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Influence of the moisture-tension parameter on sedigraphs and hydrographs from a semiarid region in Brazil

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Abstract Several sorts of models of various complexities have been used for predicting erosion but before simulating the sediment yield, the infiltration process must be simulated. In the infiltration process the main parameters consist of the soil moisture content and suction; thus these parameters can be combined in one single moisture-tension parameter as represented by N_s in the Green & Ampt infiltration equation. This paper discusses the effect of this parameter on hydrographs and, subsequently, sedigraphs, using data from a test field located in a typical semiarid area in Brazil simulated with a runoff–erosion kinematic model.

INTRODUCTION

Predicting sediment yield using kinematic cascade models has become a useful tool since Brakensiek (1967) introduced this concept. The theory of kinematic flow was first set forth by Lighthill & Whitham (1955) when they published a paper dealing with flood movement in rivers, but the kinematic wave technique was first applied to flow over a sloping plane by Henderson & Wooding (1964). However, in order to model the runoff–erosion process special care must be taken when the infiltration for a given event is estimated. The increase of semiarid areas in the world has brought the aim of much research to the delicate problem of runoff–erosion by heavy rainfall in the area. Physically-based distribution models have been used to predict the runoff–erosion process for such areas, and herein a model of this sort is presented and tested. However, attention has mainly been given to modelling the infiltration process, including the estimation of parameters involved in this particular process such as the moisture-tension parameter in the Green & Ampt infiltration equation, because it affects the sediment yield directly since it controls rainfall excess. This parameter depends mainly on the antecedent condition of the soil, which is difficult to estimate without a permanent measuring system on site. Thus, a better way to estimate such a parameter would be a relationship between two single variables, because this would simplify the whole process of estimating this parameter according to all conditions that have an influence, such as rainfall intensity, duration, and so forth. A simple relationship between the moisture-tension parameter and the number

Fig. 1 View of the selected micro-basin with a bare surface.

of antecedent dry days to a rainfall event is proposed.

Particular attention will be given to runoff hydrographs and sedigraphs for different initial infiltration capacities and various types of rainfall, using data obtained from an experimental basin in a semiarid area of Brazil, through which the complex infiltration process during a rainfall event and the behaviour of the moisture-tension parameter according to the number of antecedent dry days are discussed.

DATA

The selected micro-basin is located in the experimental basin of Sumé, which has been operated since 1972 (Cardier & Freitas, 1982) by UFPB (Federal University of Paraíba, Brazil), SUDENE (Superintendency of Northeast Development, Brazil) and ORSTOM (French Office of Scientific Research and Technology for Overseas Development). This was used to obtain data concerning runoff and sediment yield produced by heavy rainfall in a natural environment. The experimental basin incorporates four micro-basins, nine experimental plots, one sub-basin, and several micro-plots operated by simulated rainfall. Each micro-basin or experimental plot has different surface conditions and slope.

The selected micro-basin (Fig. 1) has an area of 5200 m^2, mean slope of 7.1% and a perimeter of 302 m. Its soil is classified as brown non calcic "vertic" soil, which is typical of most Brazilian semiarid regions. Several rainfall events were chosen between 1987 and 1988 based on the work of Santos *et al.* (1994). This period was selected because during this time there was no vegetation cover.

RUNOFF-EROSION MODEL

Lopes (1987) developed a physically-based, distributed parameter, event-oriented, nonlinear, numerical model named the Watershed Erosion Simulation Program (WESP), which computes runoff and sediment yield based on the kinematic waves assumption. It was especially developed for small basins, which was the reason why this model was chosen in this paper.

The infiltration process is modelled using the Green & Ampt equation and Darcy's law during a steady rain, which can be written in the form, after the beginning of overland flow:

$$f(t) = K_s\left(1 + \frac{N_s}{F(t)}\right) \tag{1}$$

where $f(t)$ is the infiltration rate (m s^{-1}), K_s is the effective soil hydraulic conductivity (m s^{-1}), $F(t)$ is the cumulative depth of infiltrated water (m), t is the time variable (s), and N_s is the soil moisture-tension parameter (m), which can be represented as:

$$N_s = (1 - S_e)pS \tag{2}$$

where p is the effective porosity ($0 < p < 1$), S is the average suction at the wetting front (m) and S_e is relative effective saturation equal to θ_i/θ_s with θ_i as the initial soil moisture content and θ_s as the soil moisture content at saturation.

The overland flow caused by rainfall excess is considered one dimensional. Manning's turbulent flow equation is given by:

$$u = \frac{1}{\pi} R_H^{2/3} S_f^{1/2} \tag{3}$$

where R_H (x, t) is the hydraulic radius (m), u is the local mean flow velocity (m s^{-1}), S_f is the friction slope, and n is the Manning friction factor of flow resistance. Here the assumption of the kinematic approximation that the friction slope is equal to the plane slope ($S_0 = S_f$) is used; i.e. the gravity and friction components are the dominant factors of the momentum equation. This approximation results in the local velocity equation for planes ($R_H = h$):

$$u = \alpha h^{m-1} \tag{4}$$

where h is the depth of flow (m), α (equal to $(1/n)S_0^{1/2}$) and m (equal to 5/3) are parameters related to surface roughness and geometry, respectively.

Sediment transport is considered as the erosion rate in the plane reduced by the deposition rate within the reach. The erosion occurs due to raindrop impact as well as surface shear. The sediment continuity equation is used to express the sediment transport rate in the reach as a function of the concentration, the discharge and the depth. The equation is solved numerically with a four-point implicit finite-difference scheme to calculate the sediment flow as a function of time and distance. The sediment flux Φ (kg m^{-2} s^{-1}) to the flow is written as:

$$\Phi = e_I + e_R - d \tag{5}$$

where e_I is the rate of sediment detachment by rainfall impact, e_R is the rate of sediment detachment by shear stress, and d is the rate of sediment deposition. The rate e_I (kg m^{-2} s^{-1}) is obtained from the relationship:

$$e_I = K_I I r_e \tag{6}$$

in which K_I is the soil detachability parameter (kg s m^{-4}), I is the rainfall intensity (m s^{-1}), and r_e is the effective rainfall (m s^{-1}). The rate e_R (kg m^{-2} s^{-1}) is expressed by the relationship:

$$e_R = K_R \tau^{1.5} \tag{7}$$

where K_R is a soil detachability factor for shear stress (kg m N$^{-1.5}$ s^{-1}), and τ is the effective shear stress (N m^{-2}), which is given by:

$$\tau = \gamma R_H S_f \tag{8}$$

where γ is the specific weight of water (N m^{-3}); and d (kg m^{-2} s^{-1}) is expressed as:

$$d = \varepsilon V_s C \tag{9}$$

where ε is a coefficient that depends on the soil and fluid properties (set to 0.5 in this study), V_s is the particle fall velocity (m s^{-1}), and $C(x, t)$ is the sediment concentration in transport (kg m^{-3}).

The concentrated flow in the channels is also described by continuity and momentum equations. The momentum equation can be reduced to the discharge equation with the kinematic wave approximation:

$$Q = \alpha A R_H^{m-1} \tag{10}$$

where A is the area of flow (m^2). The net sediment flux Φ_c (kg m^{-1} s^{-1}) for the channel is expressed by:

$$\Phi_c = q_s + e_r - d_c \tag{11}$$

where q_s is the lateral sediment inflow into the channel (kg m^{-1} s^{-1}), e_r is the erosion rate of the bed material (kg m^{-1} s^{-1}) obtained from the relation:

$$e_r = a(\tau - \tau_c)^{1.5} \tag{12}$$

in which a is the sediment erodibility parameter, and τ_c is the critical shear stress for sediment entrainment (N m^{-2}), which is given by the relationship:

$$\tau_c = \delta(\gamma_s - \gamma) d_s \tag{13}$$

where δ is a coefficient (0.047 in the present study), γ_s is the specific weight of sediment (N m^{-3}) and d_s is the mean diameter of sediments (m).

The deposition term d_c (kg m^{-1} s^{-1}) in equation (11) is expressed by

$$d_c = \varepsilon_c T_W V_s C \tag{14}$$

in which ε_c is the deposition parameter for channels, considered as unity in the present case, T_W is the flow top width (m) and the other terms are as defined in equation (9).

MODEL PARAMETERS

The parameters

Most of the parameters shown here can be assumed constant either as universally

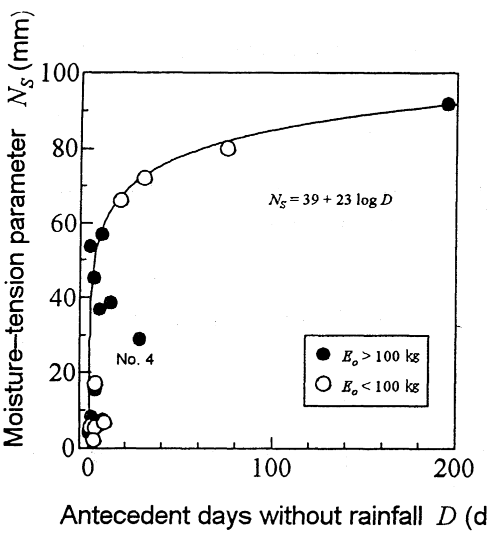

Fig. 2 Relationship between N_s and the number of antecedent dry days D.

constant or specific for this studied area. The Manning friction factor of flow resistance can be assumed as 0.02 for planes and 0.03 for channels, the specific weight of water as 9779 N m^{-3}, and the specific weight of sediment as 25 914 250 N m^{-3}.

The remaining parameters are specific for this area. The effective soil hydraulic conductivity K_s was assumed equal to 5.0 m s^{-1} based on tests conducted in the field, and the others were calibrated by optimization using the Standardized Powell method (Powell, 1964), i.e. K_R equal to 2.1 kg m N$^{-1.5}$ s^{-1}, K_I equal to 5.1 × 10^8 kg s m^{-4}, and a equals 0.015 kg m^2 N$^{-1.5}$ s^{-1}.

Finally, the moisture-tension parameter could not be assumed constant because the moisture condition changes according to the rainfall event. However, a relationship between N_s and the number of antecedent dry days (Fig. 2) was found by

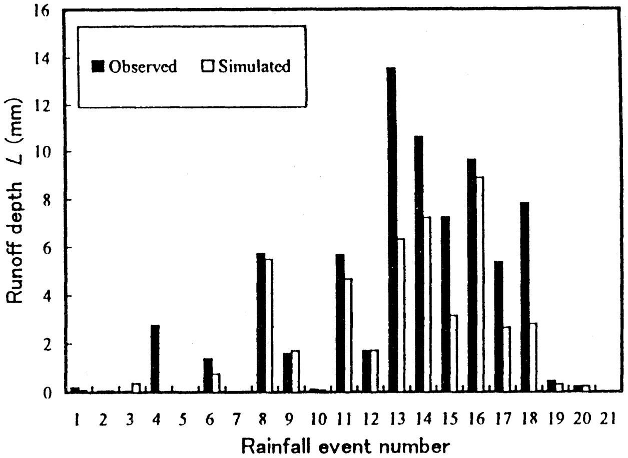

Fig. 3 Observed and simulated total runoff depths.

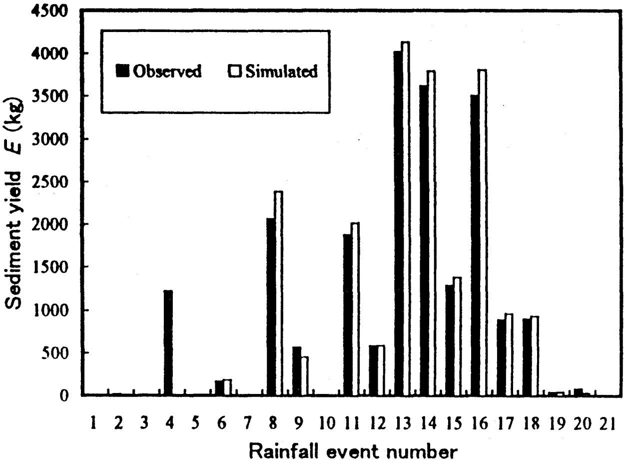

Fig. 4 Observed and simulated total sediment yields.

the authors as presented in Santos *et al.* (1994). This curve is very useful because the N_s parameter depends on several conditions but using Fig. 2 the parameter can be estimated just by one single condition, which is the number of days without rainfall between two consecutive events. Comparisons between the observed and calculated runoff depth L and sediment yield E, using the proposed N_s curve and the optimized parameters, are shown is Figs 3 and 4, respectively. As the parameter N_s has a strong influence on the hydrograph shape, it will be discussed separately in the next section.

Influence of N_s values

Figure 5 is an example of a simulated runoff, which shows how a variation of the N_s value can change the runoff hydrograph from the test field by the rainfall given in the

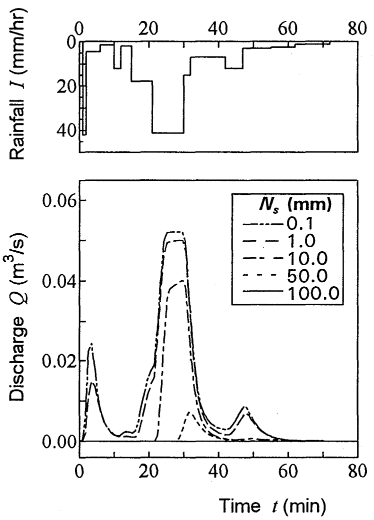

Fig. 5 Hydrograph and hyetograph for event no. 11 with different N_s values.

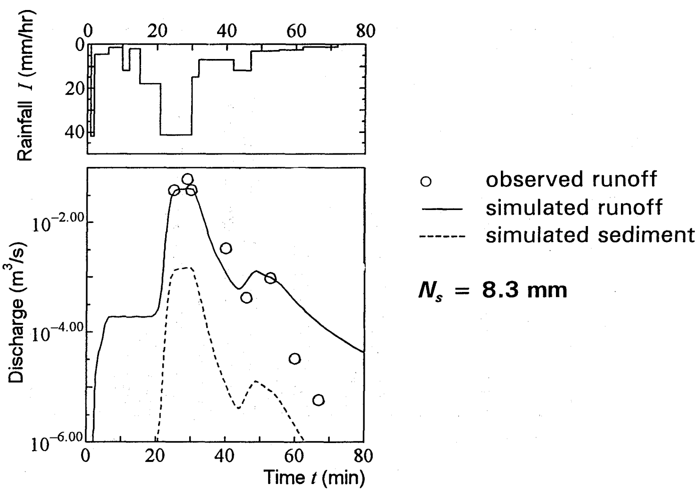

Fig. 6 Hydrograph and hyetograph with sedigraph for event no. 11.

figure. The number of antecedent dry days for this event was less than one day, and the optimized N_s is 8.3 mm. In the case of N_s equal to 10 mm, runoff occurs only when $t > 20$ min. If the N_s value decreases, a discharge peak will appear at the beginning of the rainfall, which was not observed in the field as shown in Fig. 6. If the N_s value becomes greater, the runoff will decrease and the last peak in the hydrograph will disappear, since infiltration has become greater. The moisture-tension parameter N_s can be seen to have a strong influence on the shape of the hydrograph.

Figures 6–10 show the sedigraphs and the comparison between the simulated hydrograph and the observed discharge data for several selected rainfall events, in which the observed discharge data are plotted in dots, and the calculated ones are plotted by a line, where the initial time ($t = 0$ min) for the measurement of discharge was different from that of rainfall, and the observed time was adjusted for some

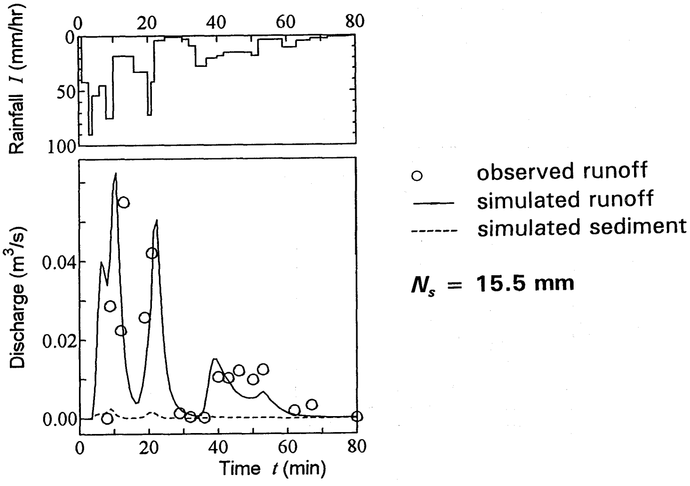

Fig. 7 Hydrograph and hyetograph with sedigraph for event no. 16.

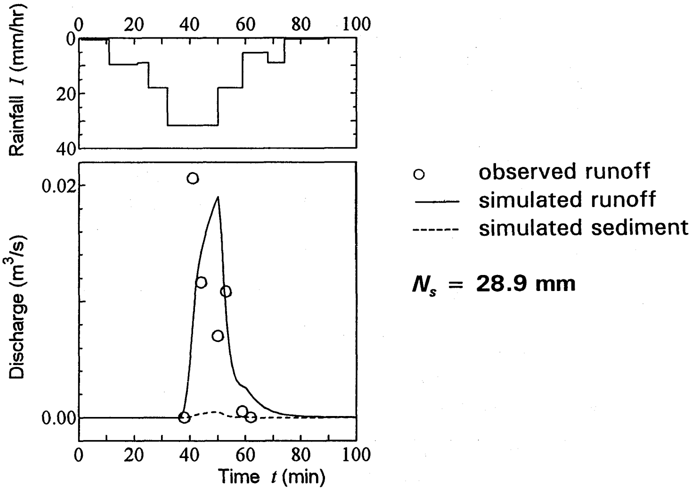

Fig. 8 Hydrograph and hyetograph with sedigraph for event no. 4.

events. Unfortunately, the measurement equipment in the micro-basin is conceived to collect just the total sediment yield.

Typical events with several different values of N_s, which range from 8.3 to 91.8 mm were selected with the first event plotted on a logarithmic scale to allow for an understanding of the relationship between the runoff and sediment discharges. The simulated runoff and sediment yield values seem to approximate the observed ones on the whole as shown in Figs 3 and 4. However, the degree of agreement seems to be different according to the values of N_s. For smaller values of N_s, which are for the rainfall events that occur a short time after the previous rainfall, the simulated hydrographs seem to follow the observed data very well for the simple hydrograph as shown in Fig. 6 as well as for complex rainfall patterns as shown in Fig. 7. On the other hand, the simulated hydrographs for large values of N_s do not follow the variation of the observed discharge data very well as shown in Figs 9 and 10. More

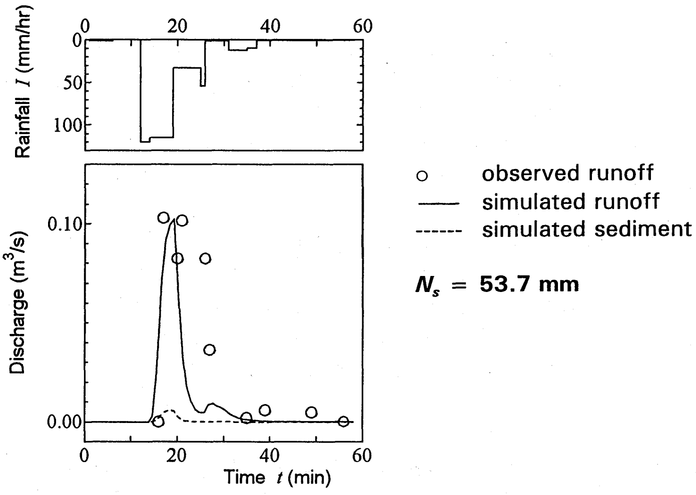

Fig. 9 Hydrograph and hyetograph with sedigraph for event no. 13.

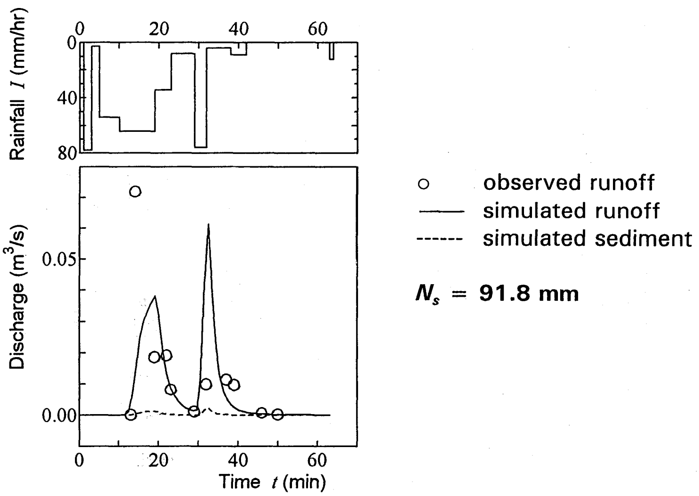

Fig. 10 Hydrograph and hyetograph with sedigraph for event no. 8.

accurate consideration of the N_s values for dry conditions of soil is needed. In addition, as shown in Fig. 2, the N_s value can range from near zero up to 60 mm when the number of dry days D is very small.

CONCLUSIONS

The runoff–erosion process, using data obtained from an experimental basin in a semiarid region of Brazil, was studied. The obtained conclusions are summarized below.

- The moisture-tension parameter N_s in the test basin is proved to depend mainly on the number of days D between the consecutive storms, and the relationship between N_s and D is determined for the basin, for example $N_s = 90$ mm for $D > 50$ days, and N_s varies from 0 to 60 mm within a few antecedent days without rainfall.
- Generally, the simulated sediment yields and runoff depths seem to approximate the observed ones. However, the degree of agreement seems to be different according to the values of N_s. For smaller values of N_s, which are for the rainfall events occurring a short interval after the previous rainfall event, the simulated hydrographs appear to follow the observed data very well for both the simple hydrograph, and for complex rainfall patterns.
- On the other hand, the simulated hydrographs for large values of N_s do not follow the variation of the observed discharge data very well. More accurate consideration of the N_s values for dry conditions of soil is needed. In addition, the determination of N_s for wet conditions is difficult because it can range from near zero up to 60 mm according to the proposed curve.

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