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Influence of Initial Infiltration on Runoff Hydrographs from a Test Field in a Semiarid Region of Northeastern Brazil

by

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Abstract

Predicting runoff using a kinematic model has become a useful tool, but to model this process special care must be taken when the infiltration for a given event is estimated. In this paper, hydrographs due to runoff with different initial infiltration capacity of soil and various types of rainfall are discussed for a Brazilian semiarid area using data obtained from a test field in the area. In the discussion, the Green and Ampt infiltration equation during a steady rain is used and the moisture-tension parameter is studied separately. Thus a new method for estimating this parameter for a Brazilian semiarid area is proposed.
Keywords: runoff hydrograph, moisture-tension parameter, infiltration

1. Introduction

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 distributed models have been used to predict the runoff-erosion process for such areas, and Srinivasan et al. 1) have calibrated and tested a model of this sort. They have also proposed parameters for this type of kinematic model. However, attention has mainly been given to modeling 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. 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. Santos et al. 2) have proposed a simple relationship between the moisture-tension parameter and the number of antecedent dry days to a rainfall event.

In this paper, particular attention will be given to runoff hydrographs for different initial infiltration capacities and various types of rainfall, using data obtained from an experimental watershed in the area, through which the complex infiltration process during a rainfall event and the behavior of the moisture-tension parameter according to the number of antecedent dry days are discussed.

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2. Test Field

The test field is located in a Brazilian semiarid area, which is in northeastern Brazil. It is an experimental watershed conceived to measure the runoff and sediment yield from most of the low to heavy rainfall events. This Sumé Experimental Watershed has been studied since 1972 [3] by SUDENE (Superintendency of Northeast Development) and ORSTOM (French Office of Scientific Research and Technology for Overseas Development). The Sumé Experimental Watershed has four micro-basins with areas between 0.5 to 1 ha, nine experimental plots, one sub-basin with 10 km^2 operated by natural rainfall and several micro-plots with 1 m^2 operated by simulated rainfall. Brown non calcic "vertic" soil covers more than 85% of the watershed and this soil is typical of most of the Brazilian semiarid regions. The surface conditions as well as the slope for each of either micro-basins or experimental plots are different.

Figure 1 shows one of the micro-basins that was selected to be studied here because it had no vegetation, thus it was very useful for studying the effects of human intervention on soil erosion. This micro-basin has a mean slope of 7.1%, area of 5200 m^2 and a perimeter of 302 m. At the outlet (point A in Fig. 1) of the micro-basin, a rectangular collector for the measurement of sediment discharge is settled, terminating with a 90° triangular weir for the measurement of flow discharges. The collector holds all the surface runoff and sediment discharges from most of the low to medium rainfall events, thereby providing a means for accurate runoff and sediment measurement, but only the runoff discharge data are used in this paper.

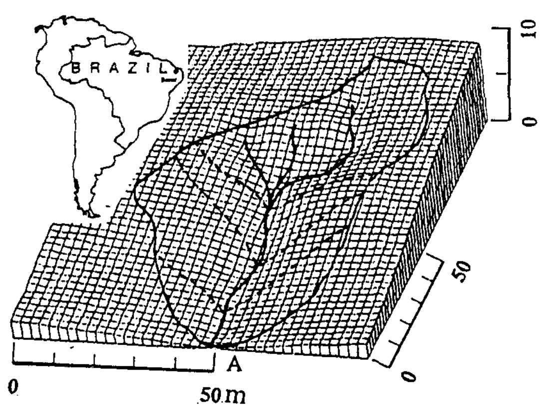

Fig. 1 Aerial view of the micro-basin.

The runoff discharge is measured by a water level recorder in the collector, and a recording rain gauge was installed close to the basin to provide the necessary precipitation data of every minute.

3. Summary of Runoff Model to be Used

Lopes [4] developed a physically-based, event-oriented, numerical model, named WESP (Watershed Erosion Simulation Program), which is used here to simulate the runoff. Its basic runoff equations are presented below.

3.1 Basic equations

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

$$f(t) = K_s\left(1 + \frac{N_s}{F(t)}\right) \quad (1) \qquad N_s = (1 - S_e)pS \quad (2)$$

where $f(t)$ is the infiltration rate (m/s), K_s is the effective hydraulic conductivity (m/s), $F(t)$ is the cumulative depth of infiltrated water (m), t is the time variable (s), and N_s is the soil moisture-tension parameter (m), S_e is the relative effective saturation = θ_i/θ_s ($0 \le S_e \le 1$), where θ_i is the initial soil moisture content and θ_s is the soil moisture content at saturation; p is the effective porosity ($0 \le p \le 1$); and S is the average suction at the wetting front (m).

Runoff is assumed to be caused by overland flow of excess rainfall and channel flow. These flows are simulated by the well-known kinematic wave model.

For the overland flow, continuity and momentum equations are given as follows, respectively:

$$\frac{\partial h}{\partial t} + \frac{\partial(uh)}{\partial x} = i - f \quad (3), \qquad u = \alpha h^{m-1} \quad (4)$$

where h is the local flow depth (m), u is the local mean flow velocity (m/s), i is the rainfall intensity (m/s), x is the distance in the flow direction (m), α is a parameter related to slope and surface roughness, m is an exponent depending on the form of the hydraulic resistance law, and the other variables are as defined earlier.

For the channel flow, the basic equations are:

$$\frac{\partial A}{\partial t} + \frac{dQ}{dA}\frac{\partial A}{\partial x} = q_A \quad (5) \qquad\qquad Q = \alpha A R_H^{m-1} = \frac{\alpha A^m}{P_w^{m-1}} \quad (6)$$

where the local flow discharge $Q(x,t)$ is assumed to be expressed as a function of the section area $A(x,t)$, q_A is the lateral inflow per unit length of channel, $Q(0,t) = Q_0(t)$ for $t \geq 0$, $Q(x,0) = 0$ for $x \geq 0$, R_H is the hydraulic radius (m), and P_w is the wetted perimeter (m).

3.2 Parameters to be optimized

In order to simulate the runoff-erosion process it is necessary to optimize four major parameters for the specific field; however, to simulate only the runoff process, discussed here, this number is reduced to just one parameter, which is the soil moisture-tension parameter N_s in Eq. (1). The effective hydraulic conductivity K_s can be assumed to be equal to 5.0 mm/hr based on field work, the exponent m to be equal to 5/3 according to Manning's law, and Manning's coefficient in α is assumed to be 0.020 for the planes and 0.030 for the channels.

4. Analysis of Rainfall-Runoff Data

4.1 Optimization of N_s value

A set of 21 rainfall events between 1987 and 1988 was selected for this study, because during this period the vegetation cover was maintained bared. However, water runoff data of only 12 events in which total sediment yield exceeded 100 kg will be discussed here, because they are assumed to be more accurate than those less than 100 kg.

In order to start the modeling it is necessary to represent the micro-basin as a cascade of planes, then the micro-basin was divided into 10 elements as shown in Fig. 2, although a more detailed study of the influence and the best configuration for this micro-basin can be found in Santos et al.[5] The data are simulated using the above kinematic model and parameters in the model are optimized by the Standardized Powell Method [6] for the runoff and erosion data; thus, in a few cases a great difference between the total runoff depth and the calculated one can be explained, since the total sediment yield is adjusted to agree very well.

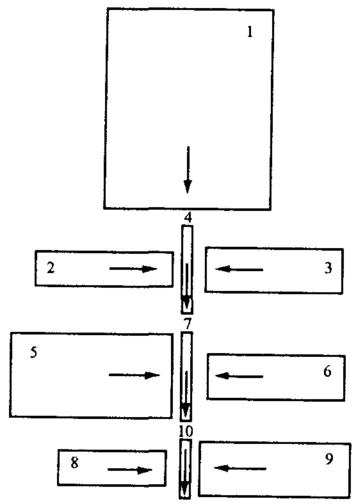

Fig. 2 Modeling of the micro-basin.

A comparison between the observed runoff depth and the calculated one with the optimized parameters for the events can be seen in Fig. 3. The events numbered 1, 2, 3, 5, 7, 10, 19, 20 and 21 do not appear in this figure because only relatively large rainfalls in which the sediment yield was more than 100 kg are analyzed. As stated above, better agreement can be seen in the total sediment yield. However, it is not relevant for this present study.

In previous works the authors compared only the total runoff depths; nevertheless, the value of N_s parameter has a great influence on the runoff, since N_s controls the initial infiltration rate into the soil.

The authors [2] have found an empirical relationship between the optimized values of N_s and the number of antecedent dry days for the test field as shown in Fig. 4. This fitting curve can be used to estimate N_s in

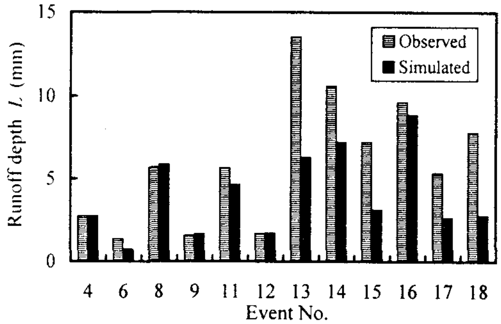

Fig. 3 Observed total runoff depths and simulated one.

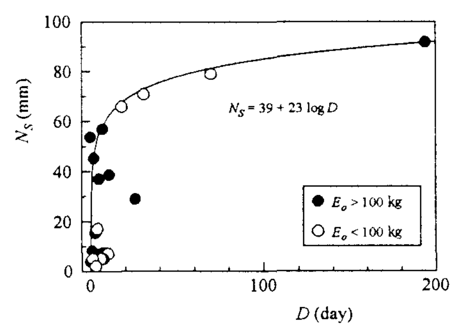

Fig. 4 Optimized moisture-tension parameter N_s and number of antecedent dry days D.

the semiarid area including the test field, but it is only convenient because the values of N_S depend not only on the antecedent dry days but also the antecedent rainfall intensity and other conditions.

4.2 Influence of N_S values on hydrograph

Figure 5 is an example of a simulated runoff, which shows how a variation on N_S value can change the runoff hydrogaph from the test field by rainfall given in the figure. The antecedent dry days for this event were less than one day, and the optimized N_S is 8.3 mm. In the case of N_S to be equal to 10 mm, runoff occurs only when $t > 20$ min. If the N_S value decreases, a discharge peak in the beginning of the rainfall will appear, which was not observed in the field as shown later 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.

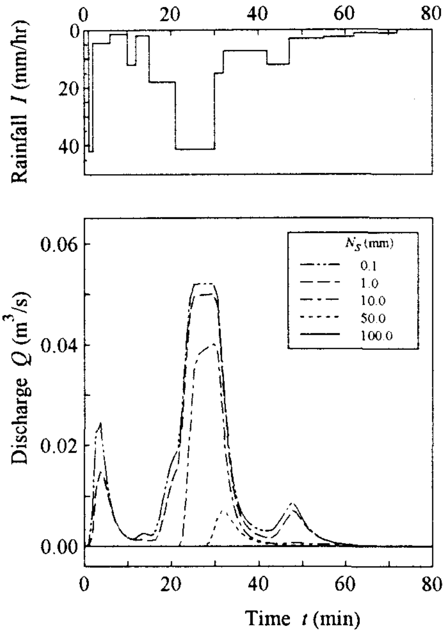

Fig. 5 Hydrograph and Hyetograph for event No. 11 with different N_S.

4.3 Results of simulation

Figures 6 to 10 show 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

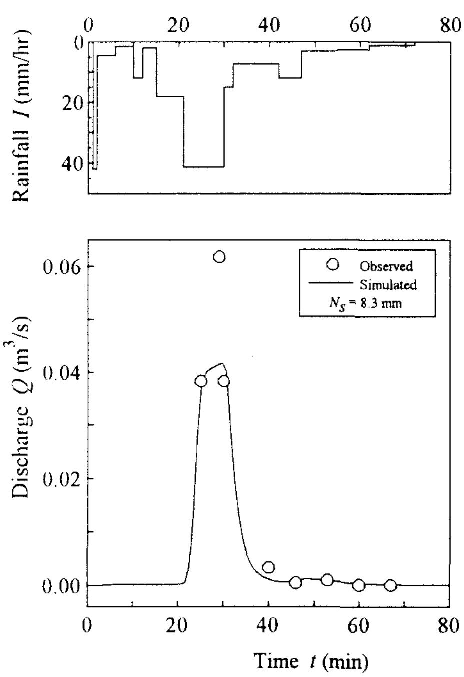

Fig. 6 Hydrograph and Hyetograph for event No. 11.

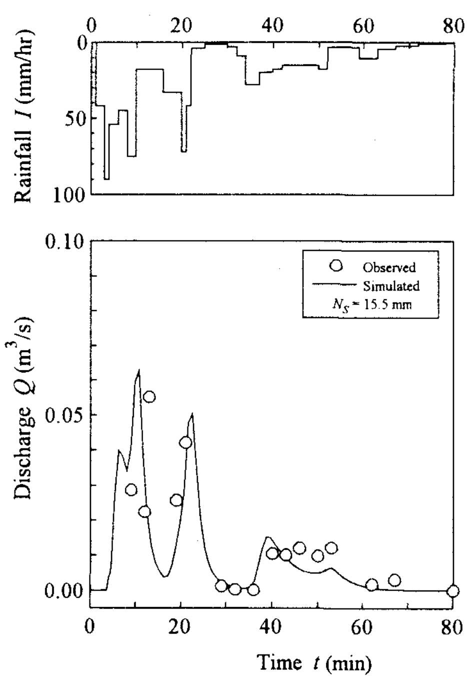

Fig. 7 Hydrograph and Hyetograph for event No. 16.

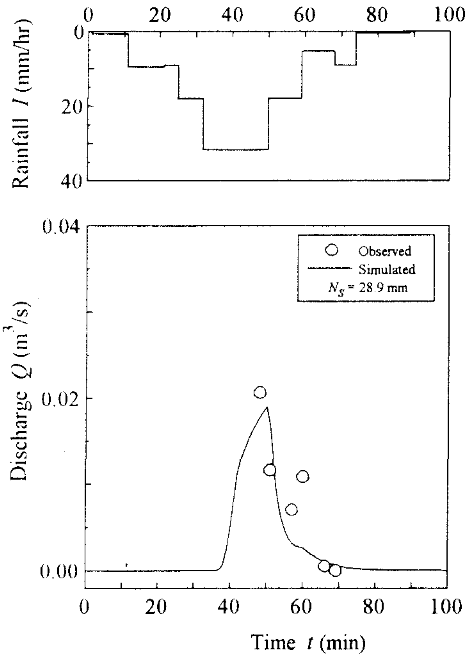

Fig 8 Hydrograph and Hyetograph for event No. 4.

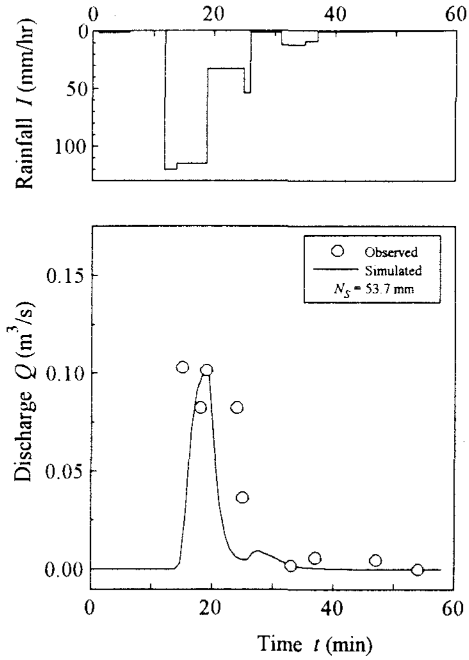

Fig. 9 Hydrograph and Hyetograph for event No. 13.

different from that of rainfall, and the observed time was adjusted for some events. Typical events with several different values of N_S, which range from 8.3 to 91.8 mm were selected. The simulated values seem to approximate the observed ones on the whole. 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 after short time from 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 well as shown in Figs. 9 and 10. More accurate consideration of the N_S values for dry conditions of soil is needed, because as it is seen in Fig. 4 the N_S value can range from near zero up to 60 mm when the number of days D in very small.

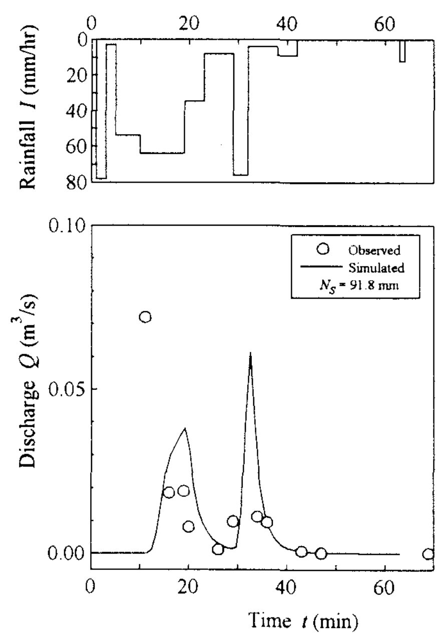

Fig. 10 Hydrograph and Hyetograph for event No. 8.

5. Discussions and Conclusions

Hydrograph data for the runoff observed at the outlet of a test field watershed in a semiarid area in northeastern Brazil were simulated with a runoff model based on kinematic wave assumption, where the moisture-tension parameter N_S of the soil is to be assumed for the specific area. N_S optimized with total runoff and sediment discharges observed in the specific test field was related only to the antecedent dry days, and the value of N_S is proved to have a strong influence on time variation of runoff discharges as well as total discharge. It can be concluded that if the N_S value is estimated properly and the infiltration rate is expressed by the Green & Ampt infiltration equation, Eq. (1), runoff hydrographs due to various patterns of rainfall can be simulated with the runoff model. However, more detailed consideration is needed for the estimation of the initial infiltration capacity especially for dry soil after many dry days.

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