REVUE DES SCIENCES DE L'EAU, Rev. Sci. Eau 16/3(2003) 459-474

Evaluation of a rangeland model

Évaluation d'un modèle des zones de pâturages et de prairies naturelles

F. BOURAOUI[1]*, M. L. WOLFE[2]

Reçu le 29 novembre 2002, accepté le 11 juillet 2003.

RÉSUMÉ

Une grande quantité d'eau est perdue dans les zones de pâturage et prairies naturelles du fait de la présence dans ces régions de plantes à forte transpiration. La gestion du couvert végétal et des bassins versants a été proposée comme moyen pour augmenter la disponibilité des ressources en eau. Des efforts accrûs ont été consacrés au développement de pratiques de gestion et d'outils pour évaluer le potentiel d'augmentation de la ressource en eau. La modélisation hydrologique joue un rôle clé dans ces efforts. Un des outils les plus complets pour la modélisation dans les zones de pâturage et prairies naturelles est le modèle SPUR. Il s'agit d'un modèle de bassin versant, spatialement semi-distribué. Le modèle est constitué de cinq modules principaux qui incluent les aspects suivants : climat, hydrologie, plantes, animaux et économie. La composante hydrologique du modèle prend en compte à un pas de temps journalier les phénomènes de ruissellement, évapotranspiration, percolation et écoulement latéral. Le ruissellement est calculé à partir du numéro de courbe qui dépend du couvert végétal, des pratiques culturales, ainsi que des conditions hydrologiques. Cependant l'utilisation par le modèle de la méthode du numéro de courbe pour déterminer le ruissellement pose de sérieux problèmes quant à l'efficacité du modèle. Dans notre recherche, nous avons substitué la méthode des numéros de courbe par l'équation de Green et Ampt. Un avantage majeur de cette approche est l'utilisation de l'intensité de la pluie comme variable de forçage au lieu de la pluie journalière. De plus, cette équation d'infiltration utilise des paramètres physiques comme la conductivité hydraulique à saturation. L'objectif de cet article est de présenter les performances du modèle SPUR original et modifié sur trois types de couvert végétal : sol nu, sol enherbé et buissons.

Trois années de mesures collectées sur le bassin versant de Throckmorton (Texas, États-Unis d'Amérique) ont été utilisées pour la calibration et la vali-

---

[1] Institute for Environment and Sustainability, Joint Research Centre of the European Commission, TP 460, I-21020 Ispra (VA), Italy.– e mail : faycal.bouraoui@jrc.it – Tél. : 00 39 0332 785173, Fax : 00 39 0332 785601.

[2] Biological Systems Engrg. Dept., Virginia Polytechnic Institute and State University, Blacksburg, VA 24061-0303, USA.

* E-mail of corresponding author: faycal.bouraoui@jrc.it

** Les commentaires seront reçus jusqu'au 30 juin 2004.

dation des modèles. Les performances des modèles ont été évaluées en utilisant le coefficient d'efficience de Nash et Sutcliff. Le calage a porté sur la première année de mesure. Pour le modèle original, le calage a consisté à ajuster les numéros de courbe de manière à optimiser l'efficience. Pour le modèle modifié, il n'a été procédé à aucun calage. Les valeurs de conductivité hydraulique à saturation ont été estimées en utilisant des équations de pédotransfert en se basant sur les propriétés texturales et structurales des sols. L'introduction dans le modèle SPUR de l'équation de Green et Ampt a considérablement amélioré la performance du modèle pour la prévision du ruissellement sur tous les sites. L'efficience moyenne pour les prévisions du ruissellement mensuel sur sol nu est de 0.16, alors que celle-ci est négative pour le modèle original (– 0.11). Pour les sites enherbés l'efficience du modèle modifié est de 0.48 alors qu'elle est négative pour le modèle original. L'utilisation du numéro de courbe a résulté en une surestimation systématique du ruissellement sur tous les sites. De manière générale, le modèle original et le modèle modifié présentent de meilleures performances sur les sites non nus. Ceci est dû au fait que les deux modèles sous-estiment de manière significative l'évaporation sur les sols nus. Un des désavantages des deux modèles est en effet de limiter l'évaporation aux premiers 15 cm du sol. L'introduction de l'équation de Green et Ampt a amélioré les performances du modèle pour la prévision du ruissellement aussi bien à l'échelle mensuelle qu'annuelle. De plus, le modèle modifié est sensible au type d'occupation du sol et est donc adapté comme outil pour l'analyse de scénario en vue de préserver les ressources en eau.

Une analyse de sensibilité a été conduite afin d'évaluer l'impact des paramètres d'entrée sur les sorties des deux modèles. L'analyse de sensibilité a consisté à modifier systématiquement les paramètres d'entrée de plus ou moins 10 %. Pour le modèle original, l'analyse a porté sur l'influence du numéro de courbe, et pour le modèle modifié celle-ci a porté sur l'étude de l'impact lié aux paramètres utilisés pour calculer la conductivité hydraulique à saturation. Concernant le modèle original, une augmentation du numéro de courbe de 10 % entraîne une augmentation du ruissellement de 120 % pour le sol nu, et aux alentours de 100 % pour les autres sites. L'impact de ces variations sur l'évaporanspiration est minimal, avec une variation maximale de 16 % pour le sol nu. Concernant le modèle modifié, la teneur du sol en sable est le paramètre ayant la plus grande influence sur la quantité d'eau ruisselée pour le sol nu. Par contre, pour les lysimètres ayant un couvert végétal, le pourcentage de sol couvert par la canopée est le facteur majeur contrôlant la quantité d'eau ruisselée. Les paramètres liés au couvert végétal ont un plus grand impact sur le ruissellement que les paramètres liés aux propriétés intrinsèques du sol.

Globalement l'introduction de l'équation de Green et Ampt a amélioré les capacités prédictives du modèle. Outre le fait que le modèle modifié ne nécessite pas un calage particulier pour la détermination des paramètres de transfert de l'eau dans le sol, il se base sur l'intensité de la pluie pour la détermination du ruissellement. Il a été montré que le modèle modifié est sensible aux changements de type d'occupation du sol. Il peut donc être donc utilisé comme outil pour évaluer l'impact de différents scénarios d'occupation du sol sur les ressources en eau dans les zones de pâturage et prairies naturelles. Toutefois, des améliorations, telles que l'introduction de l'impact du développement de fissures sur l'infiltration (écoulement préférentiel) ainsi que sur le phénomène d'évaporation devraient être prises en compte afin d'améliorer les prévisions du bilan hydrologiques, notamment sur sol nu.

Mots clés : *modèle SPUR, prairie, numéro de courbe SCS, équation Green et Ampt.*

SUMMARY

A large amount of water is lost on rangelands due to the conditions of the watersheds, specifically due to the presence of plant species with a high transpiration rate. Vegetation manipulation and watershed management have been proposed as means to increase water yield. Increasing efforts have focused on developing management practices and tools to evaluate the potential for increased water yield. Hydrologic modeling plays a key role in these efforts, and one the most comprehensive tools for simulating rangelands is the SPUR model. However, some limitations seem to arise from the use of the SCS curve number method for simulating the runoff/infiltration process. In this project, the SCS curve number method was replaced by the Green and Ampt infiltration equation. One of the major advantages of the approach is that it relies on rainfall intensity rather than on daily rainfall, and it uses physical parameters such as the saturated hydraulic conductivity. The original and the modified SPUR models were tested for three different covers: bare, grass and mesquite. The use of the Green and Ampt infiltration equations improved model prediction of surface runoff. Furthermore, the model was shown to be sensitive to vegetation manipulation, and could be used as a water resources management tool.

Key words: *SPUR model, rangeland, SCS curve number, Green-Ampt.*

1 - INTRODUCTION

In the past, rangeland management was dedicated to the improvement of plant and animal production and range conditions. Increasing pressure on range managers to save and supply more water has added to the complexity of range management. Population growth and economic expansion have increased demands on a limited water supply, and water has become one of the most important products provided by rangelands. A large amount of water is lost on rangelands due to the conditions of the watersheds, specifically due to the presence of highly transpirating plant species. The replacement of grasslands and savannas with shrubs and wood species lead to the decline of water yield (HIBBERT, 1979; THUROW and HESTER, 1997). Vegetation manipulation and watershed management have been proposed as means to increase water yield (GRIFFIN and MCCARL, 1989; HIBBERT, 1983). In Texas, rangelands contribute the most to the recharge of the Edwards aquifer, which is the primary source of drinking water for the town of San Antonio. The water balance of the Edwards aquifer is negative due to the increasing pumping. Brush management has been proposed to increase water recharge in view of a sustainable use of the Edwards aquifer (THUROW *et al.*, 2001). WILCOX (2002) reported literature on the positive impact of juniper control on the flow of springs in the Edwards Plateau. Increasing efforts have focused on developing management practices and tools to evaluate the potential for increased water yield (THUROW *et al.*, 2001; WU *et al.*, 2001). Hydrologic modeling plays a key role in these efforts.

One of the most comprehensive models developed specifically for rangeland management and research is SPUR – Simulation of Production and Utilization of Rangelands – (WIGHT and SKILES, 1987). SPUR simulates broad aspects of the rangeland ecosystem, including climate, hydrology, plant, animal and economics components. The SPUR model has been tested successfully for predicting runoff on several watersheds (SPRINGER *et al.*, 1984), however some limitations seem to come from the use of the Soil Conservation Service curve number (USDA, 1972) as highlighted by CARLSON and THUROW (1996). The SCS curve number was developed using site-specific data collected mainly in the Midwestern United States, potentially restricting the range of its applicability and transposability to other regions. Furthermore, runoff is not related to storm event duration or rainfall intensity, which may cause problems for discontinuous storms or storms of duration of few days (RALLISSON, 1980). In addition, extensive tables have been developed to determine the curve number on cropland based on soil type, hydrologic conditions, and land treatment and practices, but the availability of these tables for rangelands is limited and the available tables do not include important soil characteristics. RALLISSON (1980) suggested that the SCS method could be improved by including additional characteristics in the division of soil groups, such as saturated hydraulic conductivity and soil porosity.

WOOD and BLACKBURN (1984) tested the SCS curve number method on rangelands. The results showed that the runoff was overpredicted 67% of the time, underestimated 22% of the time, and predicted adequately in only 11% of the cases. They attributed these poor predictions to the limited hydrologic soil group classification. They suggested that this classification should be abandoned when determining the curve number for arid or semi-arid rangelands, because the hydrologic soil groups are based on assumptions that may not be valid. Furthermore, they also noted that the method gave better results when there was less rangeland vegetation, approaching the conditions under which the method was developed. This inherent problem with the curve number and its impact on predictions of surface runoff was noted by CARLSON and THUROW (1996) when using the SPUR model. Additional information about the main advantages and disadvantages of the curve number approach can be found in PONCE and HAWKINS (1996). An alternative to the SCS curve number approach is the Green-Ampt infiltration equation (GREEN and AMPT, 1911). This equation has been increasingly used in hydrological modeling because of the development of pedotransfer functions, which allow the determination of soil hydraulic transfer parameters (saturated hydraulic conductivity and pressure at the wetting front) from readily available local soil textural and structural information, and plant growth characteristics (RAWLS *et al.*, 1989). The ability of the GREEN and AMPT method (1991) to estimate infiltration and runoff on rangelands is illustrated by WILCOX *et al.* (1992), KIDWELL *et al.* (1997) and SAVABI *et al.* (1995).

The purpose of the following research is to present the evaluation of two versions of the SPUR-model: one using the SCS curve number approach and the other one based on the Green-Ampt infiltration equation, called respectively SPUR-SCS and SPUR-GA. Both models were tested on three different covers.

2 - MODEL DESCRIPTION

The SPUR model (WIGHT and SKILES, 1987) was developed as a research and management tool for rangelands. The model is composed of five basic components: 1) climate, 2) hydrology, 3) plant, 4) animal, and 5) economics. The hydrologic component is subdivided into three phases, including an upland phase, a snowmelt phase and a channel phase. The upland phase is based on the SWRRB model (WILLIAMS *et al.*, 1985) and simulates the processes of runoff, evapotranspiration, percolation, and return flow on a daily basis. The soil is discretized into vertical layers to take into account the variability of soil properties and plant rooting patterns.

2.1 Runoff / Infiltration

The original model simulates runoff using the SCS curve number method (USDA, 1972). The runoff is related to daily precipitation as follows:

$$Q = \frac{[CN(aP+2)-200]^2}{CN[CN(aP-8)+800]} \tag{1}$$

where Q is the daily runoff (cm), P represents the daily rainfall (cm), CN is the curve number, and a is a unit conversion factor equal to 0.3937. The curve number for a watershed depends on the antecedent soil moisture content, land use and treatment practices, the hydrologic surface conditions and the hydrologic soil group. The SPUR model uses a daily curve number based on a soil moisture accounting procedure developed by WILLIAMS and LASEUR (1976). The curve number method has been widely used because of its simplicity and because it relies on the determination of only one parameter: the curve number for soil moisture condition II (average condition).

The SPUR-GA model uses the Green-Ampt equation (GREEN and AMPT, 1911) to simulate infiltration. This approach assumes (i) a step water retention function h(θ) describing the relation between volumetric water content θ (cm^3/cm^3) and soil water pressure h (cm); and (ii) a one-point hydraulic conductivity function K_S (cm/hr), where K_s is the hydraulic conductivity for volumetric water content at natural saturation θ_S (cm^3/cm^3). The infiltration process is represented as a wetting front traveling down the soil profile with $\theta = \theta_S$ and $K = K_S$ behind the wetting front and $\theta = \theta_0$ and $K = 0$ ahead of the wetting front. The basic Green-Ampt equation to compute cumulative infiltration is:

$$K_s t = I - N_s \ln\left[1 + \frac{I}{N_s}\right] \tag{2}$$

where I is cumulative infiltration (cm), t is time (hr) and Ns (cm) is the effective matric potential defined as the product of the available porosity and the wetting front capillary potential. The capillary potential is supposed to be constant and to be invariant with depth and time. The original Green-Ampt equation was developed considering that the surface was ponded when infiltration started. The equation was modified by MEIN and LARSON (1971) to consider ponding for steady rainfall and by CHU (1978) to account for unsteady rainfall. The later version is used in the SPUR model. Prior to ponding the infiltration rate is equal to rainfall rate. After ponding, the infiltration is determined by solving equation (2) using Newton's approximation method.

The saturated hydraulic conductivity and the wetting front capillary potential can be estimated from field tests or values found in literature. They can also be determined from textural and structural soil properties (clay, silt, organic matter content, porosity) using statistical regression functions given by RAWLS *et al.* (1989). In this study the functions developed by RAWLS *et al.* (1989) were used. The saturated hydraulic conductivity is expressed as:

$$K_s = 0.0002C^2 \frac{(CP-RW)^3}{(1-CP)^2}\left(\frac{BD}{RW}\right)^2 \qquad (3)$$

where K_S is the saturated hydraulic conductivity (cm/hr), Cp is the effective porosity (cm), BD represents the bulk density (g/cm^3), RW is the residual soil water (cm), and C is a soil texture coefficient determined based on the textural composition of the soil. The effective hydraulic conductivity for an area under canopy cover, K_c (cm/hr), is computed using the following equation (RAWLS *et al.*, 1989):

$$\frac{K_c}{K_s} = C_f C_r\left[\frac{B_c}{A_c}\right] + MPF\left(1-\left[\frac{B_c}{A_c}\right]\right) \qquad (4)$$

where MPF is a macroporosity factor, B_c is the bare area under canopy (%), A_c is the canopy area (%), C_r is a crust reduction factor, and C_f is the canopy factor. The effective hydraulic conductivity for the area outside the canopy, K_0 (cm/hr), is computed by (RAWLS *et al.*, 1989):

$$\frac{K_o}{K_s} = C_r\left[\frac{B_o}{A_o}\right] + MPF\left(1-\left[\frac{B_o}{A_o}\right]\right) \qquad (5)$$

where B_0 represents the bare area outside canopy (%), and A_0 is the open area outside the canopy (%). The total effective hydraulic conductivity is determined by combining equations 4 and 5. Additional details about the determination of the various factors can be found in (RAWLS *et al.*, 1989).

2.2 Evapotranspiration

Evapotranspiration in both the SPUR-GA and SPUR SCS models is determined using the Ritchie approach (RITCHIE, 1972). Potential soil evaporation and plant transpiration are partitioned based on the leaf area index (LAI). Potential soil evaporation, E_S, (cm) is determined as:

$$E_S = E_0 e^{-0.4LAI} \qquad (6)$$

where E_0 is the potential evapotranspiration (cm). Soil evaporation is assumed to take place in two different stages. In the first stage (constant rate stage), soil evaporation is limited just by the amount of energy available and proceeds at the potential rate. Beyond an upper limit, depending of the soil water transmission characteristics, the second stage begins. During this stage, the falling rate stage, the soil evaporation rate decreases as a square root function of time.

The potential plant transpiration, E_{po} (cm), is determined as a function of E_o and LAI (RITCHIE, 1972):

$$E_{PO} = \frac{E_o LAI}{3} \text{ for } 0 \leq LAI \leq 3 \tag{7}$$

If LAI is larger than 3, potential plant transpiration is taken as the difference of potential evapotranspiration and potential soil evaporation. For any given day, the sum of plant transpiration and soil evaporation cannot exceed E_0. The potential transpiration rate is then distributed in the soil profile based on root distribution.

3 - MODEL TESTING

3.1 Experimental data

The two versions of the SPUR model were validated using data collected at the Wagon Creek Spade Research area located in Throckmorton County, 22 km north of Throckmorton, Texas. The soils in the study area are in the Nuvalde silty clay loam series. These soils are deep, well drained, calcareous, moderately permeable, located on gently sloping uplands (1-3% slope). The upper layer is dark grayish silty clay loam about 28 cm thick. The subsoil is dark brown silty clay loam about 50 cm thick. The underlying material is browny calcitic silty clay.

Hydrologic data were collected for nine independent circular, non-weighing, free draining lysimeters: three bare plots, three grass plots and three mesquite plots. The size of the lysimeters varied between 15 and 27 m^2. The average slopes for the bare plots, mesquite and grass plots were 2.5%, 1.8%, and 2%, respectively. Surface runoff flowed through a trough attached to the downslope side of each lysimeter, then was filtered to determine sediment yield. The volumetric soil water content was determined by a neutron probe. Deep drainage was computed as the amount of water percolating beyond 3.05 m. Evaporation was determined using monthly and annual water balances.

A micrologger weather station was used to collect three years of climatic data at the Throckmorton watershed. The collected data included daily values of maximum and minimum air temperature, maximum and minimum relative humidity, and total radiation. These data were used to estimate the potential evapotranspiration. The rainfall intensity was measured using a tipping bucket precipitation gauge. A soil textural analysis was performed to determine the particle size distribution, bulk density and organic matter content. Additional details about the experimental design, and analytical procedures are given by CARLSON *et al.* (1990).

3.2 Calibration

Three years of data, 1986 through 1988, were available. The original model was calibrated for runoff using the data from 1986. The calibration consisted in adjusting the curve number until the highest coefficient of efficiency (NASH and SUTCLIFF, 1970) was obtained. The coefficient of efficiency (EFF) is determined as follows:

$$EFF = 1 - \frac{\sum_{i=1}^{n} \left|O_i - P_i\right|^j}{\sum_{i=1}^{n} \left|O_i - \overline{O}\right|^j} \qquad (8)$$

where j equals 2, n is the number of observed (predicted) points, O_i and P_i represent the ith observation and prediction, respectively. In addition, the root mean squared error (RMSE) was computed and decomposed as suggested by WILMOTT (1984) as follows:

$$RMSE^2 = \frac{\sum_{i=1}^{n} (P_i' - O_i)^2}{n} + \frac{\sum_{i=1}^{n} (P_i - P_i')^2}{n} \qquad (9)$$

where $P'_i = f(O_i)$, where f is the simple linear regression function between the observed and predicted values. The square root of the first term on the right hand side of the equation is referred to as the systematic RMSE, while the square root of the second term corresponds to the unsystematic RMSE. A good modeling exercise should explain most of the systematic variation of the observations. An indicator of the model performance is then computed as the squared ratio of the systematic RMSE and the total RMSE. For a good model this ratio should be as close to zero as possible (WILMOTT, 1984).

The calibrated initial values of the curve number along the estimated saturated hydraulic from the RAWLS *et al.* (1989) pedotransfer function are listed in table 1. The predicted mean and the coefficient of efficiency were computed to determine the performances of both the original and modified models. No calibration was done for the determination of the Green and Ampt infiltration equation parameters.

Table 1 Effective saturated hydraulic conductivity obtained from pedotransfer function (RAWLS *et al.*, 1989) and the curve numbers for the nine lysimeters.

Tableau 1 *Conductivité hydraulique à saturation effective obtenue à partir de la fonction de pédotransfert de RAWLS* et al. *(1989) ainsi que les numéros de courbe pour les neuf lysimètres.*

	Effective Saturated hydraulic conductivity, K_e (cm/hr)			**Curve Number**		
	plot #1	plot #2	plot #3	plot #1	plot #2	plot #3
bare ground	0.183	0.253	0.267	75	81	83
grass	0.437	0.230	0.211	64	56	65
mesquite	0.242	0.318	0.231	66	69	72

3.3 Results and discussion

Table 2 includes the mean measured and predicted monthly runoff for the validation period (1987 and 1988) for the three kinds of cover. The average monthly runoff was generally well predicted by the SPUR-GA model for all three plots on the three types of cover. Table 3 summarizes the coefficient of efficiency along the ratio between the systematic and total RMSE for the three covers. The SPUR-SCS model systematically overpredicted runoff for all types of cover. This could be explained by the fact that the calibration of the value of the initial curve number was done for 1986, a relatively wet year. The annual precipitation was 76, 67 and 53 cm for 1986, 1987, and 1988, respectively. The selection of an average wet year for calibration might have led to better results for the validation. However, since the available time series of measured data was limited, the calibration was just performed using the first year of available data. Using year 1987 for calibration would have biased the performance of the model, since to get the best efficiency for the calibration year would have meant also taking partially into account year 1986 (in order to simulate accurately the beginning of year 1987) and partially 1988 (to simulate accurately the end of year 1987). Furthermore, a different calibration might have improved the results only slightly, considering that the ratio between the systematic and total RMSE is small for all nine plots (the highest value of the ratio being 12%). It can be clearly seen that the percent systematic error of the RMSE is much lower on all plots for the SPUR-SCS than for SPUR-GA. This illustrates that through calibration, the results of the SPUR-GA model could be improved much more than those obtained when using SPUR-SCS. Most of the improvement for the SPUR-GA model can be done on the grass-plots (highest percent systematic error). The coefficient of efficiency was positive for all plots for the SPUR-GA model, and negative for all plots for the SPUR-SCS.

Table 2 Mean measured and predicted monthly runoff for the three kinds of cover for the 1987-1988 period.

Tableau 2 *Ruissellement mensuel moyen prédit et mesuré pour les trois types d'utilisation du sol pour la période 1987-1988.*

	Mean Monthly Runoff (cm)								
	Plot #1			Plot #2			Plot #3		
	Measured	GA	SCS	Measured	GA	SCS	Measured	GA	SCS
Bare ground	0.47	0.40	0.76	0.75	0.83	1.03	0.54	0.86	1.14
Grass	0.09	0.02	0.19	0.00	0.00	0.07	0.01	0.01	0.22
Mesquite	0.09	0.09	0.37	0.17	0.08	0.27	0.13	0.12	0.45

Table 3 The coefficient of efficiency for the monthly runoff for the three kinds of cover for the period of 1987-1988.

Tableau 3 *Coefficients d'efficience pour le ruissellement mensuel pour les trois types d'utilisation du sol pour la période 1987-1988.*

	Bare ground		Grass plot		Mesquite plot	
	GA	**SCS**	**GA**	**SCS**	**GA**	**SCS**
Plot #1	0.21 (11%)*	– 0.09 (3%)	0.47 (9%)	– 0.47 (5%)	0.32 (25%)	– 0.98 (11%)
Plot #2	0.20 (28%)	– 0.02 (12%)	0.31 (25%)	– 0.76 (9%)	0.50 (9%)	– 0.22 (4%)
Plot #3	0.10 (9%)	– 0.24 (7%)	0.49 (74%)	– 0.35 (9%)	0.72 (3%)	– 0.57 (8%)
Combined	0.16 (15%)	– 0.11 (6%)	0.48 (40%)	– 0.41 (6%)	0.43 (10%)	– 0.54 (7%)

* the number is parenthesis is the squared ratio of the systematic and total RMSE

The SPUR-GA model was extremely sensitive to the type of cover and predicted quite well the change of monthly runoff for the different types of cover (table 3). The SPUR-SCS model overpredicted the monthly runoff for all types of cover, especially for the three grass and mesquite plots. Figure 1 illustrates the average (over the three plots) measured and predicted monthly runoff for the bare plots. It can be seen that the SPUR SCS overpredicted the runoff by more than four centimeters for October 1986. The modified model predictions followed much closer the trend of monthly runoff than those predicted by the original model. The same observation can also be made for the grass and mesquite plots (figures 2 and 3). The performance of the SPUR-SCS was not satisfactory for the grass plots as some high runoff was predicted whereas none was measured. The highest efficiencies for both the original and modified SPUR models were obtained on the grass and mesquite plots.

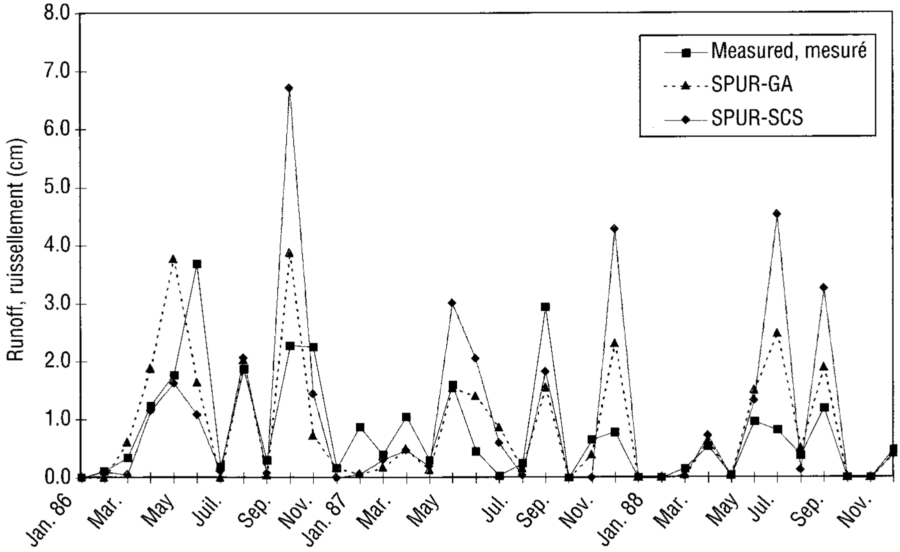

Figure 1 Measured vs. predicted (SPUR-GA and SPUR-SCS) monthly average runoff for the bare plots.

Ruissellement moyen prédit et mesuré (SPUR-GA et SPUR-SCS) pour le sol nu.

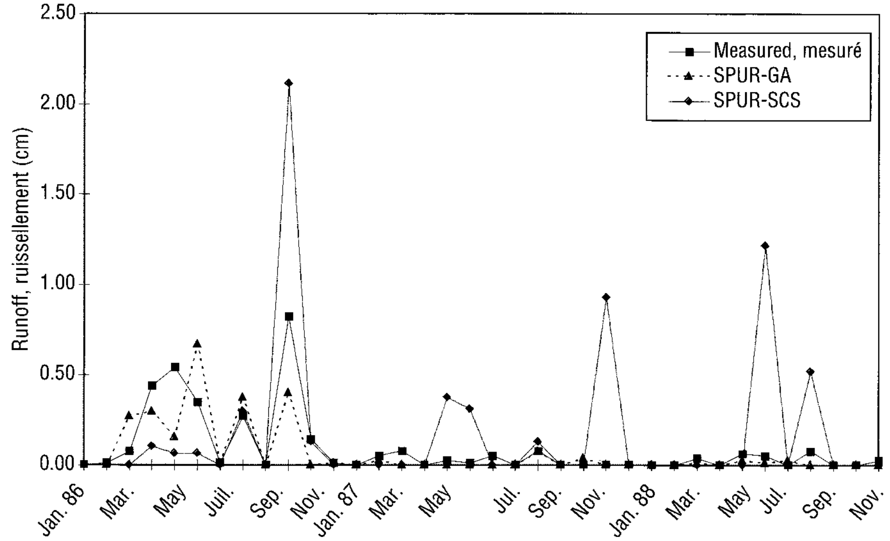

Figure 2 Measured vs. predicted (SPUR-GA and SPUR-SCS) monthly average runoff for the grass plots.

Ruissellement moyen prédit et mesuré (SPUR-GA et SPUR-SCS) pour le sol enherbé.

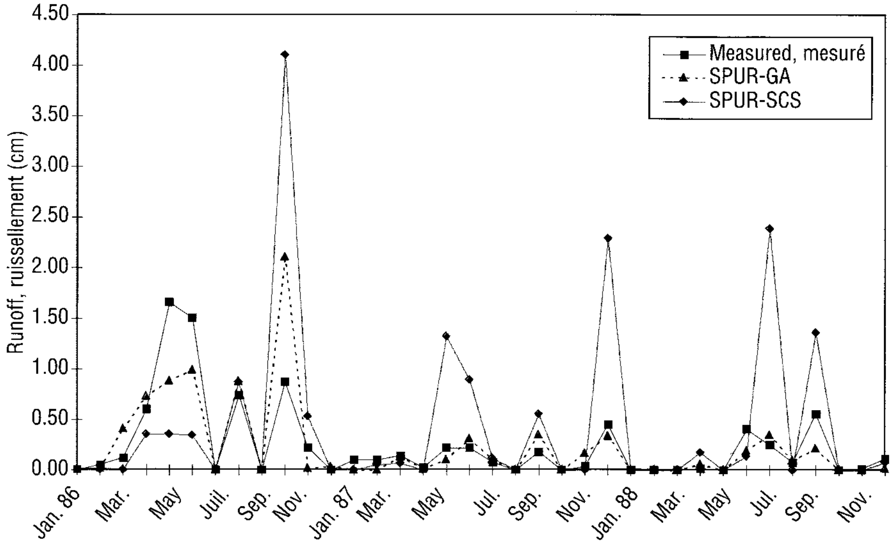

Figure 3 Measured vs. predicted (SPUR-GA and SPUR-SCS) monthly average runoff for the mesquite plots.

Ruissellement moyen prédit et mesuré (SPUR-GA et SPUR-SCS) pour le sol sous buissons.

The annual measured and predicted runoff values are given in table 4. The SPUR-GA model performed better than the SPUR-SCS, for all three types of cover. Since the monthly runoff for the grass and mesquite plots was overpredicted by the SPUR-SCS model, the annual runoff was also largely overpredicted. Figure 4 represents the average (of the three plots) annual runoff for the three types of cover. Both the original and modified SPUR models represented well the influence of the cover on annual runoff. However, the SPUR-GA model performed much better than SPUR-SCS, especially on the mesquite plots and the grass plots.

Tableau 4 Ruissellement et évapotranspiration annuels moyens prédits et mesurés pour les trois types d'utilisation du sol pour la période 1987-1988.

Table 4 *Mean predicted and measured annual runoff, and evapotranspiration for the three kinds of cover for the period of 1987-1988.*

	Runoff (cm)			Evapotranspiration (cm)		
	Measured	**GA**	**SCS**	**Measured**	**GA**	**SCS**
Bare ground	7.07	8.35	10.23	58.53	36.39	35.05
Grass	0.31	0.12	1.80	67.78	70.52	68.4
Mesquite	1.50	1.19	4.77	62.58	67.27	64.89

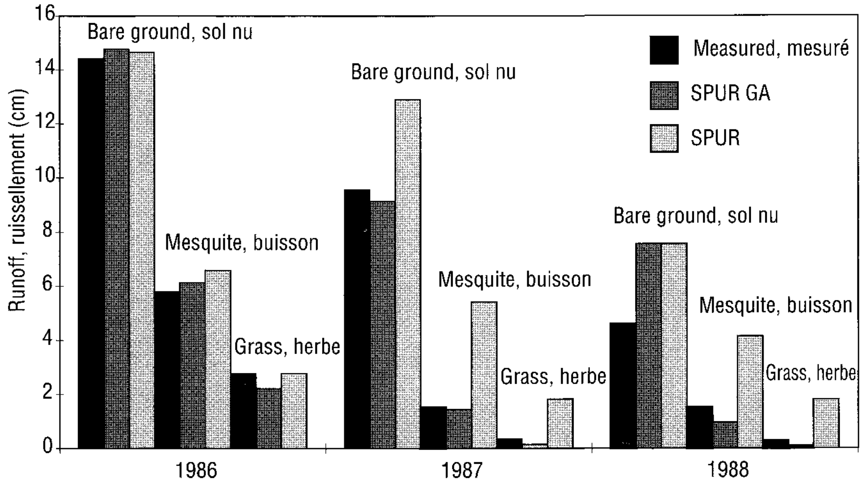

Figure 4 Mean annual runoff for the bare, grass and mesquite cover.

Ruissellement annuel moyen pour les sols nus, enherbés, et sous buissons.

The predictions of annual evapotranspiration were less accurate for the bare plots (table 4). This was expected since the Ritchie equation was developed to estimate evapotranspiration for covered agricultural lands. Furthermore, the model limits the evaporation from the upper two layers, which sum to a depth of 15 cm. Once the available water in these two layers is depleted, evaporation stops. When examining soil pressure profiles (the original soil moisture was converted to pressure head using RAWLS and BRAKENSIEK (1985) pedotransfer function) it can be clearly determined that the impact of evaporation calculated as the depth at which the gradient of pressure head is zero, commonly called the zero flux plane (KUTILEK and NIELSEN, 1994), extends beyond 30 cm. The presence of cracks reported by CARLSON *et al.* (1990) on the bare soils is also responsible for evaporation extending beyond 15cm in the soil profile. It is thus of extreme importance to include the impact of cracks on preferential infiltration and on deep evaporation in order to simulate accurately the water balance for bare soils.

Predictions of annual ET were much better for the vegetated plots. Both models predicted well the trend of annual evapotranspiration on the grass and mesquite plots. It can be seen from table 4 that both the original and modified models predicted correctly that the grass and mesquite plots have a negative water balance (evapotranspiration larger than rainfall). This is of extreme importance and illustrates that the SPUR model can be used as a mean to estimate the effects of vegetation management on soil water yield. The better predictions of both models of runoff on the vegetated plots can be explained by the better estimates of evapotranspiration (and thus soil moisture content) when compared to that on the bare plots.

3.4 Sensitivity analysis

A sensitivity analysis of the SPUR-SCS and SPUR-GA models was conducted to evaluate how changes in the input data could affect the values of monthly runoff and evapotranspiration. To do so, the curve number was increased and decreased by 10% in SPUR-SCS, while for the SPUR-GA model, the modified input parameters (±10%) included organic matter, clay and silt content for the bare plots. For the grass and mesquite plots, additional parameters were tested during the sensitivity analysis and included the percent canopy cover, percent bare ground under the canopy, the percent bare ground in inter-space and the percent grass cover. All these parameters are used to correct the hydraulic conductivity according to equations 4 and 5. The models were run using a 9-year weather time series (obtained by repeating twice the 1986-1988 climatic data) for each of the replicates for the three covers. The results were then averaged for each cover. As expected, runoff was very sensitive to variation of the curve number on the three types of cover. An increase of the curve number by 10% resulted in an increase in the runoff by 118%, 99% and 102% for the bare, grass and mesquite plots, respectively. Considering that runoff represents a small fraction of total precipitation, the impact of variation of the curve number was about an order of magnitude smaller on evapotranspiration than on runoff. The largest impact was observed on the bare plot, where an increase of the curve number resulted in a decrease of the actual evapotranspiration by 16%. The amount of water percolation decreased by almost 60%. However, the percolation was very low on the bare plots, with an average annual value below 10 mm. For the grass cover, percolation was unaffected by variation of the curve number, since most of the precipitation is lost through evapotranspiration.

For the SPUR-GA model, runoff on the bare soil was mostly sensitive to variation in sand content. An increase in sand content decreased runoff by 13% and resulted in a slight decrease in actual evapotranspiration. For the grass and mesquite plots, water balance was most sensitive to the crop cover parameters. A decrease by 10% of the crop canopy cover resulted in an increase in runoff of 360% (however, the original runoff was very small). None of the considered factors had an impact on water percolation. A similar pattern was observed for the mesquite plots. Runoff was most sensitive to the variation of the crop canopy cover: a decrease of the cover by 10% increased the runoff volume by almost 400%.

PIERSON *et al.* (2001) analyzed the sensitivity of the SPUR2000 model to various input parameters. Both infiltration models used in SPU2000 and the SPUR-GA model are similar, but they differ greatly in their parameterization. For SPUR2000, among the soil textural properties, sand content was the parameter most affecting surface runoff. According to PIERSON *et al.* (2001), plant cover had a lesser impact. For SPUR-GA, the crop cover had a major impact on the runoff calculation because the macroporosity factor used in equations 4 and 5 was less than one, as explained by WILCOX *et al.* (1992).

4 - CONCLUSIONS

Previous research has shown that water yield on rangeland watersheds can be increased through vegetation manipulation. Thus, increasing interest has been given to the development of models that could evaluate the effects of vegetation changes on water yield in range watersheds. The SPUR model was developed to simulate major aspects of the rangeland ecosystem, including climate, hydrology, plant, animal and economics components. The original version of SPUR uses the SCS curve number to estimate runoff volume, and the Ritchie method to compute evapotranspiration. The Green-Ampt infiltration equation has been proposed as an alternative to compute infiltration. This approach has the advantage that its parameters can be determined based on readily available soil and vegetation information, and it does not require any calibration.

Three years of data collected at the Throckmorton watershed were used for validation and calibration of both versions of the SPUR model. The Green Ampt method performed better in predicting monthly and annual runoff on the three types of cover (bare, grass and mesquite plots). Both models did a better estimation of runoff for the vegetated plots than from the bare plots, mainly because the prediction of evapotranspiration was better on the vegetated plots. Evaporation was greatly underestimated for the three bare plots. This shortcoming can be alleviated by allowing evaporation to occur deeper in the soil profile. An additional important aspect to consider is also the impact of cracks and macropores on the water balance.

As an overall result, the introduction of the Green-Ampt equation improved the performance of the SPUR model for the simulation of infiltration and runoff. The improvement is mainly due to the introduction of a direct relationship between runoff and rainfall rate, an aspect that is not considered by the SCS curve number approach.

REFERENCES

CARLSON D.H., THUROW T.L., KNIGHT R.W., HEITSCHMIDT R.K., 1990. Effect of honey mesquite on the water balance of Texas Rolling Plain rangeland. *J. Range Manage*, 43, 491-496.

CARLSON D.H., THUROW T.L., 1996. Comprehensive evaluation of the improved SPUR model (SPUR-91). *Ecol. Model.*, 85, 229-240.

CHU S.T., 1978. Infiltration during unsteady rain. *Wat. Resour. Res.*, 14, 461-466.

GREEN W.H., AMPT G., 1911. Studies of soil physics, Part I. The flow of air and water through soils. *J. Agr. Sci.*, 4, 1-24.

GRIFFIN R.C., MCCARL B.A., 1989. Brushland management for increased water yield in Texas. *Wat. Res. Bull.* 25, 175-186.

HIBBERT A.R., 1979. Managing vegetation to increase flow in the Colorado River Basin. USDA Forest Service, Fort Collins, CO, *General Technical Report RM-66*, 27 p.

HIBBERT A.R., 1983. Water yield improvement potential by vegetation management on Western rangelands. *Wat. Resour. Bull.*, 19, 375-381.

KIDWELL M.R., WELTZ M.A., GUERTIN D.P., 1997. Estimation of Green-Ampt effective hydraulic conductivity for rangelands. *J. Range Manage*, 50, 290-299.

KUTILEK M., NIELSEN D.R., 1994. Soil Hydrology, Catena Verlag, Cremlingen-Desteds, Germany.

MEIN R.G., LARSON C.L., 1971. Modeling infiltration component of the rainfall-runoff process. University of Minnesota, Minneapolis, MN, USA, *Water Resources Research Center Bulletin* 43, 72p.

NASH J.E., SUTCLIFF J.V., 1970. River flow forecasting through conceptual models Part I. A discussion of Principles. *J. Hydrol.*, 10, 282-290.

PIERSON F.B., CARSLON D.H., SPAETH K.E., 2001. A process-based hydrology submodel dynamically linked to plant component of the simulation of production and utilization on rangelands SPUR model. *Ecol. Model.*, 141, 241-260.

PONCE V.M., HAWKINS R.H., 1996. Runoff Curve Number: has it reached maturity? *J. Hydrol. Eng.*, 1, 11-19.

RALLISON R. E., 1980. Origin and evolution of the SCS runoff equation. *Proceedings Watershed Management Symposium*, ASCE, Boise, ID.

RAWLS W.J., BRAKENSIEK D.L., 1985 Prediction of soil water properties for hydrologic modeling. Watershed Management in the Eighties. *Proceedings of the Irrigation and Drainage Division of the ASCE*, Denver, Colorado, April 30-May 1 1985.

RAWLS W.J., BRAKENSIEK D.L., SAVABI M.R., 1989. Infiltration parameters for rangeland soils. *J. Range Manage*, 42, 139-142.

RITCHIE J.T., 1972. A model for predicting evapotranspiration from a row crop with incomplete cover. *Wat. Resour. Res.*, 8, 1204-1213.

SAVABI M.R., RAWLS W.J., KNIGHT W., 1995. Water erosion prediction project (WEPP) rangeland hydrology component evaluation on a Texas range site. *J. Range Manage*, 48, 535-541.

SPRINGER E.P., JOHNSON C.W., COOLEY K.R., ROBERTSON D.C., 1984. Testing of the SPUR hydrology on rangeland watershed in Southwestern Idaho. *Trans. ASAE*, 27, 1040-1046, 1054.

THUROW P.A., CONNER J.R., THUROW T.L., GARRIGA M.D., 2001. A preliminary analysis of Texas ranchers' willingness to participate in brush control cost-sharing program to improve off-site water yields. *Ecol. Econ.*, 37, 139-152.

THUROW P.A., HESTER J.W., 1997. How an increase or reduction in juniper cover alters rangeland hydrology. *Texas A&M University Research Station, Technical Report 97-1*, Sonora, TX, USA.

USDA, Soil Conservation Service, 1972. *National engineering handbook, hydrology section 4*, Chapter 4-10.

WIGHT J.R., SKILES J.W., 1987. SPUR: Simulation of Production and Utilization of Rangelands: Documentation and user guide. *USDA, ARS, ARS 63*, December. 367 p.

WILCOX B.P., 2002. Shrub control and streamflow on rangelands: a process based view point. *J. Range Manage*, 55, 318-326.

WILCOX B.P., SBAA M., BLACKBURN W.H., MILLIGAN J.H., 1992. Runoff prediction from sagebrush rangelands using water erosion prediction project (WEPP). *J. Range Manage*, 45, 470-474.

WILLIAMS J.R., NICKS A.D., ARNOLDS J.G., 1985. Simulator for Water Resources in Rural Basins. *J. Hydraul. Div. ASCE*, 111(HY6), 970-987.

WILLIAMS J.R., LASEUR W.V., 1976. Water yield using SCS curve numbers. *J. Hydraul. Div. ASCE*, 102(HY9), 1241-1253.

WILMOTT C.J., 1984. On the evaluation of model performance in physical geography. In *"Spatial Statistics and Models"*, GAILE G.L. and WILMOTT C.J. [Ed.], pp. 443-460.

WOOD M.K., BLACKBURN W.H., 1984. An evaluation of the hydrologic soil groups as used in the SCS runoff method on rangelands. *Wat. Resour. Bull*, 20, 379-389.

WU X.B., REDEKER E.J., THUROW T.L., 2001. Vegetation and water dynamics in an Edwards Plateau Watershed. *J. Range Manage*, 54, 98-105.