

## Applications of a Surface Runoff Model with Horton and Dunne Runoff for VIC

XIE Zhenghui<sup>\*1</sup> (谢正辉), SU Fengge<sup>1</sup> (苏凤阁), LIANG Xu<sup>2</sup> (梁旭), ZENG Qingcun<sup>1</sup> (曾庆存)  
HAO Zhenchun<sup>3</sup> (郝振纯), and GUO Yufu<sup>1</sup> (郭裕福)

<sup>1</sup>*Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing 100029*

<sup>2</sup>*Department of Civil and Environmental Engineering, University of California, Berkeley, CA 94720-1710, USA*

<sup>3</sup>*Hohai University, Nanjing 210098*

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### ABSTRACT

Surface runoff is mainly generated by two mechanisms, infiltration excess (Horton) runoff and saturation excess (Dunne) runoff; and the spatial variability of soil properties, antecedent soil moisture, topography, and rainfall will result in different surface runoff generation mechanisms. For a large area (e.g., a model grid size of a regional climate model or a general circulation model), these runoff generation mechanisms are commonly present at different portions of a grid cell simultaneously. Missing one of the two major runoff generation mechanisms and failing to consider spatial soil variability can result in significant under/over estimation of surface runoff which can directly introduce large errors in soil moisture states over each model grid cell. Therefore, proper modeling of surface runoff is essential to a reasonable representation of feedbacks in a land-atmosphere system. This paper presents a new surface runoff parameterization with the Philip infiltration formulation that dynamically represents both the Horton and Dunne runoff generation mechanisms within a model grid cell. The parameterization takes into account the effects of soil heterogeneity on Horton and Dunne runoff. The new parameterization is implemented into the current version of the hydrologically based Variable Infiltration Capacity (VIC) land surface model and tested over one watershed in Pennsylvania, USA and over the Shiguanhe Basin in the Huaihe Watershed in China. Results show that the new parameterization plays a very important role in partitioning the water budget between surface runoff and soil moisture in the atmosphere-land coupling system, and has potential applications on large hydrological simulations and land-atmospheric interactions. It is further found that the Horton runoff mechanism should be considered within the context of subgrid-scale spatial variability of soil properties and precipitation.

**Key words:** Horton runoff, Dunne runoff, subgrid-scale spatial variability, soil heterogeneity, land surface model, hydrologic model, soil moisture

### 1. Introduction

Soil heterogeneity plays an important role in determining surface runoff generation mechanisms. At the spatial scales represented by land surface models used in regional climate models and/or global general circulation models (GCMs) for numerical weather prediction and climate studies, both infiltration excess (Horton) and saturation excess (Dunne) runoff may be present within a studied area or a model grid cell. Proper modeling of surface runoff is essential to provide a reasonable representation of feedbacks in the

land-atmosphere system. This is because the generated amount of surface runoff directly affects soil moisture which can significantly affect the regional atmospheric budgets of water and energy at different time scales. The partitions of rainfall into runoff and soil moisture storage, however, vary widely among the current generation of land surface models used for numerical weather prediction and climate studies. This is clearly illustrated by the different study phases of the Project for Intercomparison of Land-surface Parameterization Schemes (PILPS) (Shao and Henderson-Sellers, 1995; Chen et al., 1997; Liang et al., 1998;

\*E-mail: zxie@lasg.iap.ac.cn

Lohmann et al., 1998; Wood et al., 1998). Most of the current generation land surface models do not take into account the infiltration and saturation excess runoff effectively and simultaneously within a model computational grid cell under the context of subgrid-scale spatial variability of soil properties and rainfall (Liang and Xie, 2001). Although the variable Infiltration Capacity (VIC) land surface model considers the effects of subgrid spatial variability of soil heterogeneity and precipitation, it does not simulate the infiltration excess runoff. Therefore, the VIC model would have difficulty in simulating surface runoff and soil moisture well under arid climate where the infiltration excess runoff generation mechanism is important. Nijssen et al. (1997, 2001) coupled VIC with a simple grid-based network routing scheme (including both within grid cell routing and channel routing) to study streamflow simulations for continental-scale river basins. They found that the integrated model (i.e., VIC plus the network routing scheme) performed quite well over moist areas in their study. For arid and semi-arid areas, however, their studies indicated difficulties in reproducing monthly observed streamflows. In PILPS phase-2c, VIC simulated higher flows than observations, similar to many others, over the summer months. Although the poor runoff simulations over arid and semi-arid areas may result from a combination of different reasons, (for example, the weaknesses associated with the routing scheme used as discussed in Nijssen et al. (2001), one of the main possible reasons could be the lack of inclusion of the infiltration excess runoff generation mechanism which plays an important role under arid climate conditions. Without the inclusion of such a runoff generation mechanism, soil moisture, surface runoff, and relevant energy budgets may not be simulated well.

Liang and Xie (2001) present a new model for surface runoff parameterization that dynamically represents both the Horton and Dunne runoff generation mechanisms within a model grid cell. Two spatial distributions for the Horton and Dunne runoff mechanisms are used to represent the spatial heterogeneity of soil properties. The spatial distribution for Dunne runoff does not vary with time, while the one for Horton does by the time compression analysis (TCA) similar to that of Salvucci and Entekhabi (1994). TCA is an approximation commonly used to relate the maximum infiltration rate at any given time during an event to the initial soil moisture and the cumulative moisture exchange up to that time. The magnitude of the potential infiltration rate at each point generally decreases when the soil moisture increases at that point, as is evidenced by field measurements and the Horton infiltration equations.

This paper presents a surface runoff parameterization with the Philip infiltration formulation that dynamically represents both the Horton and Dunne runoff generation mechanisms within a model grid cell section 2 and 3. The parameterization takes into account the effects of soil heterogeneity on Horton and Dunne runoff. The new parameterization is implemented into the current version of the hydrologically based Variable Infiltration Capacity (VIC) land surface model and tested over one watershed in Pennsylvania, USA and, over the Shiguanhe Basin in the Huaihe watershed in China, which is described in section 4. Primary conclusions are provided in section 5.

## 2. A surface runoff parameterization for VIC

Liang and Xie (2001) presented a new surface runoff parameterization which dynamically represents both the Horton and Dunne runoff generation mechanisms within a model grid cell together with a consideration of the subgrid-scale soil heterogeneity. The saturation excess runoff in the parameterization is computed following the concepts used in the VIC-3L/VIC-2L model (Three-Layer/Two-Layer Variable Infiltration Capacity model). The VIC-3L model has three soil moisture layers. They are a thin layer (usually taken as 100 mm deep from the surface), an upper layer which includes the top thin layer, and a lower layer (Liang et al., 1996). The thin layer allows a quick bare soil evaporation following small summer rainfall events. The upper layer is designed to represent the dynamic response of soil to rainfall events, and the lower layer is used to characterize seasonal soil moisture behavior. We will focus on the upper soil layer because this layer is closely related to the surface runoff generation. For more details of the VIC model, the reader is referred to (Liang et al., 1994, 1996a, b; Cherkauer and Lettenmaier, 1999).

The soil moisture capacity in the upper layer is assumed to vary within a studied area or a model grid cell. This spatial variability of soil moisture capacity is mainly due to the heterogeneity in the depth of the soil column and in the soil properties. The spatial variation of soil moisture capacity is expressed by a spatial probability distribution following (Wood et al., 1992; Zhao, 1992),

$$i = i_m [1 - (1 - A)^{1/b}], \quad (1)$$

where  $i$  and  $i_m$  are the point soil moisture capacity (called infiltration capacity in VIC-3L/VIC-2L) and maximum soil moisture capacity (called maximum infiltration capacity in VIC-3L/VIC-2L), respectively,  $A$

is the fraction of an area for which the soil moisture capacity is less than or equal to  $i$ , and  $b$  is the soil moisture capacity shape parameter, which is a measure of the spatial variability of the soil moisture capacity, defined as the maximum amount of water that can be stored in the upper layer of the soil column. It is a surrogate for the spatial heterogeneity of soil properties. In the new parameterization, saturation excess runoff (represented by  $R_1$ ) is parameterized to be generated from the fraction of the area  $A_s$  that is initially saturated and the fraction of the area ( $A'_s - A_s$ ) that becomes saturated during the time step (see Fig. 1a). The infiltration excess runoff ( $R_2$ ) is then generated from the area of  $1 - A_s$  and is redistributed over the entire area for numerical representation as indicated by the shaded-area with back-slashed-lines (see Fig. 1a). The magnitude of  $R_1$  can be determined following the concepts of the current version of the VIC model, and can be expressed as a function of vertical depth of  $y$  shown in Fig. 1a,

$$R_1(y) = \begin{cases} y - \frac{i_m}{b+1} \left[ \left(1 - \frac{i_0}{i_m}\right)^{b+1} - \left(1 - \frac{i_0+y}{i_m}\right)^{b+1} \right], & 0 \leq y \leq i_m - i_0 \\ R_1(y)|_{y=i_m-i_0} + y - (i_m - i_0), & i_m - i_0 < y \leq P, \end{cases} \quad (2)$$

where  $i_m$  and  $i_0$  represent the maximum point soil moisture capacity and the point soil moisture capacity corresponding to the initial soil moisture  $W_t$  (see Fig. 1a), respectively,  $b$  is the soil moisture capacity shape parameter,  $P$  is the amount of precipitation over a time step  $\Delta t$ , and  $y$  is the vertical depth shown in Fig. 1a. The change of soil moisture  $\Delta W(y)$  is as follows (see Fig. 1a),

$$\Delta W(y) = y - R_1(y) = \begin{cases} \frac{i_m}{b+1} \left[ \left(1 - \frac{i_0}{i_m}\right)^{b+1} - \left(1 - \frac{i_0+y}{i_m}\right)^{b+1} \right], & 0 \leq y \leq i_m - i_0 \\ i_m - i_0 - R_1(y)|_{y=i_m-i_0}, & i_m - i_0 < y \leq P. \end{cases} \quad (3)$$

The magnitude of infiltration excess runoff  $R_2(y)$  is determined by the shaded-slashed dashed-lines shown in Fig. 1b where the potential infiltration rate (with units of [length/time]) is also described by a function from the beta distribution family, similar to that used

in Fig. 1a,

$$R_2(y) = \begin{cases} P - R_1(y) - f_{mm}\Delta t \left[ 1 - \left(1 - \frac{P - R_1(y)}{f_m\Delta t}\right)^{B+1} \right], & \frac{P - R_1(y)}{f_m\Delta t} \leq 1 \\ P - R_1(y) - f_{mm}\Delta t, & \frac{P - R_1(y)}{f_m\Delta t} \geq 1, \end{cases} \quad (4)$$

where  $f_{mm}$  is the average potential infiltration rate (i.e., average infiltration capacity) over the area of  $1 - A_s$ , which can be expressed as,

$$f_{mm} = \int_0^1 f_m [1 - (1 - C)^{1/B}] dC = \frac{f_m}{1+B}. \quad (5)$$

Here  $f_m$  is the maximum potential infiltration rate which is a function of soil moisture at each time step, and thus should vary with time,  $C$  is the fraction of an area for which the potential infiltration rate is less than or equal to  $f$ , and  $B$  is the potential infiltration rate shape parameter.

The value of  $f_{mm}$  in Equation (4) also varies with time which can be estimated by applying the concept of time compression analysis (TCA). Assume that the spatially averaged point infiltration rate in the studied area can be represented by a point infiltration function  $f_p(t)$ . The infiltrated water over time  $[0, t_f]$  that is obtained by applying  $f_p(t)$  should be equal to the total amount of water that is actually infiltrated during the time period  $[0, t + \Delta t]$  over the studied area. That is,

$$\int_0^{t_f} f_p(t) dt = W_t + \Delta W, \quad (6)$$

where  $W_t$  is the soil moisture at time  $t$ , and  $\Delta W$  is the change of soil moisture between  $t$  and  $t + \Delta t$ . Therefore,  $f_{mm}(t)$  can be obtained by

$$f_{mm} = f_p(t_f). \quad (7)$$

For a detailed description of the new surface runoff parameterization of VIC and the derivation of the above equations, the reader is referred to the paper by Liang and Xie (2001).

### 3. Philip infiltration formulation

The Horton infiltration cure is used in Liang and Xie (2001) as the infiltration formulation in (5) and (6). In this paper, we use the Philip infiltration formulation. The spatially averaged point infiltration function  $f_p(t)$  is as follows:

$$f_{philip} = f_p(t) = \frac{S_2}{2} t^{-1/2} + K_p, \quad (8)$$

where  $S_p$  and  $K_p$  are two parameters that can be estimated based on soil properties which are usually required by (available for) a land surface model. In other words, no more extra parameters need to be introduced.  $S_p$  and  $K_p$  can be calculated as follows:

$$K_p = \frac{1}{2} \left[ 1 - \left( \frac{\theta_r}{\theta_s} \right)^{2c+3} \right], \tag{9}$$

$$S_p = \left\{ \frac{1}{2} K_s \theta_s |\psi_s| \times \frac{c+3 + (\theta_r/\theta_s)^{2(c+4)} - (\theta_r/\theta_s)(c+4)}{(c+3)(c+4)} \right\}^{\frac{1}{2}}, \tag{10}$$

where  $K_s$  is the saturated hydraulic conductivity,  $\theta_s$  the saturated moisture,  $\psi_s$  the saturated soil potential, and  $c$  the Clapp and Hornberger constant (Clapp and Hornberger, 1978). From Equation (6), we have

$$f_{mm}(t) = f_{philip}(t_f) = \frac{S_p}{2} t_f^{-1/2} + K_p. \tag{11}$$

**4. Validation and applications**

The new surface runoff parameterization with the Philip infiltration formulation is tested in this section through comparisons between the model-simulated total runoff and observed streamflows. The surface runoff generation mechanism in the current version of VIC-3L is replaced by the new parameterization (called the new VIC-3L hereafter). Also, the total runoff from the new VIC-3L is compared with that from the current version of VIC-3L (called the old VIC-3L hereafter). The difference between the new and the old VIC-3L is the lack of consideration of the infiltration excess runoff generation mechanism in the old VIC-3L, while everything else is kept the same.

**4.1 Comparisons from one watershed in Pennsylvania, USA**

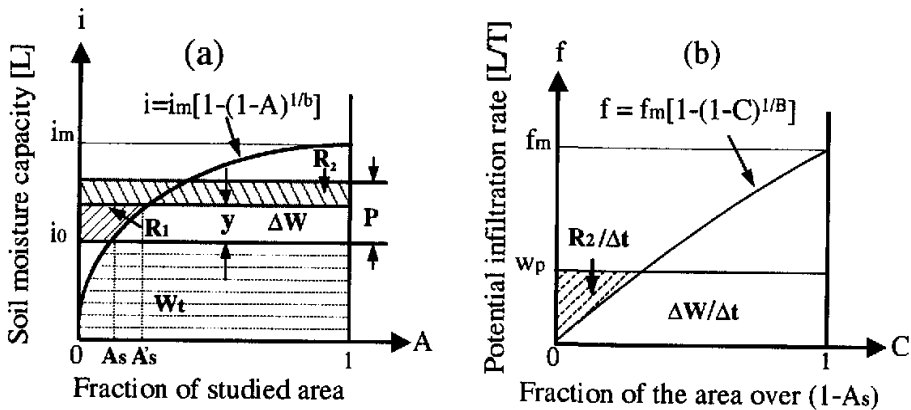
The Little Pine Creek watershed near Etna, Pennsylvania is used in the comparison study, which is in the Lower Susquehanna Basin with drainage areas of 428 km<sup>2</sup> (see Table 1).

**Table 1.** Information on streamflow stations and watersheds

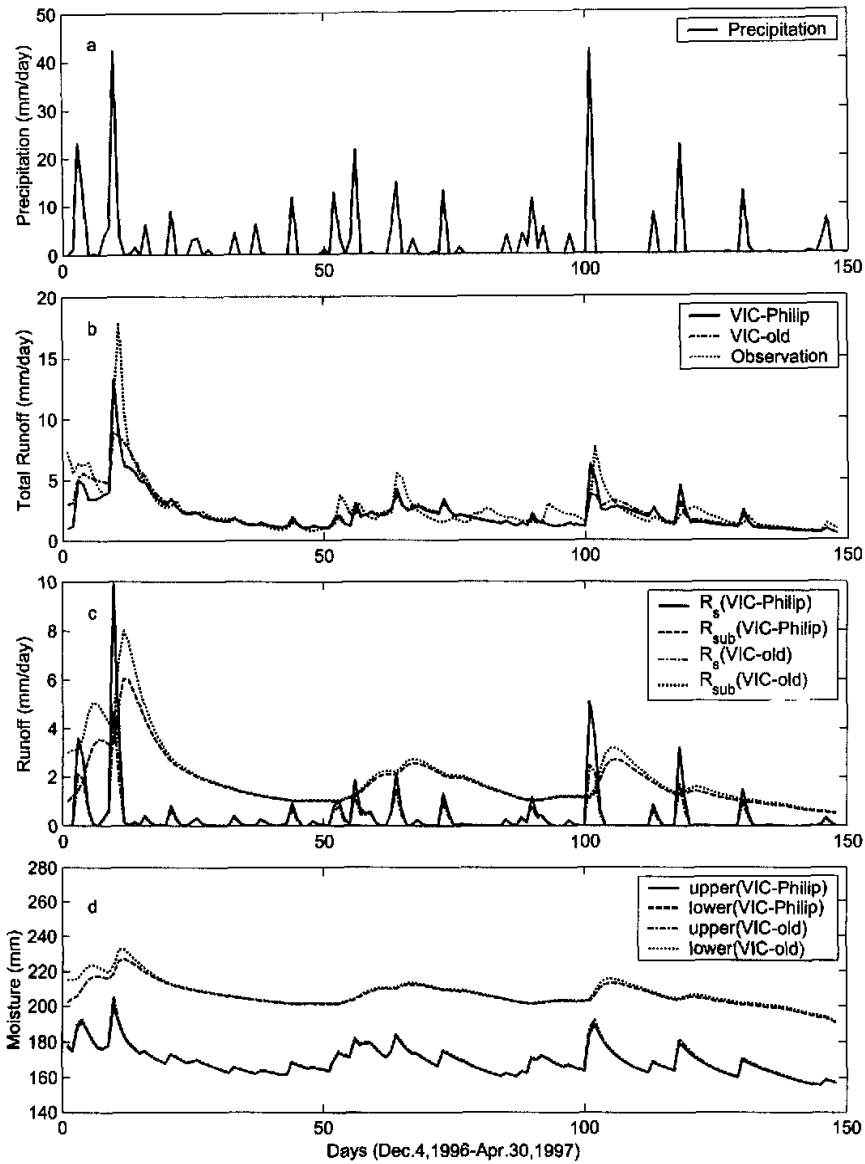
Station	Latitude	Longitude	Basin Name	Drainage (km <sup>2</sup> )
01572190	40°28'45"N	76°31'52"W	Swatara Creek near Inwood	428

**Table 2.** Information on surface meteorologic stations

Station	Latitude	Longitude	Basin Name
364896	40°20'N	76°28'W	Swatara Creek near Inwood



**Fig. 1.** Schematic representation of upper soil layer: (a) spatial distribution of soil moisture capacity ([L]) for saturation excess runoff, and (b) spatial distribution of potential infiltration rate ([L/T]) (i.e., infiltration capacity) for infiltration excess runoff.



**Fig. 2.** Comparison of daily observed streamflow with total runoff from the new and old VIC-3L model at the Little Pine Creek watershed 3 between December 1996 and April 1997: (a) daily precipitation time series; (b) comparison of daily total runoff among the observed streamflow (dotted line), new VIC-3L (solid line), and old VIC-3L (dash-dot line); (c) comparison of daily surface and subsurface runoff between the new VIC-3L (solid line for surface runoff and dashed line for subsurface runoff) and old VIC-3L (dash-dot line for surface runoff and dotted line for subsurface runoff); and (d) comparison of daily upper and lower layer soil moisture between the new VIC-3L (solid line for upper layer and dashed line for lower layer) and old VIC-3L (dash-dot line for upper layer and dotted line for lower layer).

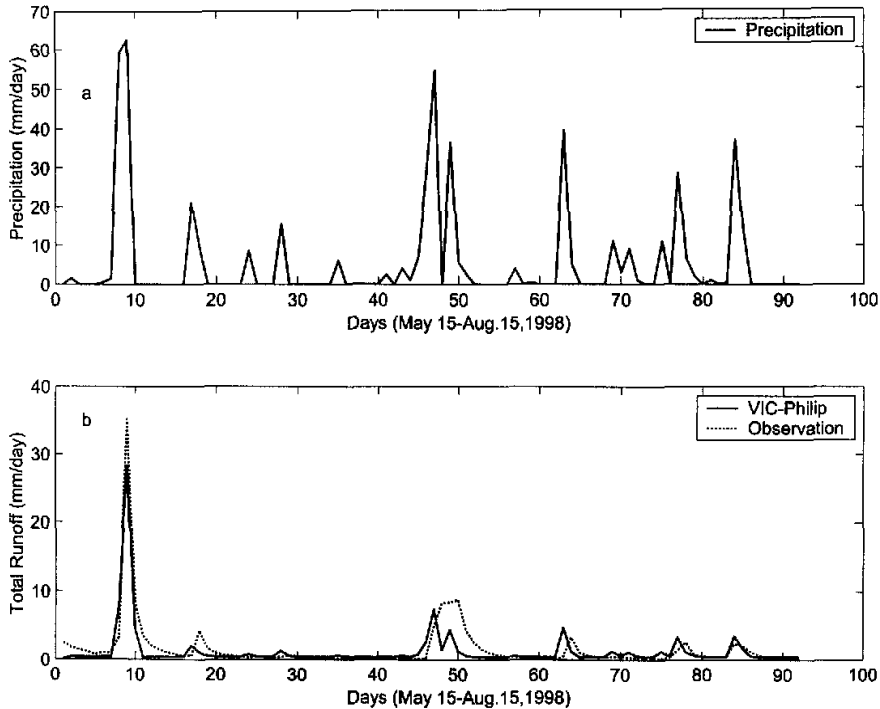


Fig. 3. Comparison of daily observed streamflow with total runoff from the new VIC-3L model at Huangnizhuang station between May and August 1998: (a) daily precipitation time series; (b) comparison of daily total runoff between the observed streamflow (dotted line) and new VIC-3L (solid line).

The forcing data needed to run VIC-3L are obtained from a nearby surface meteorologic station (see Table 2). Information on vegetation, soil properties, and VIC parameters is obtained from the corresponding grid cells (at 1/8 degree resolution) compiled by the University of Washington. The three parameters related to the Philip infiltration equation are determined based on the corresponding soil properties. No calibrations on VIC-3L model parameters (both new and old) were conducted. The two versions of the VIC-3L model were run for a few years for the watershed. The model simulated total runoff is routed through the channel and then compared with the observed streamflow. The routing scheme used here is a modified version used in the study by Nijssen et al. (1997). Results from the last year simulations were taken for comparison analysis to limit the effects of model initializations.

Comparisons between model simulated total runoff

and observed streamflow, and between the two versions of VIC-3L on surface runoff, sub-surface runoff, and soil moisture in the upper and lower layers at the watershed are presented in Fig. 2, which shows the comparison from December 1996 to April 1997. It can be clearly seen that both the new and the old VIC-3L compare well with observed streamflow for a series of small rainfalls associated with wet soil moisture conditions. For the observed peak flow in early December, the new VIC-3L simulates a higher peak with narrower width, while the old VIC-3L simulates a lower peak with wider width which is contributed by its larger subsurface runoff (Figs. 2b, 2c, and 2d).

The comparisons between observed streamflow and the total runoff from the new and the old VIC-3L clearly indicate again that it is very important to consider the infiltration excess surface runoff to simulate more reasonably both large peak flows. The comparison also shows that the differences between the new

and the old VIC-3L could be small with smaller rainfalls and moist soil conditions.

#### 4.2 The Shiguanhe River in the Huaihe River Watershed, China

The Shiguanhe River is the first-order southern tributary of the Huaihe River Watershed and is of humid climate. The Shiguanhe Basin is located between latitudes 31°12'N and 32°18'N and between longitudes 115°17'E and 115°55'E. The hydrological simulation area is upstream of Huangnizhuang station, which is located at 31°28'N, 115°37'E with a drainage area of 805 square kilometers.

The forcing data needed to run VIC-3L and streamflow data of observation are obtained from HUBEX intensive observation period data from 15 May to 15 August 1998. The two parameters related to the Philip infiltration equation are determined based on the corresponding soil properties. No calibrations on VIC-3L model parameters were conducted. The model-simulated total runoff is routed through the channel and then compared with the observed streamflow. The routing scheme used here is a modified version used in the study by Nijssen et al. (1997).

Comparisons between model-simulated total runoff and observed streamflow from 15 May to 15 August 1998 are presented in Fig. 5. The simulated results with the Philip infiltration formulation show that the new version of VIC properly simulates the total runoff.

#### 5. Conclusions

A surface runoff parameterization for the VIC model with Philip infiltration formulation is presented in this paper. The new parameterization dynamically considers the two major surface runoff generation mechanisms, infiltration excess runoff and saturation excess runoff, within a studied area or a model grid cell. Also, the effects of spatial subgrid-scale variability of soil heterogeneity on surface runoff are effectively considered. Although the new parameterization is developed under the context of the VIC model framework, the concept and methodology of the new parameterization can be applied to other land surface models. It was implemented into the current version of VIC-3L and tested over one watershed in the USA and over the Shiguanhe Basin in the Huaihe Watershed. The results show that it is very important to consider the infiltration excess runoff mechanism within the context of subgrid-scale spatial variability of soil heterogeneity and precipitation for land surface models. Due to the close relationship between the potential infiltration rate (i.e., infiltration capacity) and soil

moisture state, the spatial distribution of potential infiltration rate should vary with time. An assumption of time-invariant spatial distribution of potential infiltration rate may result in large errors in surface runoff and soil moisture. The Philip infiltration formulation in the TCA has the characteristics of having less parameters and that all the parameters can be computed from parameters of current land surface models. The simulated results with the Philip infiltration formulation show that the new version of VIC properly simulates the total runoff.

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## 具有Horton及Dunne机制的径流模型在VIC模型中的应用

谢正辉 苏凤阁 梁旭 曾庆存 郝振纯 郭裕福

### 摘 要

地表径流主要由蓄满(Dunne)和超渗产流(Horton)机制产生;土壤性质的空间变异性、前期土壤水、地形及降水的空间变异性导致不同的径流机制。在研究区域或模型网格内,蓄满产流及超渗产流可能同时出现,缺乏考虑任何一种机制以及土壤性质的次网格空间变率可能导致地表径流的过高或过低估计,从而影响土壤水的计算。利用Philip入渗公式用于时间压缩逼近(TCA)给出了一种径流参数化方法,该方法可以动态实现模型网格中的Horton及Dunne产流机理,它考虑了土壤空间变异性对Horton和Dunne径流的影响。该径流模型应用到基于水文原理的陆面过程模型VIC,在淮河流域及美国宾西法尼亚州的一个流域进行了测试,结果表明:新的参数化方法对地表径流和土壤水分含量的分配起着重要作用,对于改进径流和土壤水的模拟有重要意义。

关键词:蓄满产流,超渗产流,次网格空间变异性,陆面模型