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Important factors in land–atmosphere interactions: surface runoff generations and interactions between surface and groundwater

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Abstract

This paper presents two recent improvements on the current version of the three-layer variable infiltration capacity (VIC-3L) model. One is to include the infiltration excess runoff generation mechanism in the variable infiltration capacity (VIC) by considering effects of subgrid spatial soil heterogeneities, which is consistent with the VIC's earlier subgrid spatial variability treatment for the saturation excess runoff process. The other is to dynamically take into account the effects of surface and groundwater interactions on soil moisture, evapotranspiration, and recharge rate. The new version of the VIC model is applied to a watershed of Little Pine Creek near Etna in Pennsylvania for multiple years. Results show that the new version of the VIC properly simulates the total runoff and groundwater table, and that the two processes affect the partition of water budget for the study site. Although the new surface runoff parameterization and the process for surface and groundwater interactions are developed under the context of the VIC model, the framework and methodology presented in this paper could be applied to other land surface models as well.

Keywords: surface runoff; surface and groundwater interactions; subgrid-scale variability; soil heterogeneity; land surface models; hydrologic models; soil moisture; evaporation

1. Introduction

The hydrologically based variable infiltration capacity (VIC) land surface model has actively participated in various phases of the Project for Intercomparison of Land-surface Parameterization Schemes (PILPS) (e.g., Shao and Henderson-Sellers, 1996; Chen et al., 1997; Liang et al., 1998; Lohmann et al., 1998; Wood et al., 1998; Pitman et al., 1999) since the beginning of the PILPS project. Based on the various PILPS activities and different applications of the VIC model at various basins ranging from small watersheds to continental and global scales (e.g., Wood et al., 1997) under different climate conditions, the VIC model has been constantly improved over the past years.

At the beginning, the version of the two-layer VIC model (i.e., VIC-2L) participated in phase-1 (1a, 1b, and 1c) and phase-2b of the PILPS. The VIC-2L model is a semidistributed grid-based hydrologic model that parameterizes the dominant hydrometeoro-

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logical processes by considering subgrid spatial variabilities of precipitation and infiltration, and a mosaic representation of vegetation cover (i.e., different vegetation covers and bare soil). The model uses two soil layers and one vegetation layer with energy and moisture fluxes exchanged between the layers. The upper soil layer is designed to represent dynamic response of soil moisture to rainfall events, and the lower layer is used to characterize seasonal soil moisture behavior. Two different time scales of runoff (fast runoff and slow runoff) are included in the model to capture the dynamics of runoff generation. The fast component of runoff is represented by surface runoff, and the slow component is represented nonlinearly by subsurface runoff.

Based on the HAPEX study of the PILPS (phase-2b), VIC-2L was modified to add one thin surface layer (i.e., three-layer variable infiltration capacity (VIC-3L)) to better represent bare soil evaporation process after small summer rainfall events. In addition, diffusion process was included in the representation of the VIC soil column. This version of the VIC-3L model was used in phase-2a of the PILPS study. In the phase-2c study, the version of the VIC model with a better ground heat flux parameterization (Liang et al., 1999) was used that resulted in more reasonable ground heat flux simulation (Liang et al., 1998) among other features of the VIC model. In the PILPS phase-2e, the version of the VIC with better features of frozen soil processes for cold climate conditions (Cherkauer and Lettenmaier, 1999) was used. The VIC model did not participate in the PILPS phase-2d.

It is clear that over the course of various phases of the PILPS and other applications, the VIC has been constantly improving. Since the PILPS phase-2e, two more major improvements with the VIC model have been implemented. One of them is the ability of VIC to generate both infiltration and saturation excess runoff within a model computational grid cell simultaneously to improve the partitioning of water and energy budgets under a wide range of wet and dry climate conditions. The new parameterization of infiltration and saturation excess runoff considers effects of subgrid-scale spatial variability of soil properties. The other improvement is to dynamically represent interactions between surface and groundwater within the VIC soil column. It should be mentioned that no new parameters are introduced into the VIC model associated with the introduction of the two new improvements.

2. Background

2.1. Surface runoff generation mechanisms in land surface models

In the phase-2c of the PILPS intercomparison study, Lohmann et al. (1998) showed that a number of land surface schemes have too much runoff in the summer due to their wet soil moisture, while others have too little runoff most of the time. That study suggested that infiltration excess runoff process under dry conditions should be improved. In the pilot phase study of the ongoing Global Soil Wetness Project (GSWP) (Dirmeyer et al., 1999), a large spread is present in the estimations of soil moisture and the partitioning of surface energy and water budgets. Dirmeyer et al. (1999) suggested that the subgrid-scale variability in infiltration, whether due to the heterogeneity in soil properties or the distribution of rainfall within a grid box, had played an important role for the wide spread among the participating schemes.

In fact, most of current generation land surface models do not take into account of 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). Western and Grayson (1998) showed that for the small Tarrawarra experimental catchment (0.1 km^2) in southeastern Australia, the soil moisture for a typical wet season day within the top 30 cm shows a distinct spatial distribution. Under such a condition, both infiltration and saturation excess runoff may be generated at different locations of the catchment simultaneously due to the distinct soil moisture distribution within the area. Therefore, it is very important to include the two different runoff generation mechanisms within each grid of a land surface model to effectively represent the effects of heterogeneity of soil properties and spatial variability of precipitation.

Although the VIC 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 a difficult time in simulating surface runoff and soil moisture well under arid climate where infiltration excess runoff generation mechanism is important. Nijssen et al. (1997, 2001) coupled the VIC model 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) performs quite well over moist areas in their study. For arid and semiarid areas, however, their studies indicated difficulties in reproducing monthly observed streamflows. In the 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 semiarid areas may be resulted by a combination of different reasons, (for example, the weaknesses associated with the used routing scheme as discussed in Nijssen et al. (2001)), one of the possible main reasons could be due to the lack of inclusion of infiltration excess runoff generation mechanism that plays an important role under arid climate conditions. Without an inclusion of such runoff generation mechanism, soil moisture, surface runoff, and relevant energy budgets may not be simulated well.

2.2. Surface and groundwater interactions

Groundwater–surface water interaction is another important aspect in land–atmosphere interaction studies. Water table positions close to the surface would likely result in saturation excess runoff, yield evaporation at the atmosphere-demanded rate, and produce a net discharge of groundwater. On the other hand, deep water tables generally indicate drier areas where evaporation is limited by the available soil moisture. In this situation, surface runoff is likely to be generated by infiltration excess runoff mechanism, and groundwater is recharged when infiltration is enhanced. Under both conditions of the water tables, the soil moisture is modified through the groundwater and surface water interactions. Field observations showed that the interactions between surface water and groundwater could alter hydrological consequences, such as runoff production (e.g., Waddington et al., 1993), water table fluctuations, and surface hydrology (e.g., Verry and Boelter, 1978; Taylor and Pierson, 1985; Whiteley and Irwin, 1986; Devito and Dillon, 1993; Devito et al., 1996; Katz et al., 1997).

Salvucci and Entekhabi (1995) presented a statistical approach to estimate the groundwater table under a steady-state equilibrium condition at the hillslope scale, where the groundwater table is estimated by coupling saturated and unsaturated flows throughout rectangular hillslope domains. Their study showed the importance of interactions between groundwater and surface water (at the steady-state equilibrium condition) to long-term evaporation, surface runoff generation, and groundwater recharge at the hillslope scale. Levine and Salvucci (1999) used a modified version of MODFLOW to study the interactions between saturated and unsaturated zones under equilibrium conditions for a Canadian catchment of 16 km^2 with prairie cover. The groundwater table was estimated through a look-up table-type of iteration approach. Depth to the water table ranging from zero to the deep drainage asymptote (at 1-cm intervals) is obtained by solving a modified surface water balance model offline (Salvucci and Entekhabi, 1995). The water balance for each depth is stored in a look-up table that is used as input to the MODFLOW. Their study showed that the position of groundwater table would impact the partitioning of rainfall, and that the uncoupled vadose zone models (e.g., SVAT models) would overpredict recharge at the expense of evaporation when the groundwater table is deep.

The concept and hydrologic characteristics of the TOP model, which considers the effects of topography and groundwater table on water and energy budgets, have been implemented in some land surface models (e.g., Famiglietti and Wood, 1994; Peters-Lidard et al., 1997; Chen and Kumar, 2001; Ducharne et al., 2000; Koster et al., 2000). However, the inclusion of the groundwater table is again under a steady-state assumption. Walko et al. (2000) implemented a modified form of the TOP model into the Land Ecosystem–Atmosphere Feedback (LEAF-2) model. Recognizing the limitation of the steady-state assumption, Walko et al. (2000) modified the steady-state expression of the local height of water table in the original TOP model by introducing a characteristic time-scale used as a decay constant of baseflow. Sensitivity analysis of the LEAF-2 coupled with the Regional Atmospheric Modeling System (RAMS) for hypothetical experiments (grid size of 20 km for a 200-km-wide island with different configurations of the number and type of vegetation) showed that significant differences could be found in the daily averaged sensible and latent heat fluxes as well as surface temperature when the TOP model groundwater component is implemented in the LEAF-2. In addition, significant differences were found in soil moisture distribution with soil depth in the two simulations with and without the TOP model groundwater component. Again, the study by Walko et al. (2000) suggested that the runoff process and groundwater table could have significant effects on water and energy budgets in the land–atmosphere coupling system, although their modifications to the steady-state assumption have not been validated using groundwater observations, and their study was only for a short period of time.

In summary, sensitivity analyses and field observations have shown that soil moisture plays an important role in the global energy and water budgets. Knowledge of the state of soil moisture has been shown to be essential for improving climate predictability on seasonal to interannual time scales. However, as reviewed briefly above, soil moisture is not well simulated in current generation of land surface models. Field measurement of soil moisture with large spatial coverage is not practical. Remote sensing techniques provide a very useful alternative for estimating soil moisture with good spatial coverage, but are only partially effective at present due to their shallow penetration into the ground. Therefore, it is crucial to simulate soil moisture through a combination of remote sensing data assimilation with a land surface model. Land surface models must be improved to include critical physical processes and the important factor of subgrid spatial variability that impact soil moisture simulations. This paper focuses on two recent improvements: surface runoff generations under the context of subgrid spatial variability and the surface and groundwater interactions where the groundwater table is computed dynamically. Although the two processes are presented using the VIC model, the framework and methodology proposed here can be extended to other land surface models as well.

3. Model enhancements

3.1. New surface runoff parameterization

Liang and Xie (2001) extended the current version of the widely used VIC-3L model with a statistical approach to include the infiltration excess runoff generation mechanism by considering effects of subgrid spatial heterogeneity of soil properties. The current version of the VIC-3L model already incorporates saturation excess (Dunne) runoff generation through a probability distribution function of soil storage capacity. The new statistical approach is consistent with the treatment of the VIC in its original form for the saturation excess runoff calculation. To have the paper self-contained, basic concepts and main formulations of the new surface runoff parameterization of the VIC model are briefly described in this section. It is worth mentioning that no new model parameters need to be introduced to calculate the infiltration excess runoff in the work presented here, while three additional soil parameters were introduced in the earlier work described by Liang and Xie (2001).

For a studied area (e.g., a model grid cell, or a catchment), the saturation excess runoff (R_1) in the surface runoff parameterization is computed over both area A_s (see Fig. 1) that is initially saturated and the area ($A_s' - A_s$) that becomes saturated during the time step. 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 (i.e., y) shown in Fig. 1a,

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

where i_m and i_o represent, respectively, the maximum point soil moisture capacity and the point soil moisture capacity corresponding to the initial soil moisture W_t (see Fig. 1a), b is the soil moisture capacity shape

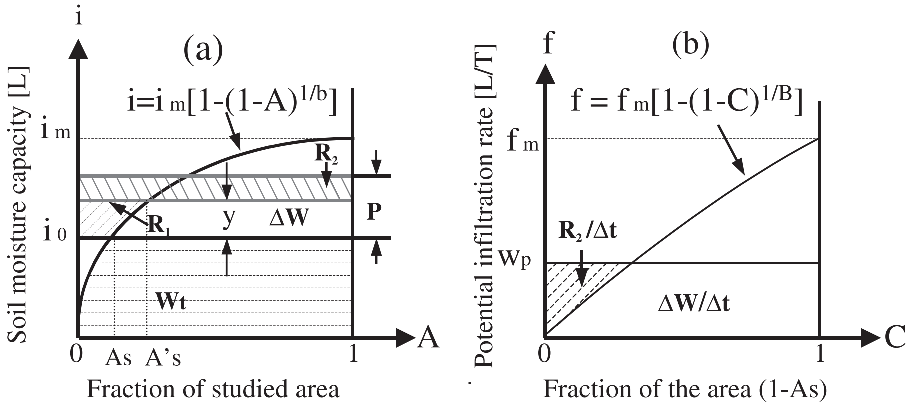

Fig. 1. Schematic representation of the VIC upper soil layer. (a) Spatial distribution of soil moisture capacity (L) for saturation excess runoff. (b) Spatial distribution of potential infiltration rate (L/T) (i.e., infiltration capacity) for infiltration excess runoff.

parameter, P is the amount of precipitation over a time step Δt, and y is the vertical depth shown in Fig. 1a that represents the difference between precipitation and infiltration excess runoff over a time step Δt for a study area. The vertical depth, y, is related to the saturation excess runoff $R_1(y)$ and the change of soil moisture $\Delta W(y)$ as follows (see Fig. 1a),

$$y \cdot 1 = R_1(y) + \Delta W(y) \tag{2}$$

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

$$R_2(y) = \begin{cases} P - R_1(y) - f_{\mathrm{mm}}\Delta t\left[1 - \left(1 - \frac{P - R_1(y)}{f_{\mathrm{m}}\Delta t}\right)^{B+1}\right], & \frac{P - R_1(y)}{f_{\mathrm{m}}\Delta t} \le 1 \\ P - R_1(y) - f_{\mathrm{mm}}\Delta t, & \frac{P - R_1(y)}{f_{\mathrm{m}}\Delta t} \ge 1 \end{cases} \tag{3}$$

where f_{mm} is the average potential infiltration rate over the area of $1 - A_{\mathrm{s}}$, which can be expressed as,

$$f_{\mathrm{mm}} = \int_0^1 f_{\mathrm{m}}\left[1 - (1 - C)^{1/B}\right]\mathrm{d}C = \frac{f_{\mathrm{m}}}{1 + B} \tag{4}$$

where 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 that is taken to be 1 in this study as well (Liang and Xie, 2001).

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

$$\int_0^{t_f} f_{\mathrm{p}}(t)\mathrm{d}t = W_t + \Delta W \tag{5}$$

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

$$f_{\mathrm{mm}}(t) = f_{\mathrm{p}}(t_f) \tag{6}$$

For a detailed description of the new surface runoff parameterization of VIC and the derivation of above equations, the reader is referred to the paper by Liang and Xie (2001) where the Horton infiltration formulation is used in Eqs. (5) and (6).

If Philip infiltration equation is used as the spatially averaged point infiltration function $f_{\mathrm{p}}(t)$, we have,

$$f_{\mathrm{Philip}}(t) = f_{\mathrm{p}}(t) = \frac{S_{\mathrm{p}}}{2}t^{-1/2} + K_{\mathrm{p}} \tag{7}$$

where S_p and K_p are the two parameters and can be estimated based on initial soil moisture and soil property (Bras, 1990), which is usually required by (available for) a land surface model. In other words, no additional parameters would need to be introduced. From Eq. (6), we have,

$$f_{mm}(t) = f_{Philip}(t_f) = f_p(t_f) = \frac{S_p}{2} t_f^{-1/2} + K_p \tag{8}$$

It is worth mentioning that the process of reinfiltration is not considered here. For arid regions, the process of reinfiltration could be important and is worth of future investigation.

3.2. Parameterization of surface and groundwater interactions

Based on one-dimensional Richards equation applied to unsaturated zone, we have,

$$\frac{\partial\theta}{\partial t} = \frac{\partial}{\partial z}\left(D(\theta)\frac{\partial\theta}{\partial z}\right) - \frac{\partial K(\theta)}{\partial z} \tag{9}$$

where θ is the volumetric soil moisture content [L^3/L^3], $D(\theta)$ is the hydraulic diffusivity [L^2/T], $K(\theta)$ is the hydraulic conductivity [L/T], and z is the vertical direction and assumed positive downward. The upper boundary condition (i.e., at the surface when $z=0$) can be expressed as,

$$q_o(t) = K(\theta) - D(\theta)\frac{\partial\theta}{\partial z} \tag{10}$$

where $q_o(t)$ is the flux across the surface (i.e., $z=0$). Let $\alpha(t)$ be the groundwater level, which is the distance from ground surface to the water table (also called moving boundary here). For the saturated zone, we have,

$$\theta(z,t) = \theta_s, \quad \alpha(t) \le z \le L \tag{11}$$

where L represents the depth from ground surface to the bedrock. The groundwater table (i.e., the moving boundary) separates the saturation region from the unsaturated zone. Although such a situation may not always occur in reality, Bear (1972) shows that such an assumption is a good approximation. The zero pressure condition and prescribed flux across the groundwater table are two common approaches used to describe the moving boundary. In this study, we use the latter. The moving boundary condition can be expressed by,

$$\left(K(\theta) - D(\theta)\frac{\partial\theta}{\partial z}\right)\bigg|_{z=\alpha(t)} = Q_{b2} + E_2 - n_e(t)\frac{d\alpha}{dt} \tag{12}$$

where Q_{b2} is subsurface flow rate from the saturated zone, E_2 is transpiration rate from the saturated zone, and $n_e(t)$ is effective porosity of the porous media which is a function of time. Here the effective porosity is defined as the absolute difference of soil moisture content over $d\alpha$ between two time steps. The initial conditions, respectively, for the unsaturated and saturated zones are,

$$\theta(z,0) = \theta_o(z), \quad 0 \le z < \alpha(0) \tag{13}$$

$$\theta(z,0) = \theta_s, \quad \alpha(0) \le z \le L \tag{14}$$

where θ_s is the soil porosity. The soil moisture profile $\theta(z, t)$ and groundwater table $\alpha(t)$ are to be determined by applying Eqs. (9) and (11) with (10), (12), (13), and (14). If the position of the groundwater table $\alpha(t)$ is determined, then the soil moisture profile $\theta(z, t)$ within the unsaturated zone can be determined by using mass-lumped finite element method (Xie et al., 1999) that allows for an upward flux of moisture from the groundwater table to the root zone in case the groundwater table lies below the root zone. In our approach, $\alpha(t)$ is to be determined dynamically for unsteady state conditions. Let

$$\overline{\theta(t)} = \int_0^{\alpha(t)} \theta(z,t)dz \tag{15}$$

Integrating Eq. (9) over soil depth (0, $\alpha(t)$) with Eqs. (10) and (12), and considering subsurface flow rate from the unsaturated zone (Q_{b1}), bare soil evaporation from a thin layer (e.g., the top 10-cm soil depth in VIC), and transpiration from a specified root region within the unsaturated zone, it yields,

$$\frac{d\bar{\theta}}{dt} - \frac{d\alpha}{dt}(\theta_s + n_e(t)) = P - R - Q_b - E_t \tag{16}$$

where P is precipitation rate, R is total surface runoff rate (i.e., infiltration excess and saturation excess runoff), E_t is total combined evaporation rate that includes bare soil evaporation, and transpiration from the root region in both unsaturated and saturated zones, and

$$Q_b = Q_{b1} + Q_{b2}$$

Integrating Eq. (16) over time (t, $t+\Delta t$), we have,

$$\alpha(t+\Delta t) - \alpha(t) = \frac{1}{\overline{\theta_s + n_e(t)}}\left[\bar{\theta}(t+\Delta t) - \bar{\theta}(t) - \int_t^{t+\Delta t}(P - R - Q_b - E_t)\mathrm{d}t\right] \tag{17}$$

where $\overline{\theta_s + n_e(t)}$ is the average of $\theta_s + n_e(t)$ over two time steps. The soil moisture profile $\theta(z, t+\Delta t)$ within unsaturated zone and the position of groundwater table $\alpha(t+\Delta t)$ at time $t+\Delta t$ are computed by applying finite element method in space and finite difference method in time. The numerical steps are briefly summarized below:

(a) Initializing $\theta(z, 0)$ with $\alpha(0)$.
(b) Preestimate moisture profile $\theta(z, t+\Delta t/2)$ through linear extrapolation from the old moisture distribution. Compute the coefficient matrix associated with the finite element method using moisture profile $\theta(z, t+\Delta t/2)$.
(c) Compute $\theta(z, t+\Delta t)$. Iterate on $\theta(z, t+\Delta t)$ until it converges.
(d) Compute $\alpha(t+\Delta t)$ based on $\theta(z, t+\Delta t)$ and $\alpha(t)$ with Eq. (17).
(e) Repeat steps (b)–(d) until $\alpha(t+\Delta t)$ converges.
(f) Repeat steps (b)–(e) for the next time step.

4. Experiments and results

The two improvements described in Section 3 are implemented into VIC-3L. The two improvements are tested by comparing the model-simulated total runoff and groundwater table with observations at the watershed of Little Pine Creek near Etna (about 15 km^2 large) in Pennsylvania. In addition, results from different configurations of the VIC model are compared with each other. Specifically, two types of experiments were conducted. Type 1 experiment focuses on investigating the effects of infiltration formulations between Philip (called VIC-Philip1 or Philip1)) and Horton (called Horton). Results from the current version of VIC (called VIC-Old1), where the infiltration excess runoff mechanism is not considered, is also included. It should be mentioned that in the type 1 comparison study, the effect of surface and groundwater interactions is not considered in all of the VIC simulations (i.e., VIC-Philip1, Horton, and VIC-Old1). In the type 2 experiment, the significance of surface and groundwater interactions is investigated where the Philip infiltration formulation is used in the VIC simulations. The model simulations of the type 2 experiment are called VIC-Philip2 and VIC-Old2, respectively.

At the watershed of Little Pine Creek near Etna, daily forcing data needed to run the VIC model in water balance mode are available from a nearby surface meteorological station (Station ID # 366993) with latitude of 40°30′ and longitude of 80°14′, respectively. The information on vegetation, soil properties, and the VIC model parameters is obtained from the corresponding grid cell (at 0.125° resolution) compiled by the University of Washington (Maurer, 2002). The configuration of VIC-3L has soil depths of 0.1, 0.4, and 2.1 m for the top thin layer, layer 2 (i.e., upper layer), and layer 3 (i.e., lower layer), respectively. The configuration of soil layers used to compute the groundwater table with finite element method is 0.026 m for each layer. The soil moisture of VIC-Philip1, Horton, and VIC-Old1 is initialized at half-saturation level. For the VIC-Philip2 simulation, the soil moisture within the unsaturated zone is initialized at half-saturation level, and the initial groundwater table is set at the observed value. A preiteration process is then conducted to obtain an initial soil moisture profile within the unsaturated zone to be consistent with the prescribed initial groundwater table. The processes of infiltration, evapotranspiration, surface runoff, and subsurface runoff are computed based on the VIC-3L configuration like before (Liang et al., 1994, 1996a,b; Cherkauer and Lettenmaier, 1999; Liang and Xie, 2001). The soil moisture of each of the VIC's three layers (i.e., with VIC-3L configuration) is updated at each time step by the soil moisture computed from the finer resolution using the mass-lumped finite element method. In this application, two to three iterations are typically needed to reach the convergence for both the shape of the soil moisture profile (i.e., step (c) of Section 3.2) and the location of the water table (i.e., step (e) of Section 3.2) as well. Due to the daily available forcing data at this site, all of the model simulations were run at daily time step. The model simulations are then compared with the daily observations of streamflow and groundwater table.

Fig. 2a shows the daily precipitation time series for the period of October to December 1997, which represents a typical transition from dry to wet period. Fig. 2b shows the comparison between daily observed streamflow and the VIC-simulated daily total runoff with and without the infiltration excess runoff mechanism for the same period. Fig. 2c shows the comparison of daily surface and subsurface runoff between VIC-Philip1 and VIC-Old1 simulations. In Fig. 2b, it can be seen that for the large storm with a precipitation peak over 30 mm/day around November 10, the total runoff (i.e., surface plus subsurface runoff) simulated from the VIC-Philip1 (i.e., with infiltration excess runoff mechanism) compares quite well with the observed streamflow while the total runoff from

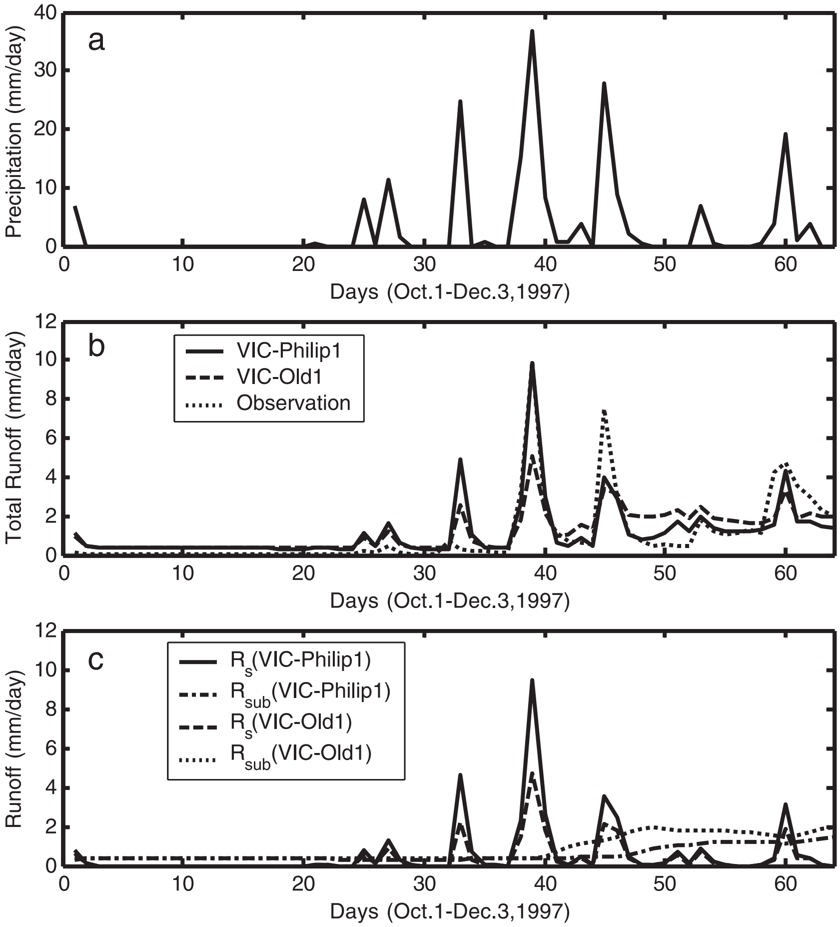

Fig. 2. Comparison of model simulations at the watershed of Little Pine Creek near Etna in Pennsylvania for the period of October 1 to December 3, 1997. (a) Daily precipitation time series. (b) Comparison of daily total runoff among the observed streamflow (dotted line), VIC-Philip1 with the infiltration excess runoff mechanism using Philip formulation in Eqs. (5) and (6) (solid line), and VIC-Old1 without the infiltration excess runoff mechanism (dashed line). (c) Comparison of daily surface runoff and subsurface runoff with (solid line for surface runoff and dash–dot line for subsurface runoff) and without (dashed line for surface runoff and dotted line for subsurface runoff) the infiltration excess runoff mechanism using the Philip formulation.

the VIC-Old1 (i.e., without the new surface runoff feature) underestimates the observation by about half. Fig. 2c shows that the main reason of the significant underestimation by VIC-Old1 is due to its significant underestimation of the surface runoff rather than the subsurface runoff. The underestimation of the surface runoff results in much higher soil moisture in VIC-Old1 (figures not shown). For the second largest

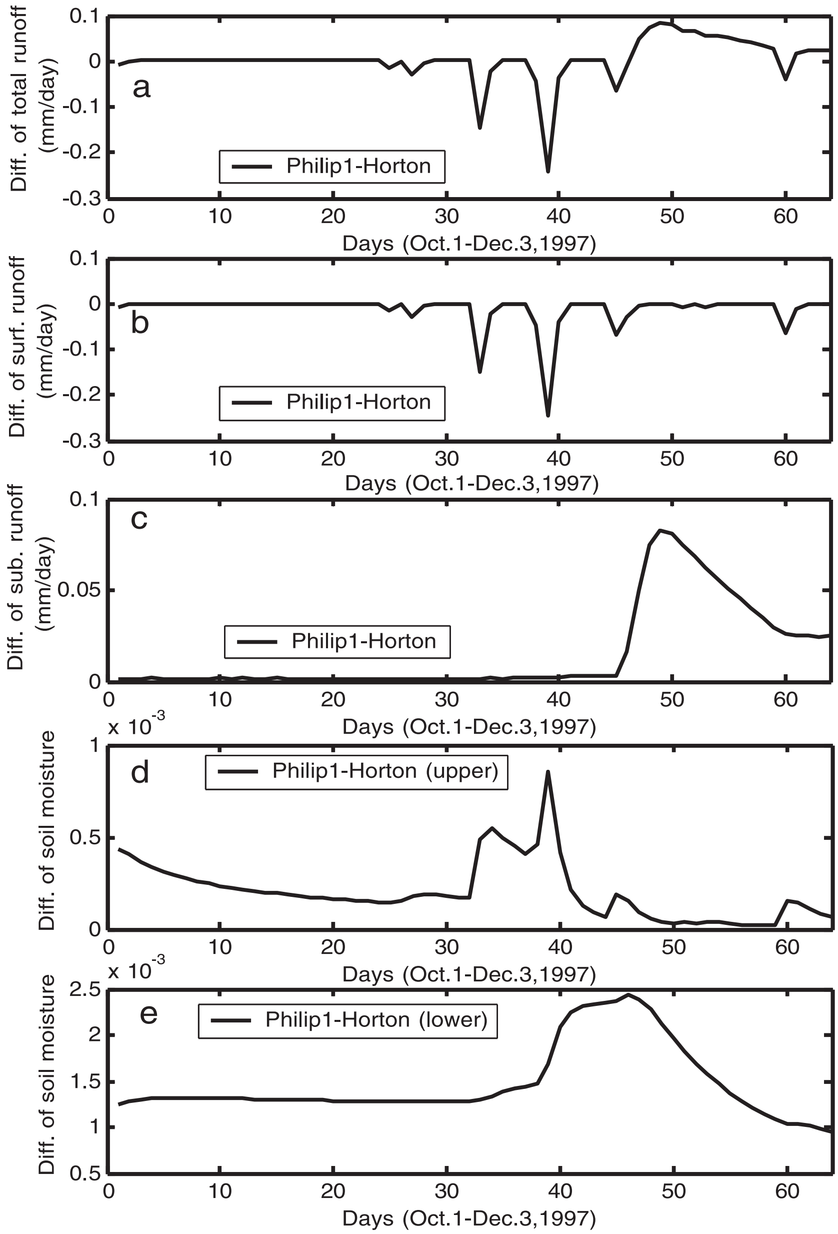

Fig. 3. Comparison of daily flows and volumetric soil moisture between using Philip and Horton formulations in Eqs. (5) and (6) at the watershed of Little Pine Creek near Etna in Pennsylvania for the period of October 1 to December 3, 1997. (a) Difference in total simulated runoff. (b) Difference in simulated surface runoff. (c) Difference in simulated subsurface runoff. (d) Difference in simulated soil moisture of the upper layer (i.e., layer 2). (e) Difference in simulated soil moisture of the lower layer (i.e., layer 3).

storm right after the big one, both simulations (with and without the infiltration excess runoff mechanism) underestimate the observed runoff, and the difference between VIC-Philip1 and VIC-Old1 is small. The reason for the reduced difference is due to the larger contribution of the subsurface runoff in VIC-Old1, which resulted from its higher soil moisture. After the two big storms, VIC-Old1 overestimates low flows due to higher contribution of the subsurface runoff caused by less surface runoff but more infiltration from the previous large storms. However, the low flows from VIC-Philip1 compares well with the observations (see Fig. 2b). Fig. 3a–c shows the differences between using Philip and Horton formulations in Eqs. (5) and (6) on the total, surface, and subsurface runoff, respectively. Fig. 3a–c shows that these differences are quite small comparing to the effects of considering versus not considering the Hortonian flow mechanism (see Fig. 2b and c). Fig. 3d and e shows the differences of volumetric soil moisture in upper and lower layers, respectively, between using Philip versus Horton formulations. In

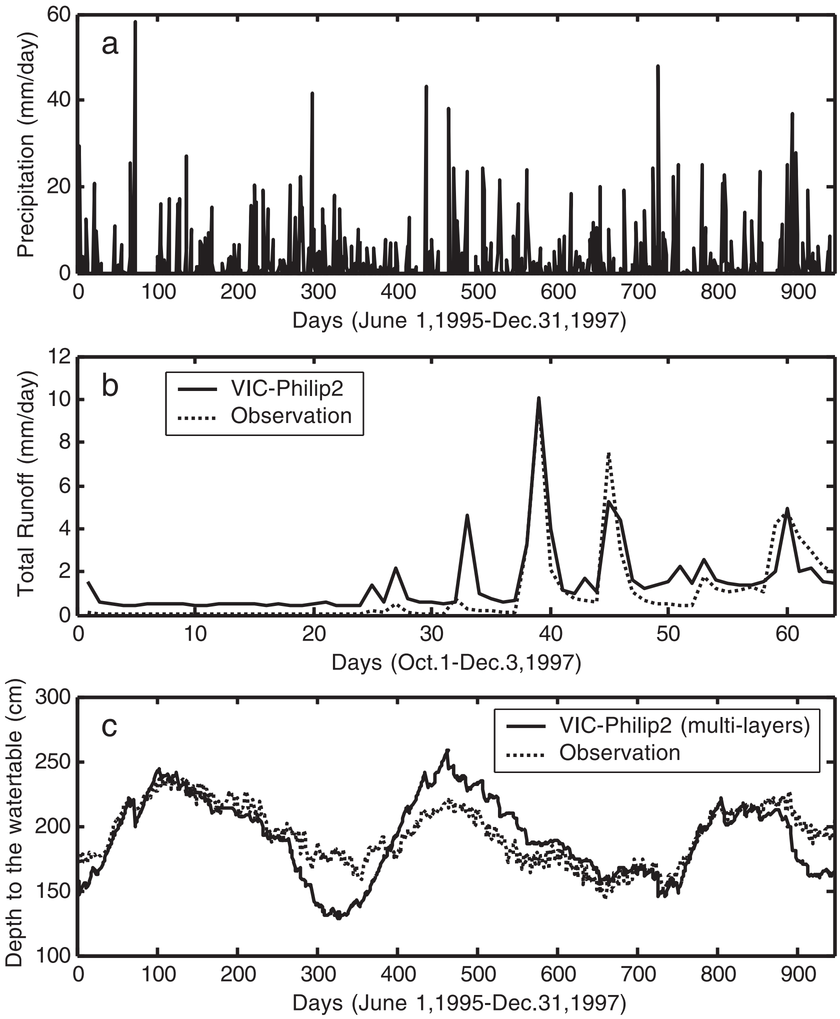

Fig. 4. Comparison of model simulations with observations at the watershed of Little Pine Creek near Etna in Pennsylvania. (a) Daily precipitation time series for the period of June 1, 1995 to December 31, 1997. (b) Comparison of daily simulated total runoff of VIC-Philip2 with observations for the period of October 1 to December 3, 1997. (c) Comparison of daily groundwater table simulated from VIC-Philip2 with observations for the period of June 1, 1995 to December 31, 1997.

Fig. 3d and e, it can be seen clearly again that the differences are quite small. For drier and wetter conditions, the differences of the model simulations between using Philip versus Horton formulations are also small (figures not shown). It should be mentioned that when soil is wet, the differences between VIC-Philip1 and VIC-Old1 simulations become quite small (figures not shown), similar to those shown by Liang and Xie (2001).

Comparisons shown in Figs. 4 and 5 are focused on the effects of considering versus not considering the process of surface and groundwater interactions. Two VIC simulations represented by VIC-Philip2 and VIC-Old2 were conducted in which VIC-Philip2 considers the effect of surface and groundwater interactions, while VIC-Old2 does not consider such interactions. Fig. 4a shows the daily precipitation time series from June 1, 1995 to December 31, 1997. Fig. 4b shows the daily comparison of total runoff between VIC-Philip2 and observations for the period of October 1 to December 3, 1997 (the same period as shown in Fig. 2b). Fig. 4c shows the daily comparison of groundwater table between VIC-Philip2 and observations for the period from June 1, 1995 to December 31, 1997. The comparison started on June 1, 1995 after the simulation of the first 3 years is discarded as a warm up period to reduce the soil moisture initialization effect. In Fig. 4b, it can be seen that the effects on total runoff by including the surface and groundwater interactions are not significant, although VIC-Philip2 results in slightly higher runoff for both high and low flows comparing with the one without considering the surface and groundwater interactions at this study site. The reason may be due to higher soil moisture level in layer 3 (figures not shown) in VIC-Philip2. In Fig. 4c, it can be seen clearly that VIC-Philip2 can dynamically simulate the groundwater table well. Fig. 5 shows that the evapotranspiration

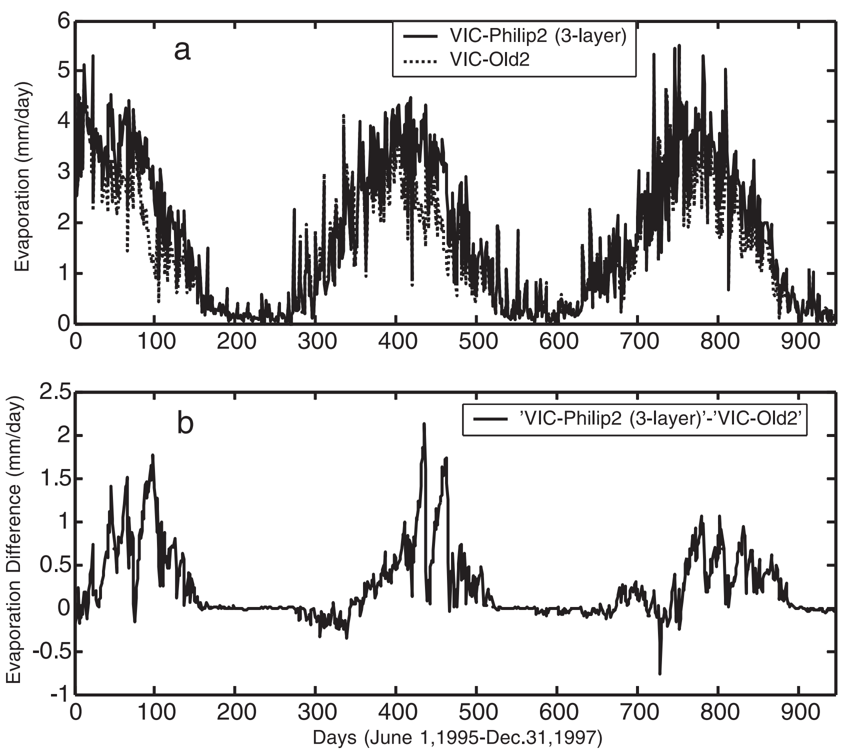

Fig. 5. Comparison of evaporation at the watershed of Little Pine Creek near Etna in Pennsylvania for the period of June 1, 1995 to December 31, 1997. (a) Comparison of evapotranspiration between considering the surface and groundwater interactions (solid line) and not considering such interactions (dotted line). (b) Difference between them as shown in (a).

from VIC-Philip2 is generally higher than that from VIC-Old2, and sometimes the differences can be quite large.

Table 1 lists daily statistics on evapotranspiration and total runoff obtained from VIC-Philip and VIC-Old simulations, respectively, for the period of June 1, 1995 to December 31, 1997. In addition, the daily statistics on precipitation and observed streamflow for the same period are listed in Table 1. From the table, it can be seen that the VIC-Philip2 simulated daily mean total runoff is closer to the observed mean than those of VIC-Philip1 and VIC-Old1, although the standard deviations (S.D.) from all three of the VIC simulations underestimate the observed one for the period of June 1, 1995 to December 31, 1997, with the VIC-Old1 the worst. In addition, the daily mean evapotranspiration and its standard deviation of the VIC-Philip2 are larger than those of VIC-Old2 over the period of June 1, 1995 to December 31, 1997. The ratios of daily absolute differences between VIC-Philip2 and VIC-Old2 on evapotranspiration, total runoff, and volumetric soil moisture of the upper (i.e., layer 2) and lower (i.e., layer 3) layers to their corresponding daily mean values obtained from the VIC-Old2 are listed in Table 2. From Figs. 4 and 5, and Tables 1 and 2, it can be seen that the effects of surface and groundwater interactions alone on evapotranspiration, runoff, and soil moisture can be significant.

Comparisons between observations and model simulations of VIC-Old1, VIC-Philip1, and VIC-Philip2 clearly demonstrate the significant roles of the two processes (i.e., infiltration excess runoff process and surface and groundwater interactions) in the VIC model for the study site. Due to the limitation of data availability at the site, simulations with the energy balance mode of the VIC model could not be conducted. Therefore, quantitative impact of the two processes on energy budget is not yet clear. However, due to the impact of these two processes on the water budget, it is expected that their impact on the energy budget cannot be ignored. More studies of the effects of these two new processes/mechanisms on water and energy budgets with the VIC model need to be conducted in the future. It should be mentioned that the framework presented in this paper could be applied to other land surface models as well. It is expected that properly incorporating the two processes into a land surface model could lead to general improvements in partitioning water and energy budgets of land–atmosphere interactions for a wide range of wet and dry climate conditions.

Table 1
Statistics for the period of June 1, 1995 to December 31, 1997

	Daily mean	S.D.
Precipitation (mm/day)	2.31	5.86
Observed streamflow (mm/day)	1.05	1.71
Total runoff (VIC-Philip2) (mm/day)	1.04	1.15
Total runoff (VIC-Philip1) (mm/day)	1.01	1.37
Total runoff (VIC-Old1) (mm/day)	0.96	0.95
Evapotranspiration (VIC-Philip2) (mm/day)	1.75	1.40
Evapotranspiration (VIC-Old2) (mm/day)	1.51	1.22

Table 2
Ratios of absolute differences to their corresponding mean values from VIC-Old2 for the period of June 1, 1995 to December 31, 1997

	Relative absolute difference (%)
Total runoff	4
Evapotranspiration	19
Soil moisture in layer 1	13
Soil moisture in layer 2	14
Soil moisture in layer 3	12

5. Conclusions

The current version of the VIC-3L model is extended by incorporating two important processes. One is to include the infiltration excess runoff generation mechanism in the VIC model by considering effects of spatial subgrid soil heterogeneities on surface runoff and soil moisture simulations. The other is to take into account the effects of surface and groundwater interactions on soil moisture, evapotranspiration, and recharge rate. The new version of the VIC model is applied to the watershed of Little Pine Creek near Etna in Pennsylvania. Results show that the new version of VIC properly simulates the total runoff and groundwater table, and that the two processes affect the partition of water budget for the study site. More studies of the effects of these two new processes/mechanisms on water and energy budgets with the VIC model need to be conducted in the future. Although the new surface runoff parameterization and the process for surface and groundwater interactions are developed under the context of the VIC model, the framework and methodology presented in this paper could be applied to other land surface models as well. Some primary conclusions based on our results at the study site are summarized below.

(a) Infiltration and saturation excess runoff processes are two important surface runoff generation mechanisms. Lacking one of them could result in significant errors in producing the total runoff and soil moisture at spatial scales where subgrid spatial variability of soil heterogeneity is significant.
(b) The differences in total runoff and soil moisture between using Philip versus Horton formulations in Eqs. (5) and (6) are much smaller than the differences caused by not considering the infiltration excess runoff mechanism for situations when soil is dry and/or semidry.
(c) Taking into account of surface and groundwater interactions dynamically is important in a land surface model to properly represent the partition of water budget among soil moisture, evapotranspiration, and recharge rate.
(d) The evapotranspiration that considers the surface and groundwater interactions is generally higher than that without considering such interactions, and sometimes the differences can be quite large.

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