Simulation and Model of Interflow on Hillslope of Forest Catchment

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ABSTRACT

Interflow processes on hillslope of broad-leaved Korean pine forest in catchment of Erdaobai river, which is the source of Songhua river, was simulated in Forest Hydrological Modeling Laboratory of Changbai Mountain Forest Ecosystem Research Station, Chinese Academy of Sciences. Saturated conductivity and effective porosity of soil on hillslope of broad-leaved Korean pine forest were measured, and submodels of saturated conductivity and effective porosity were established with depth from surface separately. substituting those submodels into Sloan's storage-discharge model and according to the adjusted model, the processes of interflow were simulated. After comparing the simulation results predicted by our model,exponential model(Robinson,1996), Sloan's model separately with observed results, the predicting precision of the adjusted storage-discharge model to interflow processes on hillslope of forest catchment was presented.

INTRODUCTION

Interflow is slow and steady, its current velosity is about 0.2m/h. Interflow plays a very important role in changing rainstorm-runoff processes on forest catchment, flatting-top and prolonging the runoff time, reducing the flood disaster, increasing the use efficiency of water resources. Interflow on hillslope of forest catchment is an important link of water cycling in ecosystem in which watershed is as a unit. Studying its transformation mechanism and hydrological processes, setting up and perfecting the model will not only enrich the theory of experimental forest hydrology, but also provide the basis for hydrological analysis and calculation of forest catchment, design, management and building of water conservation forest.

Interflow model developed in the whole world until now can be divided into 3 types roughly: finite element model or finite differential model based on the Richards equation, kinematic wave model and storage -discharge model based on the kinematic wave and kinematic assumptions separately. Precision of finite element or finite differential model is little bit high, but calculation is very complicated. So it is not suitable for forecasting rapidly and is difficult to expand to the whole catchment. Kinematic wave model is only fit for $\lambda<0.75$ ($\lambda=4i\cos\alpha/k_s\sin^2\alpha$), so its application is limited. Sloan put forward (Sloan and Moore,1984) storage-discharge model in 1983 . Sloan and Moore (1984) applied finite element model, kinematic wave model and storage -discharge model in forest catchment, and compared the forecasting results. It shows that storage-discharge model has higher precision, low cast, and was possible to link to be a better catchment model. Beven et al (1982b) believe that saturated conductivity k_s and effective porosity θ_s-θ_r are two important physical parameters when interflow was simulated , and both of them decrease with the depth. However,Sloan treated k_s and θ_s-θ_r as constants when he simulated interflow on hillslope of forest catchment with storage-discharge model. When Robinson and Sivapalan (1996) simulated interflow with storage-discharge model on hillslope of forest catchment, they supposed that saturated conductivity decreased exponentially with the depth. Based on this, it is possible to form a saturated zone in the soil under the rainfall intensity, then this zone will develop up and down, and finally formed a water discharge at the outlet section of hillslope. Unfortunately they did not consider this flow, therefore, they were not able to simulate the interflow processes of catchment realistically. This paper try to do some improvement.

METHOD

Using forest catchment of Erdaobai river, which is the source of Songhua river, as the background, the interflow on hillslope of broad-leaved Korean pine forest was simulated in Forest Hydrological Modeling Laboratory. Firstly, one of plot which has the same area as underlying model trough and is typical of this kind of forest, was selected, semi-decomposed and non-decomposed litters covered on the forest floor were collected for later use. All the soil were sampled according to different layers. First layer is loam soil, then albic soil and loess, total depth of soil samples is 1m. During the soil sampling, all the roots in soil were collected. After the samples, which include litter, root and different layer of soil, were taken into the laboratory, we began to simulate the forest soil characteristics in the underling model trough. Loess was put into the bottom of trough firstly, then compacted the soil until relative error of the bulk density between field soil and simulated soil is within 5%. The albic soil and loam soil were simulated in the same way. The depth of every layer is 33.3cm, and with total depth of 1m. Since most of the root distributed in up-layer of the soil, root were put into the soil at random, some of the thick roots were taken out. After all the soil layer simulation were finished, the litters were put on the surface according to the order in forest floor. Rainfall was controlled by the rainfall system. 3 different rainfall events were simulated .event 1: intensity is 0.52mm/min and precipitation is 156.0mm, event 2: intensity is 1.2mm/min and precipitation is 216.0mm, event 3: intensity is 1.9mm/min and precipitation is 342.0mm. During the rainfall, the processes of surface runoff and interflow were observed at the outlet section of the underlying model trough. Flow was measured by V-trough measuring meter in the measuring system which was controlled by computer control system.

At the hillslope of typical broad-leaved Korean pine forest, 1-2 of sampling point in upper, middle and lower slope position was arranged. In each sampling point, soil samples were taken in different soil depth at 0cm,20cm, 40cm, 60cm, 80cm and 100cm . And their saturated conductivity and effective porosity were measured. Effective porosity is : $\omega(z)=\theta_s-\theta_r$, θ_s is saturated volumetric moisture of soil sample, θ_r is residual volumetric moisture of soil sample. Taking average of saturated conductivity measured in the same depth, regressioning all of the conductivity measured in different depth with the corresponding soil depth, we establish the saturated conductivity submodel. Effective porosity submodel can be developed in the same way. Taking the soil samples from the underlying model trough in different depth, measuring their saturated conductivity and effective porosity, then substituting the measurement results into the two corresponding models, the parameters of soil in the trough were determined. Firstly, substituting the saturated conductivity submodel and effective porosity submodel, both of them use the parameters measured by experiment, into storage-discharge model, then interflow processes under different rainfall conditions were simulated . Secondly, saturated conductivity and effective porosity are taken as a constant, this means they are no change with the soil depth , simulating the interflow processes of different layer on computer under 3 diffferent rainfall condition described as above. Last, supposed that saturated conductivity decreased exponentially with the soil depth, interflow processes were simulated in the same way. Comparing the interflow processes observed by experiment with three simulated interflow processes on computer. We can estimate the precision of them separately.

ANALYSIS AND RESULTS

The idealed hillslope segment has an impermeable boundary or bed, of slope α , length L, and a soil profile of constant thickness D(as is show in Figure 1). Then, the balance of water, per unit width, can be written as:

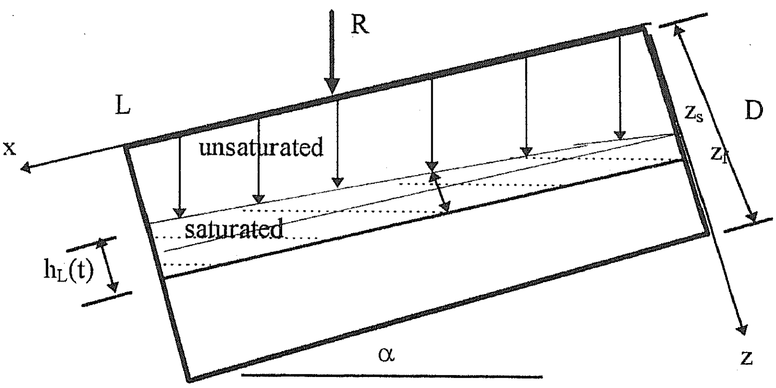

Figure 1 The idealed hillslope

$$\frac{dv}{dt}=i(t)-Q(t) \tag{1}$$

where v is the drainable volume of water in the saturated zone, i(t) is the rate of water input from the unsaturated zone to the saturated zone, t is time, Q(t) is the discharge from the hillslope. The equation of unsaturated conductivity can be written as equation : (Brooks-Corey,1984)

$$K(\theta,z)=K_s(z)\left(\frac{\theta-\theta_r}{\omega(z)}\right)^N \tag{2}$$

where $k(\theta,z)$, $k_s(z)$ are unsaturated conductivity and saturated conductivity at depth z separately, θ_s, θ_r,θ are the saturated volumetric water content, residual volumetric water content and volumetric water content separately. N is a pore size distribution index, $\omega(z)(=\theta_s-\theta_r)$ is effective porosity.

Beven(1982) had pointed out that both saturated conductivity and effective porosity tend to decrease with depth into the soil profile. and we had get the equation by experiment at fileld in forest catchment as:

$$\begin{cases} k_s(z)=k_o-f_1\ln(z) & \text{(3a)} \\ \omega(z)=\omega_0-f_2\ln(z) & \text{(3b)} \end{cases}$$

where k_0, $k_s(z)$ is the saturated conductivity at surface of soil profile and at depth z Separately; z is the depth from surface, ω_o is the effective porosity at surface of soil profile, f_1, f_2, are parameters, and the unit of z is cm.

We can suppose that the soil is isotropic, then both k_0 and ω_0 do not change on the direction paralleled with the surface of soil profile. The piston displacement model (Beven, 1982) assumed that a sharp piston-like wetting (or drying) front develops at the surface during a rainfall event and moves down vertically through the soil profile. It is further assumed that the maximum water content of the piston-like wetting front adjusts itself to the percolation rate R(R is rainfall rate), and the water content above the wetting front become steady. Then using Darcy's law and kinematic assumption in the unsaturated zone above the wetting front we can write :

$$\theta(R,z)=\theta r+\left(\frac{R}{Ko-f_1\ln z}\right)^{1/N}(\omega_0-f_2\ln z) \tag{4}$$

where $\theta(R,z)$ is the volumetric water content at depth z and under rainfall rate R.

We assume that the water content in soil before rainfall has reached residual water content θ_r, then, using the continuity equation for the unsaturated zone above wetting front we can write the rate of wetting front development in unsaturated zone as :

$$\frac{dz_f}{dt}=\frac{R}{\theta(R,z_f)-\theta_r}\cos\alpha \tag{5}$$

Because the saturated conductivity decreases with depth, under rainfall rate R a saturated zone forms probably at depth z_s, and it will became thicker gradually. The delay time is the time which wetting front reaches the depth z_s from surface of soil, and it depends on the nature of soil and rainfall rate. When the wetting front just reaches the depth z_s, the saturated zone begins to form. So, at the depth z_s we can write :

$$K_s(z_s)= R \tag{6}$$

then, the depth Z_s can be given as :

$$z_s=\begin{cases} 0 & R\geqslant K_0 \\ e^{\frac{k_0-R}{f_1}} & k_0>R>k_0-f_1\ln D \\ D & R\leqslant K_0-f_1\ln D \end{cases} \tag{7}$$

by integrating equation (5) from 0 to z_s we can write the delay time as :

$$t_d=\frac{1}{R\cos\alpha}\int_0^{Z_s}\left[\theta(R,z)-\theta_r\right]dz \tag{8}$$

When the rainfall rate R is less than the surface saturated conductivity, the percolation rate of water is affected mainly by rainfall rate, but when the rainfall rate is greater than the surface saturated conductivity, the percolation rate of water is affected by both the rainfall rate and the surface saturated conductivity, so the rate of water input from unsaturated zone to saturated zone can be written as

$$i(t)=\begin{cases} L*I & t\leq t_r+t_d \\ 0 & t>t_r+t_d \end{cases} \tag{9}$$

where t_r is rainfall time. and I is given as

$$I=\begin{cases} R\cos\alpha & R\leq k_0 \\ (2.5k_0+R)\cos\alpha/3.5 & R>k_0 \end{cases} \tag{10}$$

After the saturated zone had formed, we assumed that the rate of wetting front development can be written as

$$\frac{dz_f}{dt}=\frac{I}{\theta_s\left(z_f\right)-\theta_r} \qquad z_f<D \tag{11}$$

and after the wetting front reaches the impermeable bed, we must have

$$\frac{dz_f}{dt}=0 \quad z_f=D \tag{12}$$

by integrating equation (11) between $[z_s,D]$we can write out:

$$t_u=t_d+\frac{1}{I}[(\omega_0+f_2)D-f_2D\ln D-(\omega_0+f_2)z_S+f_2z_S\ln z_S] \tag{13}$$

then, after the saturated zone formed, the relationship between the depth of wetting front and time can be given as

$$\begin{cases} t = t_d + \dfrac{1}{I}\left[(\omega_0 + f_2)z_f - f_2 z_f \ln z_f - (\omega_0 + f_2)z_s + f_2 z_s \ln z_s\right] & t < t_u \\ z_f = D \qquad \dfrac{dz_f}{dt} = 0 & t \geq t_u \end{cases} \tag{14}$$

where z_f is the depth of wetting front.

Since the kinematic storage model assumes that the water table has a constant slope between the upslope and downslope boundaries of the sloping soil mass, and that the hydraulic gradient equals the slope of the impermeable bed (as is show in figure 1), we have

$$\begin{aligned} V &= \frac{1}{2} L \int_{Z_f - h_L}^{Z_f} \omega(z)dz \\ &= \frac{1}{2} L\omega_0 h_L - \frac{1}{2} Lf_2\left[z_f \ln z_f - (z_f - h_L)\ln(z_f - h_L) - h_L\right] \qquad z_f > h_l \end{aligned} \tag{15}$$

where h_L is the saturated thickness normal to the hillslope at the outlet

and

$$\begin{aligned} Q &= \int_{z_f - h_l}^{z_f} k_s \sin\alpha \, dz \\ &= k_0 h_L \sin\alpha - f_1 \sin\alpha\left[z_f \ln z_f - \left(z_f - h_L\right)\ln\left(z_f - h_L\right) - h_L\right] \qquad z_f > h_l \end{aligned} \tag{16}$$

when the saturated zone rises so that the water table intersects the soil surface ($z_f - h_L \leqslant 0$), (15) and (16) must be modified separately as :

$$\begin{aligned} V &= \frac{1}{2} \, (L + L_s)\int_0^{Z_f} \omega(z)dz \\ &= \frac{1}{2}(L + L_s)\left[\omega_0 z_f - f_2 z_f \ln(z_f - 1)\right] \qquad z_f \leq h_l \end{aligned} \tag{17}$$

and

$$\begin{aligned} Q &= \sin\alpha \int_0^{Z_f} k_s dz + IL_s \\ &= \sin\alpha\left[k_0 z_f - f_1 z_f (\ln z_f - 1)\right] + IL_s \qquad z_f \leq h_l \end{aligned} \tag{18}$$

where L_s is the saturated slope length

then, by substituting (9) ,(15) or (17), (16) or (18) into (1) we have:

1. $Q(t) = 0 \qquad t \leq t_d$ (19a)
2. when $td < t \leq t_r + t_d$

$$\begin{aligned} \frac{dh_L}{dt} = {} & \frac{f_2}{\omega_0 - f_2 \ln(z_f - h_L)}\left[\ln z_f - \ln(z_f - h_L)\right]\frac{dz_f}{dt} - \frac{2(K_0 + f_1)\sin\alpha}{L\omega_0 - Lf_2 \ln(z_f - h_L)} h_L \\ & + \frac{2 f_1 \sin\alpha}{L\omega_0 - Lf_2 \ln(z_f - h_L)}\left[z_f \ln z_f - (z_f - h_L)\ln(z_f - h_L)\right] \\ & + \frac{2 \mathrm{I}}{\omega_0 - f_2 \ln(z_f - h_L)} \qquad z_f > h_L \end{aligned} \tag{19b}$$

or

$$\frac{dL_s}{dt} = -\frac{2 \mathrm{I} + (\omega_0 - f_2 \ln z_f)\dfrac{dz_f}{dt}}{\omega_0 z_f - f_2 z_f \ln z_f + f_2 z_f} L_s$$

$$+\frac{2IL-2\sin\alpha\left[K_o z_f - f_1 z_f(\ln z_f - 1)\right] - L(\omega_0 - f_2\ln z_f)\frac{dz_f}{dt}}{\omega_0 z_f - f_2 z_f \ln z_f + f_2 z_f} \quad z_f \le h_L \quad (19c)$$

3. when $t>t_r+t_d$

$$\frac{dh_L}{dt} = \frac{f_2}{\omega_0 - f_2\ln(z_f - h_L)}\left[\ln z_f - \ln(z_f - h_L)\right]\frac{dz_f}{dt} - \frac{2(K_0 + f_1)\sin\alpha}{L\omega_0 - Lf_2\ln(z_f - h_L)}h_L$$

$$+\frac{2f_1\sin\alpha}{L\omega_0 - Lf_2\ln(z_f - h_L)}\left[z_f\ln z_f - (z_f - h_L)\ln(z_f - h_L)\right] \quad z_f > h_L \qquad (19d)$$

or

$$\frac{dL_s}{dt} = -\frac{2\,\mathrm{I} + (\omega_0 - f_2\ln z_f)\frac{dz_f}{dt}}{\omega_0 z_f - f_2 z_f\ln z_f + f_2 z_f}L_s$$

$$-\frac{2\sin\alpha\left[K_o z_f - f_1 z_f(\ln z_f - 1)\right] + L(\omega_0 - f_2\ln z_f)\frac{dz_f}{dt}}{\omega_0 z_f - f_2 z_f\ln z_f + f_2 z_f} \quad z_f \le h_L \qquad (19e)$$

By joining (19), (11), (14) we can obtain the values of h_L or L_s of any time, and by substituting h_L or L_S into (16) or (18) separately we can obtain the discharge from the hillslope Q(t)

Geometric and hydrogeological parameters of the underlying model trough used in these simulation are as: B(width of the underlying model trough) =280cm, D=100cm, L=500cm, α=3°, k_0=0.02cm/min, f_1=0.003cm/min, ω_0=0.16, f_2=0.2, and N=3.0 . We compared the solutions of our model, Sloan's model and J.S.Robinson's model with observed values for rainfall event 1, event2, event 3(as show in figure 2-4 and table 1-3). The results of comparison show that our model yields excellent results at simulating total value of interflow, peak time, peak flow and delay time.

DISCUSSION

In this paper we have presented a simple, approximate model of interflow for an idealized, representative hillslope for forest catchment. This model is based on the balance of water, Darcy's law and kinematic assumption. In its present form the analysis includes these condition that the saturated zone is formed at some depth between surface and bottom of soil profile, or at the surface of soil, or at the bottom of soil, which depends on the rainfall rate and the nature of soil, and the analysis includes the effect of the unsaturated zone during both wetting and drainage. It can be used to simulate the subsurface response for a general, simple rainfall event, and it can yield a good result at predicting the total volume of interflow, peak time, delay time and peak flow. But, for some big storms (such as event 1), it is not accurate at predicting the value of peak flow. In addition, its disadvantage is that it cannot predict the duration of interflow accurately, and the rising hydrograph and falling hydrograph predicted by this model is steeper than observed results. The reason is probably that the assumption of a piston-like drying front and wetting front is used in the analysis, but the assumption is clearly not a good one [Beven, 1982].

table 1 Comparison of event1

results	Dur.(min)	D.T(min)	T.V(m^3)	P.T.V	P.T(min)	P.F(l/min)	P.P
our model	606	0	0.92	70%	180	374.08	64%
Sloan's model	640	3	0.41	57%	180	157.89	78%
Robinson's model	620	12	0.94	68%	192	307.67	66%
observed value	1600	0	0.71	100%	180	240.92	100%

Table 2. Comparison of rainfall event2

results	Dur.(min)	D.T(min)	T.V(m^3)	P.T.V	P.T(min)	P.F(l/min)	P.P
our model	606	0	0.45	98%	180	150.83	94%
Sloan's model	640	3	0.26	60%	180	100.51	63%
Robinson's model	620	21	0.6	66%	201	189.84	83%
observed value	2100	0	0.44	100%	180	161.11	100%

Table 3. Comparison of rainfall event3

results	Dur.(min)	D.T(min)	T.V(m^3)	P.T.V	P.T(min)	P.F(l/min)	P.P
our model	1050	0	0.48	88%	300	107.6	96%
Sloan's model	1050	5	0.34	62%	300	77.01	70%
Robinson's model	1200	40	0.43	79%	340	84.87	76%
observed value	2300	0	0.54	100%	300	112.03	100%

Where Dur. is duration, D.T is delay time, T.V is total volume, P.T.V is precision of total volume ,P.T is peak time, P.F is peak flow, P.P is precision of peak flow.

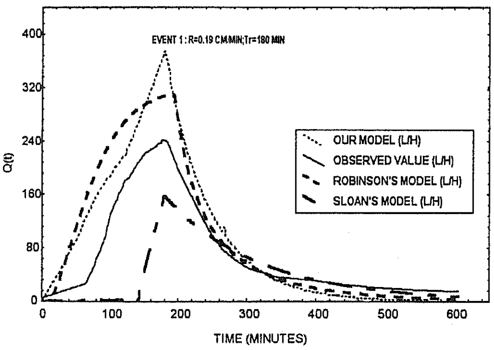

Figure 2 Hydrograph of interflow of rainfall event 1

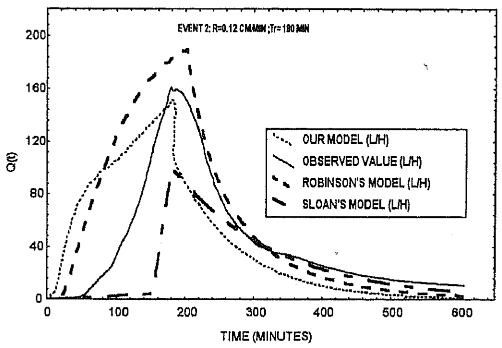

Figure 3 Hydrograph of interflow of rainfall event 2

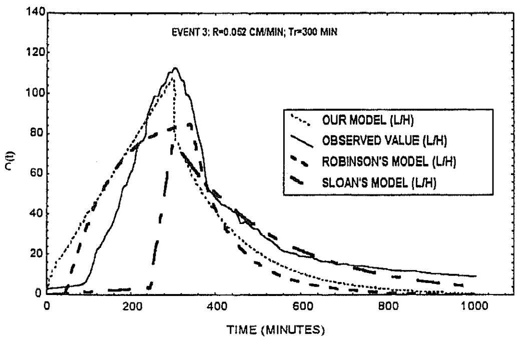

Figure 4 Hydrograph of interflow of rainfall event 3

CONCLUSION

According to the simulation of interflow on hillslope in forest catchment of Changbai Mountain we can conclude that:

1. The saturated conductivity decreases logarithmically with depth into the soil profile in forest catchment.

2. The effective porosity decreases logarithmically with depth into the soil profile in forest catchment.
3. The total volume of interflow increases with rainfall at the same rainfall rate, and decrease with rainfall rate at the same rainfall in forest catchment.
4. The delay time of interflow decreases with rainfall rate when the rainfall rate is less than the surface saturated conductivity of soil mass, and is 0 when the rainfall rate is greater than the surface saturated conductivity of soil mass.

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