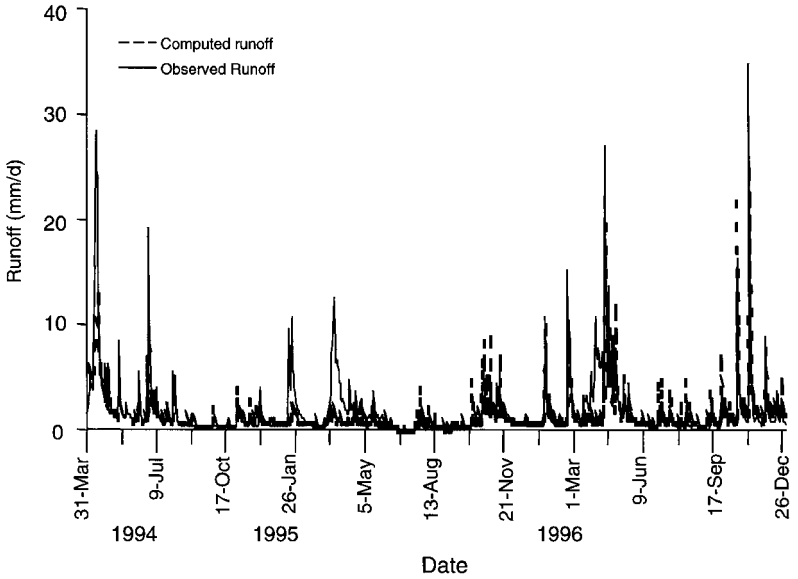

Fig. 3. Observed and SLURP-computed runoff for 1994-1996.

Table 2. SLURP-predicted average monthly evapotranspiration.

Month	Predicted monthly Et_a (mm)	
	1997	1998
January	-	-
February	-	-
March	2.2	6.1
April	39.1	72.8
May	74.1	111.6
June	139.6	92.9
July	116.6	107.5
August	90.0	91.4
September	46.4	80.1
October	23.5	24.3
November	2.6	2.4
December	-	-

- not predicted

model, which was calibrated for this region (Rochette et al. 1990). Barnett et al. (1998) tested 5 ET models and found that the BR model gave the least seasonal differences (1.5% and 7.5% for the years 1995 and 1996, respectively) when compared to ET derived from corrected pan evaporation data measured at L'Assomption, 18 km SSE from the study site. This afforded the opportunity to use the BR model as a reliable control in the comparison. Growing season average ET data from 1994 to 1998 were used.

The SLURP model computes ET_a, while the BR model estimates ET_p. Therefore, to produce a meaningful comparison, it was necessary to convert potential ET_p from the BR model into ET_a. This conversion was achieved by calculating a representative ET (the average seasonal ET_{corn}) using the corn consumptive use coefficient (k_c), and multiplying it by ET_p estimated by the BR model.

The Student *t*-test, used to test for differences between seasonal ET_a computed by the SLURP and BR models (Table 3), showed no significant difference ($P>0.25$).

Snowmelt Spring snowmelt, which generally occurs between 15 March and 30 April, was the most important hydrological event on the Saint Esprit watershed in four of five years of records (Romero 2000). In 1996, a greater than 1 in 100 year storm event (110 mm in 24 h) occurred in November. This resulted in the most important runoff event of the year.

Table 3. Comparison of mean growing season evapotranspiration derived from SLURP or the Baier-Robertson (BR) Model, based on Student *t*-Test.

Model	Mean ET_a (mm/d)				
	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
$P(H_0$: SLURP=BR)	0.79	0.29	0.95	0.57	0.82

Gangbazo et al. (1997) described the spring snowmelt as usually being the major annual hydrological event in Quebec, in which as much as 30% of the annual runoff may result from snow melting on frozen soils.

Using the SLURP model, simulations of snowmelt and its effect on total runoff were studied. For each of the two years of validation, the model predictions of the timing of the snowmelt were reasonably accurate. Predicted snowmelt averaged 352.5 mm in 1997 and 269.5 mm in 1998, respectively.

Peak snowmelt (during snowmelt period) is associated with the occurrence of maximum runoff in the watershed. In 1997, the predicted snowmelt for all land uses peaked during the last week of April. The predicted peak snowmelt (April 23, 18.3 mm), averaged over all land uses, occurred 1 day after the observed peak runoff in 1997. In 1998 peak snowmelt was distributed between March and April. The predicted peak snowmelt (March 29, 17.9 mm) occurred within 2 days of the observed peak runoff in six of nine land uses. During the two years, the predicted peak snowmelt for the bare and soybean land uses occurred later than the remaining land uses. Predicted total depletion of the snowpack for the former land uses occurred very late (mid May 1997 and late April 1998, respectively), which is unrealistic for this watershed, since by these dates most agricultural fields are being or have been planted. Moreover, by early May the parameter "initial content of the snow store" and melt rate were quite uniform for the agricultural land uses. This response, after the automatic calibration of the model, reveals problems of the estimated snow parameters (snow covered area and snow depth) throughout the watershed, and consequently the inability for the model and its calibration routine to compute more reasonable results using this data.

It is recognized that point measurements of snowmelt are not good estimates of areal snowmelt in a watershed (Kite 1998). In the upper parts of the watershed, at slightly higher elevations (10 to 20 m) and with more wooded areas, the snowpack persisted up to one week longer, depending on the land use. The

Table 4. Comparison between observed runoff, predicted runoff, and average predicted snowmelt during the snowmelt period.

Year	Observed runoff (mm)	SLURP predictions	
		Snowmelt (mm)	Runoff (mm)
1997	254.15	229.22	175.74
1998	287.33	209.35	132.33

automated weather station is located in the middle of the intensive agricultural areas. It was difficult to establish a clear trend between the measured snow depth at the weather station and the areal snowmelt predicted by the model.

To assess the importance of the snowmelt event as it contributes to total runoff, the average daily snowmelts were summed over the spring snowmelt period (March 29 to April 27 in 1997, and March 27 to April 30 in 1998). Data in Table 4 compares the results of both the observed and the predicted runoff with the predicted snowmelt during the spring snowmelt period. For both years of this study during the validation, the amount of predicted snowmelt was less than measured runoff and greater than predicted runoff. The fact that predicted snowmelt was greater than predicted runoff indicates that a combination of sinks in the model such as seepage to groundwater and moisture storage into the soil profile removed part of the snowmelt from the watershed during the snowmelt period, before it could contribute to runoff at the outlet.

These discrepancies in snowmelt predictions are likely related to the lack of sufficiently spatially-detailed snow cover, depth and water equivalents over the watershed, or the fact that after autocalibration the model does not allow one to reset parameters when these appear erroneous. For example, some of the Manning's roughness *n* values in Table 1, those for forest and pasture in particular, are unrealistically low. Similarly, the predicted timing of snowmelt for some cover types, particularly soybean, was delayed by over a week beyond the latest measured snowmelt on such land types.

Annual runoff Although SLURP over-predicted runoff, in general, on an annual basis the model performed well in both years. In 1997 the model over-predicted (541.6 mm) the observed runoff (479.4 mm) by 12.9%. In 1998, runoff was over-predicted by 13.1%. The observed and predicted runoffs were 464.8 mm and 525.5 mm, respectively. These results indicate that even though the SLURP model was developed for hydrological studies in range-land basins at the meso-and

Table 5. Seasonal runoff predicted by the SlURP model compared with observed runoff at the outlet.

Year	Season	% difference	Runoff (mm)	
			SLURP	Observed
1997	Growing	79.96	133.21	74.02
	Non-growing	0.75	408.41	405.32
1998	Growing	119.58	104.96	47.80
	Non-growing	0.84	420.49	416.98

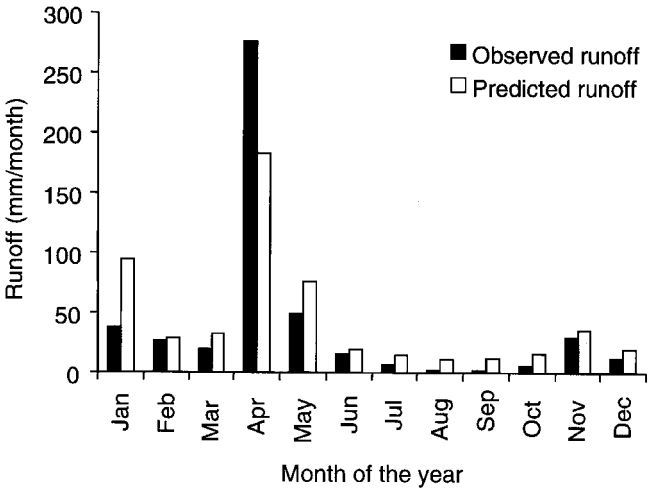

Fig. 4. Observed vs SLURP-computed monthly runoff during validation (1997).

macroscale level, it was capable of producing an acceptable result of the long term water balance of this small agricultural watershed.

Performance was also analyzed on a seasonal basis, May to September *(*growing season) vs October to April (non-growing season). Most of the runoff in the watershed occurred during the non-growing season, mainly during spring snowmelt and late fall precipitation. Table 5 shows seasonal runoff prediction by the SLURP model, compared to the observed data. The model generally over-predicted runoff during the growing season (80 and 120% in 1997 and 1998, respectively), but was accurate to within 1% during the non-growing season (Table 5). However during the non-growing season, over-estimations occurred during the period of October to February, while under-estimations of similar magnitude occurred from March to April, the period of spring snowmelt. Predicted runoffs in the non-snowmelt periods of 1997 and 1998 were 366 and 393 mm, respectively, compared to the 225 and 177 mm that were measured. Clearly these predictions were quite poor.

During the calibration period, 1995 was a somewhat dry year, whereas 1994 and 1996 were wet years. Rainfall in 1996 (1329 mm) was 38% greater than the local long term average. The validation of the model was carried out during an exceptionally dry year (1997) and somewhat dry year (1998). Calibration during an overall wet period may have introduced some bias in the final calibrated parameters, leading in general, to over-estimates of runoff during dry years of the validation period.

Performance on a monthly basis is presented in Fig. 4 for 1997 and Fig. 5 for 1998. During 1997, the model over-predicted runoff in 11 of 12 months; April was the exception. In 1998, only in June was runoff accurately predicted; whereas, for the other months except March and April, the observed runoff was over-predicted. This response shows the effect of peak snowmelt 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 during the validation. However, the difference between observed and predicted runoff was important during this event.

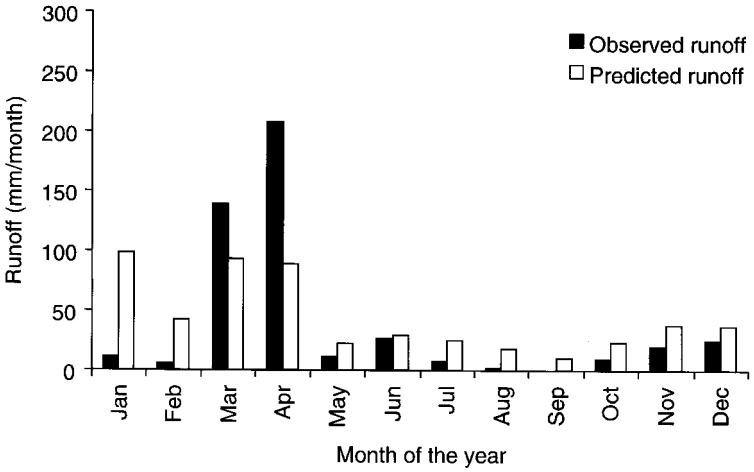

Fig. 5. Observed vs SLURP-computed monthly runoff during validation (1998).

Thus, maximum observed runoff for 1997 occurred on April 22 (20.4 mm), whereas the model predicted maximum runoff on April 23 (13.7 mm) a day-basis difference of -32.8%. In 1998 the maximum observed runoff was recorded on March 31 (26.9 mm), a day-basis difference of -50.9% compared to SLURP predicted runoff for March 30 (13.2 mm).

Most of the time however, the model over-predicted runoff. Annual differences, which might seem acceptable (i.e. 12.9% 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 only 6.23 %. The least monthly percent difference in 1998 was 8.18 %, in June. In general, monthly differences during both years were quite high. The largest differences (worst predictions) occurred during months in which particularly small flows were recorded at the outlet, e.g. August and September. The order of magnitude of inaccuracy of erroneous prediction on a monthly basis was similar to those reported by Mouzavizadeh (1998) using the ANSWERS 2000 model at this watershed.

Percent differences in observed versus predicted runoff on an annual basis differed little between 1997 (12.9%) and 1998 (13.05%). On a daily basis, the Nash Sutcliffe coefficient showed a much poorer performance in 1998 (0.483) than in 1997 (0.659). Kite (1992, 1995) reported coefficients of up to 0.91 and 0.94 for model validation. Thus, SLURP did not fully simulate the daily runoff produced in the watershed under the particular conditions existing during the years of validation.

The existence of sub-surface drainage on approximately 50% of the agricultural land affected the response to runoff of a large portion of the watershed corresponding to 32% of its surface area. Works carried out in southwestern Quebec by Sultana (1985) and Madramootoo (1985) confirm that subsurface drainage reduces peak outflow rates and runoff volumes and causes longer times to peak and increased lag time. This leads to an increased infiltration capacity of the soils before runoff occurs, while draining water out of the 0-1 m profile more rapidly, once it has infiltrated, resulting in an attenuation of the hydrograph compared to what would be observed on undrained agricultural lands. This condition in the natural system was not represented in the model and could have had an impact in both: (i) daily differences observed between the actual and the predicted runoff (increased lag time in the watershed, affecting the coefficient of performance of the model on a daily basis), and (ii) differences in the annual observed and predicted flows which might be due to water losses as a consequence of drained water which did not contribute to the total runoff at the outlet. This water may have been stored in the ditches and used for irrigation.

The accuracy of the hydrograph simulation must be judged within the objectives of the study. In water balance studies i.e. where 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.

CONCLUSIONS

Spatially distributed hydrological models have been developed to evaluate the influence of the spatial distribution of controlling parameters on the simulated hydrological behavior of a watershed. This, however, relies on the use of extensive data and knowledge of the system studied. The application of the SLURP model in the Saint Esprit watershed yielded predictions of evapotranspiration which were in good agreement with previous estimates carried out in the watershed using the generally accepted BR model. The long term seasonal average of the predicted actual ET_a from the SLURP model compared well to the seasonal average of actual ET for corn (ET_{corn}) estimated by using the potential evapotranspiration from the Baier and Robertson model calibrated for the region.

This represented the first modelling of snowmelt in this watershed. The model performed well in reproducing the timing of peak snowmelt and consequently the timing of maximum peak runoff. However, in both years of model validation, problems such as the extension of the snowmelt period for the bare and soybean land uses occurred, even when calibrated parameters such as initial content of the snow store and melt rates for these land uses were fairly similar to those of other agricultural uses. After calibration, these parameters could not be adjusted to better reflect the actual situation. Lack of studies addressing snowmelt and its contribution to total runoff at the site precluded any comparisons or solid conclusions regarding the effectiveness of the model in predicting snowmelt.

Future applications must implement more rigorous techniques to determine snow characteristics spatially over the watershed. For example, snow depth might be sampled through a snow course network, the snow-covered area measured in the field or estimated by satellite imagery techniques. This will allow a better parameterisation of the model and at the same time a solid base to evaluate the capacity of SLURP to simulate snow-related processes at this site.

Runoff predictions for the watershed obtained from the SLURP model were acceptable on an annual basis. While peak runoff, during the spring snowmelt, was predicted within one

day for both years of validation, the model over-predicted observed total spring runoff. Seasonal predictions showed an alternate pattern of poor and good performance for the growing and non-growing seasons, respectively. Over both years, predicted runoff over the non-growing season was in good agreement (error < 1%) with observed runoff; however this masked offsetting under and overpredictions at the beginning and end of the non-growing season, respectively.

Short term predictions (monthly or daily) were poor, suggesting that with the present data SLURP may only be applicable for water balance studies in the Saint Esprit watershed and for long term simulation such as on the annual basis. The model, the selection of land covers, and the collection and calibration of their associated parameters requires modifications if the model is to be used for shorter term predictions.

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LIST OF SYMBOLS and ABBREVIATIONS

ASA	Aggregated Simulation Area
BR	Baier-Robertson (evapotranspiration model)
CRAE	Complimentary Relationship Areal Evapotranspiration
DTM	digital terrain model
E_w	wet environment evaporation (mm)
E_p	Penman potential evaporation (mm)
ET_a	actual evapotranspiration (mm)
Et_{corn}	Baier-Robertson-predicted actual evapotranspiration for corn (mm)
GIS	geographic information system
IR	infrared reflectance from crop canopy (%)
J_M	number of days after May 1 (until September 30, range 0 -152)
K	hydraulic conductivity of the soil (m/s)
LAI	leaf area index (unitless)
O_i	individual observed value for runoff (mm)
$\overline{O}$	mean observed runoff value (mm)
R	red reflectance from crop canopy (%)
R_d	daily net radiation (MJ m^{-2} d^{-1})
R^2	Nash-Sutcliffe coefficient of performance (unitless)
S_i	individual simulated runoff value (mm)
SLURP	Semi-distributed Land Use Runoff Processes model
SR	simple ratio reflectance index (unitless)
T_{max}	maximum daily temperature (°C)
T_{min}	minimum daily temperature (°C)
a_{0i} - a_{3i}	empirical coefficients for regional wind speed (unitless)
b_0 - b_7	polynomial coefficients for calculation of α (unitless)
k_{cb}	basal corn consumptive coefficient
k_c	crop coefficient
k_e	evaporation from the soil surface (mm)
n	(i) number of paired observed-simulated runoff values (ii) Manning roughness coefficient
α	calibration coefficient for ET_p calculation (unitless)