J. Hydrau., Coast. Environ. Eng., JSCE, No. 586/II-42, 117-126, 1998 February

SEDIMENT YIELD DUE TO HEAVY RAINFALL FROM A TEST FIELD IN BRAZIL AND ITS ANALYSIS BY A RUNOFF-EROSION MODEL

Celso A. G. SANTOS[1], Masahiro WATANABE[2], Koichi SUZUKI[3] and Vajapeyam S. SRINIVASAN[4]

[1]Member of JSCE, Dr. of Eng., Postdoctoral Fellow, Dept. of Civil and Environmental Eng., Ehime University (3-Bunkyo-cho, Matsuyama, Ehime 790-77, Japan)
[2]Member of JSCE, Dr. of Eng., Associate Professor, Dept. of Civil and Environmental Eng., Ehime University
[3]Member of JSCE, Dr. of Eng., Professor, Dept. of Civil and Environmental Eng., Ehime University
[4]Dr. of Eng., Professor, Dept. of Civil Engineering, Federal University of Paraíba (Av. Aprígio Veloso, 882, Campina Grande, Paraíba, 58109-970, Brazil)

The runoff-erosion process is modeled for a typical Brazilian semiarid area with a kinematic model. The data are analyzed and the model is optimized by the SP method. The scale effects of the basin elements on the model coefficients are discussed by dividing the basin in three different configurations. 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. Thus, hydrographs due to runoff with different initial infiltration capacity of soil and various types of rainfall are also discussed and the moisture-tension parameter, which is one of the optimized parameters, is studied separately.

Key Words : runoff-erosion modeling, semiarid, infiltration, moisture-tension parameter

1. INTRODUCTION

The physically-based distributed models have proven to be a very useful tool in runoff-erosion modeling for small watersheds; however, there are many elements involved in the modeling, which can alter the results markedly. Various researchers have worked on this subject, and presented different ways to represent the watershed. These schemes include, for example, streamtube concept [1]; system of planes and channels [2]; system of converging surfaces, planes, and channels [3]; and uniform grid [4]. In any practical application, use of the kinematic cascade to simulate surface runoff from complex watersheds will introduce certain errors of approximation. These errors are associated with the manner in which the cascade is adapted to actual watershed configuration. Thus, in this paper a study about the influence of the representation of a watershed when represented by different configurations of cascade is carried out. For example, a configuration of 10 elements will be replaced by a complex series of 23 discrete elements with individually uniform slopes. It is evident that by making the individual elements small enough the errors of approximation associated with the kinematic cascade transformation can be minimized; however, a inverse case is also studied by simplifying the configuration in order to know how that simplication will affect the results.

Distributed models have several parameters that give different simulation results when using different values, but some of these parameters must be constant for a given soil and this must be taken in account when a method to optimize such parameters is used; thus, herein again a study is carried out to establish which parameters are constant in the presented kinematic model. Although, some parameters are not constant for a given soil but they are supposed to be constant for a given event, which is the case of the moisture-tension parameter N_S in Green and Ampt infiltration equation used in the tested model. However, when this parameter is studied separately, amazing results are revealed, which can lead to the conclusion that though it is represented in the model as a constant parameter

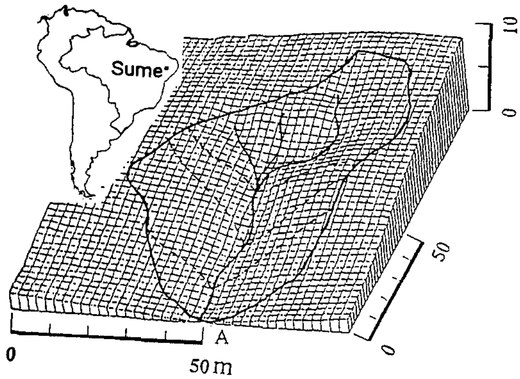

Fig.1 Aerial view of the micro-basin.

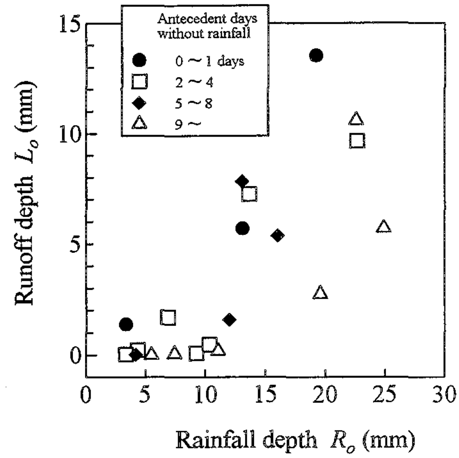

Fig.2 Total rainfall depth R_o and runoff depth L_o.

during the rainfall event, a change in the value of this parameter must occur when the rainfall water is infiltrating in the soil.

2. FIELD DATA IN SUMÉ

The field experiment is located in the Experimental Basin of Sumé, which has been operated since 1972 [5] 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) 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 subbasin, and several micro-plots operated by simulated rainfall. The surface conditions as well as the slope for each either micro-basin or experimental plot are different.

Four standard rain gauges and two recording rain gauges are installed close to the micro-basins and plots in order to provide the rainfall data.

The micro-basin 3 used in this paper (**Fig.1**) with mean slope of 7.1% has no vegetation and its area and perimeter are 5200 m^2 and 302 m, respectively. At the outlet of the basins, 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 would hold 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. **Figure 2** shows the relationship between the total depth of a continuous rainfall and the corresponding discharge, where observed data are plotted according to antecedent days without rainfall in four groups. The runoff discharge rate is very small when the total rainfall depth is less than about 10 mm due to the large infiltration capacity of the soil and large evaporation in semiarid areas. Except for few events, the runoff depth is influenced by the antecedent days without rainfall as well as by the total rainfall depth. Another parameter which may characterize the rainfall intensity and duration should be introduced to describe the exceptions.

3. ANALYSIS BY A RUNOFF-EROSION MODEL

(1) Basic equations

In this paper the runoff-erosion model developed by Lopes [6], called Watershed Erosion Simulation Program (WESP), was used, because this model was specially developed for small basins. WESP represents a physically-based, distributed parameter, event-based, nonlinear, numerical model that is capable of accommodating the change in topography, surface roughness, and soil properties.

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

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

where $f(t)$ is the infiltration rate (m/s), K_s is the effective hydraulic conductivity (m/s), N_s is the soil moisture-tension parameter (m), $F(t)$ is the cumulative depth of infiltrated water (m), and t is the time variable (s). This equation is not empirical but an approximate theory-based infiltration model; thus, it constitutes a more realistic representation of infiltration, and it is one of the quite commonly used equations [7),8)]. This model was chosen due to its simplicity and its satisfactory performance in a variety of hydrologic problems.

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

$$u = \frac{1}{n} R_H^{2/3} S_f^{1/2} \qquad (2)$$

where $R_H(x,t)$ is the hydraulic radius (m), u is the local mean flow velocity (m/s), 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 ($R_H = h$):

$$u = \alpha\, h^{m-1} \qquad (3)$$

where h is the depth of the flow (m), α (equal to $(1/n)S_0{}^{1/2}$) is a parameter related to slope and surface roughness, and m (equal to 5/3) is an exponent depending on the form of the hydraulic resistance law.

The concentrated flow in the channels is also described by continuity and momentum equations. With the kinematic wave approximation the momentum equation reduces to the discharge equation:

$$Q = \alpha A R_H^{m-1} \qquad (4)$$

in which Q is the discharge (m^3/s), A is the area of flow (m^2), and the other symbols are the same as in Eqs.(2) and (3). The continuity equation for the spatially varied flow in the channel with lateral inflow is solved numerically with a four-point implicit finite-difference scheme.

The 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 to the flow is written as:

$$\Phi = e_I + e_R - d_p \qquad (5)$$

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_p is the rate of sediment deposition. The rate e_I ($kg/m^2/s$) is obtained from the relationship:

$$e_I = K_I\, I\, r_e \qquad (6)$$

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

$$e_R = K_R\, \tau^{1.5} \qquad (7)$$

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

$$\tau = \gamma\, R_H\, S_f \qquad (8)$$

where γ is the specific weight of water (N/m^3), and other symbols are the same as in Eq.(2).

The deposition rate in the plane d_p ($kg/m^2/s$) is expressed as:

$$d_p = \varepsilon_p\, V_s\, C \qquad (9)$$

where ε_p is a coefficient that depends on the soil and fluid properties (set to 0.5 in this study), $C(x,t)$ is the sediment concentration in transport (kg/m^3), and V_s is the particle fall velocity (m/s) given by:

$$V_s = F_o \sqrt{\frac{(\gamma_s - \gamma)}{\gamma} g d_s} \qquad (10)$$

and,

$$F_o = \sqrt{\frac{2}{3} + \frac{36\nu^2}{g d_s^3\left(\frac{\gamma_s}{\gamma} - 1\right)}} - \sqrt{\frac{36\nu^2}{g d_s^3\left(\frac{\gamma_s}{\gamma} - 1\right)}} \qquad (11)$$

where γ_s and γ are the specific weights of sediment and water, respectively (N/m^3), ν is the kinematic viscosity of water (m^2/s), d_s is the mean diameter of the sediment (m), and g is the acceleration of gravity (m/s^2).

For the channel segment, the net sediment flux Φ_c (kg/m/s) is expressed by:

$$\Phi_c = q_s + e_r - d_c \qquad (12)$$

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

$$e_r = a(\tau - \tau_c)^{1.5} \qquad (13)$$

in which a is the sediment erodibility parameter ($kg{\cdot}m^2/N^{1.5}{\cdot}s$), τ is given by Eq.(8), and τ_c is the critical shear stress for sediment entrainment, which is given by the relationship:

$$\tau_c = \delta(\gamma_s - \gamma)\, d_s \qquad (14)$$

where δ is a coefficient (0.047 in the present study), and the other symbols are the same as in Eq.(10).

The deposition term d_c (kg/m/s) in Eq.(12) is expressed by:

$$d_c = \varepsilon_c \, T_W V_s \, C \quad (15)$$

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

(2) Parameters

A prior definition must be done to some parameters as follows.

The effective soil hydraulic conductivity K_s in Eq.(1) can be assumed equal to 5.0 mm/hr; the Manning friction factor of flow resistance n in Eq.(2) is 0.02 for the planes and 0.03 for the channels; the kinematic viscosity of water ν is equal to $0.894\text{x}10^{-6}$ m^2/s; the mean diameter of the sediment d_s is equal to d_{50}, which is 0.5 mm; the acceleration of gravity g is 9.81 m/s^2; the specific weight of sediment γ_s is 25914.35 N/m^3 and the specific weight of water γ is 9779.00 N/m^3, these latters in Eqs.(11) and (14).

Srinivasan et al. [9] showed that some parameters in the model should be optimized, especially for the events with small amount of rainfall and with preceding rainfall, thus the main parameters to be optimized are the soil moisture-tension parameter N_s in Eq.(1), the soil detachability parameter K_I in Eq.(6), the soil detachability factor for shear stress K_R in Eq.(7), and the sediment erodibility parameter a in Eq.(13).

4. SUMMARY OF STANDARDIZED POWELL METHOD

Santos et al. [10),11] showed that the Standardized Powell method (SP Method) could be useful to optimize the WESP model. The method is as follows.

(1) Method

Powell [12] proposed a new method to find values of M parameters $x_1, x_2, ..., x_M$, so that a function of these parameters, $J(x_1, x_2, ..., x_M)$, is a minimum.

The method of minimization, which changes one variable at a time, finds the minimum of a quadratic form in a finite number of steps. Each iteration of the procedure commences with a search down M linearly independent directions d_1, d_2, ..., d_M, starting from the best known approximation to the minimum, p_o. These directions are chosen to be the coordinate directions initially, so the start of the first iteration is identical to the method of iteration in which only one parameter is changed at a time. This latter method is modified to generate conjugate directions by making each iteration define a new direction, d, and choosing the linearly independent direction for the next iteration to be $d_2, d_3, ..., d_M, d$. After M iterations all the directions are mutually conjugate and in consequence the exact minimum of the quadratic is found. Thus, M iterations [which involves $M(M+1)$ line minimizations in each direction] would result in the true minimum of the function if it has the quadratic form. Otherwise, true minimum can still be obtained with successive repetitions of this process, as the method approaches quadratically the global minimum in each trial. The function J is assumed to be expressed by a quadratic.

Nagai and Kadoya [13),14] standardized each model parameter divided by its initial values, which makes the calculation effective even if orders of parameters to be determined are different.

(2) Optimization of the parameters

The parameters are standardized by their initial values as:

$$x_1 = \frac{N_s}{N_{s0}}, \quad x_2 = \frac{a}{a_0}, \quad x_3 = \frac{K_R}{K_{R0}}, \quad x_4 = \frac{K_I}{K_{I0}} \quad (16)$$

where suffix 0 means the initial values. When these four variables are given, runoff discharge L and sediment yield E can be calculated by the runoff-erosion model. The function J to be minimized is defined as:

$$J = \left| \frac{L_o - L_c}{L_o} \right| + \left| \frac{E_o - E_c}{E_o} \right| \quad (17)$$

where suffix o means observed data and suffix c means calculated values. L_c and E_c are functions of x_1, x_2, x_3 and x_4, and therefore so is J. These four parameters are to be optimized by the SP method so that the evaluation function J becomes a minimum. All the parameters should be positive, and if some of the parameters become negative, a penalty function V is added to J so that the evaluation function becomes excessively large. The following function is introduced here:

$$V = \sum_{i=1}^{4} V_i \quad (18)$$

where $V_i = 0$ when $x_i \geq 0$, and $V_i = (x_i - e_i)^2$ when $x_i < 0$ and $e_i = 1$.

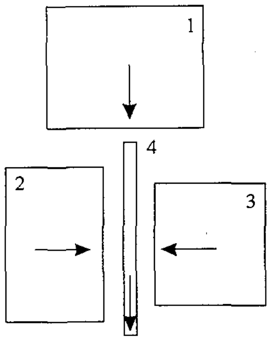

Fig.3 Schematic representation of the basin in 4 elements.

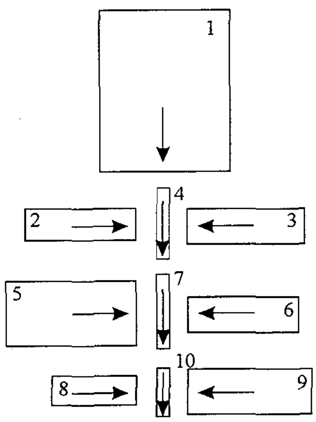

Fig.4 Schematic representation of the basin in 10 elements.

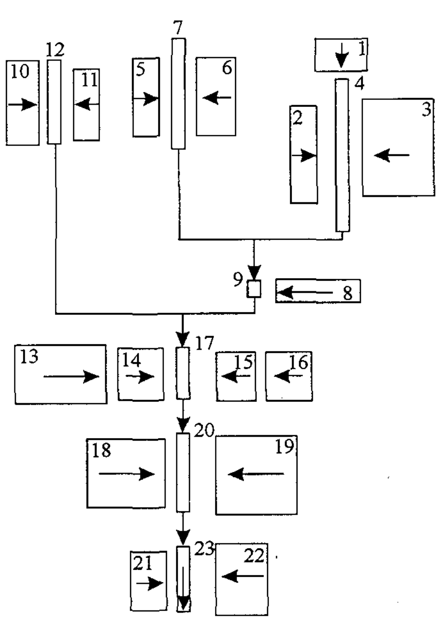

Fig.5 Schematic representation of the basin in 23 elements.

5. CONFIGURATION OF THE AREA

In order to start the modeling it is necessary to represent the micro-basin as a cascade of planes. As distortion errors may occur when representing a basin in plane and channel cascade, these distortions must be reduced in order to achieve accurate results. Segmentation of the micro-basin was made from its topographic mapping according to the delineation of the overland flow planes. The plane boundaries are either streamlines or contour lines. During the discretization process an attempt was made to minimize geometric distortion by preserving the areas and length of flow paths for each plane element, to minimize the geometric distortion mentioned above.

In order to compare the distortions among the different configurations of methods to divide a watershed, the micro-basin was divided into three different configurations of 4, 10 and 23 elements [15]. The 4 elements' division of 3 overland flow elements and only one channel element is intended for a relatively large scale element set (**Fig.3**). The 10 elements' division of 7 overland flow elements and 3 channel elements is intended for a median size element set (**Fig.4**), and the 23 elements' division of 16 overland flow elements and 7 channel flow elements is for a relatively small scale element set (**Fig.5**).

6. SIMULATIONS

The parameters a, K_R and K_I should be constant for all rainfall events because they are characterized by the sand and soil in the test basin. **Table 1** shows the parameters a, K_R and K_I, optimized for 12 rainfall events with sediment yields E_o more than 100 kg, which are assumed to be more accurate than those less than 100 kg. The orders of these optimized parameters for all the rainfall events seem to be equal for the 10 elements' division, but for the 4 and 23 elements' divisions variations of these values are relatively large. The average values of the parameters over the events can become the values for the specific test field; i.e., for the 10 elements' division: a = 0.015 kg·m^2/N$^{1.5}$·s, K_R = 2.2 kg·m/N$^{1.5}$·s, K_I = 4.0x10^8 kg·s/m^4. The initial moisture-tension parameter N_s changes largely with each rainfall event, because N_s is directly related to the moisture in the soil, therefore to the antecedent rainfall conditions. As the difference of the optimized values of N_s among three different manners of basin division was small, the relation-

Table 1 Optimized parameters values for data of $E_o > 100$ kg.

Event No.	$a \times 10^{-3}$ (kg·m²/N$^{1.5}$·s)			K_R (kg·m/N$^{1.5}$·s)			$K_I \times 10^8$ (kg·s/m⁴)		
	Number of Elements			Number of Elements			Number of Elements		
	4	10	23	4	10	23	4	10	23
4	22.6	21.5	48.5	2.1	2.4	0.7	11.7	4.8	2.1
6	16.3	13.8	6.4	2.0	1.9	2.3	0.3	1.5	2.7
8	8.4	12.8	28.1	2.1	2.1	1.5	4.5	3.4	5.4
9	24.0	18.9	46.9	2.5	2.8	0.3	10.5	1.5	2.5
11	11.1	13.9	24.4	2.0	2.1	2.6	2.3	2.0	1.3
12	15.9	14.7	32.7	2.2	2.4	0.3	6.6	1.5	0.6
13	4.2	14.4	35.3	1.5	2.2	1.9	3.7	5.1	4.5
14	4.1	14.2	32.0	1.9	2.1	1.5	3.1	3.6	4.6
15	9.6	13.9	30.2	2.1	2.1	1.8	4.7	3.1	5.2
16	9.2	13.6	30.1	2.1	2.2	2.0	3.4	6.7	6.0
17	13.2	13.9	29.4	2.2	2.0	1.1	7.2	6.9	0.1
18	15.8	14.5	32.2	2.1	2.2	0.3	3.4	8.1	0.7
Mean	12.9	15.0	31.3	2.1	2.2	1.4	5.1	4.0	3.0

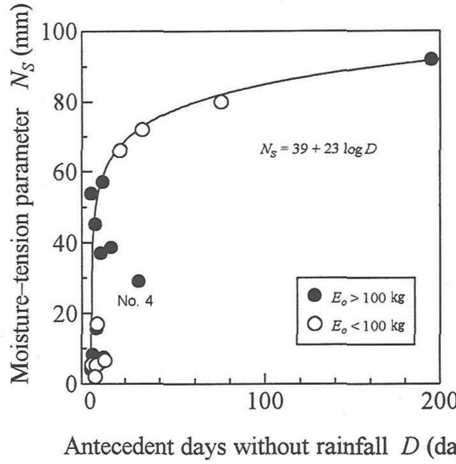

Fig.6 Parameter N_s and antecedent dry days D.

ship between optimized values of N_s and antecedent dry days D is shown in **Fig.6** only for the 10 elements' division, where data with blank circle in the figure are values optimized for $E_o < 100$ kg, using the above average value of a, K_R and K_I. This fitting curve can be used to estimate N_s in 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. The value of N_s parameter has a great influence on the runoff, since N_s controls the infiltration rate into the soil.

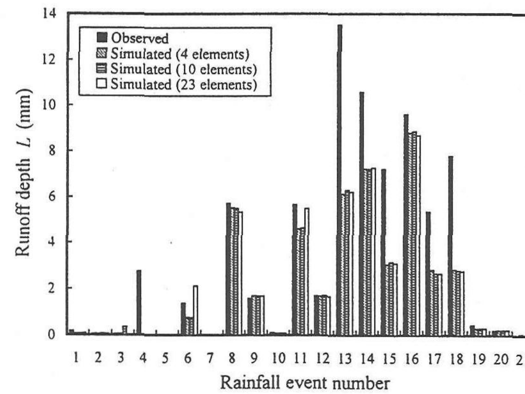

Fig.7 Observed and simulated total runoff depths.

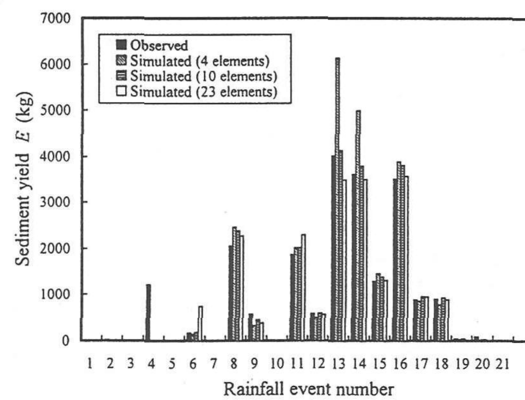

Fig.8 Observed and simulated total sediment yields.

Figures 7 and **8** show the comparison between observed and simulated runoff depth L and sediment yield E, respectively, for all the 21 rainfall events. Simulation is done with the average values of a, K_R, K_I for each way of elements' divisions and the above mentioned fitting curve for N_s. The simulated values for runoff depth L seem to be smaller than the observed data in several events, but those for sediment yield E follow the observed values for almost every rainfall event from weak to heavy rainfall except for event number 4 for which the fitting curve for N_s gives a much larger value than the optimized values as in **Fig.6**. However, calculated L is less accurate than E, which may be attributed to the direct response of L to the deviation of the N_s fitting curve from the optimum N_s value for each event. There are only small differences of simulated data among the three ways of basin division, although the 10 elements' division seems to give the best results.

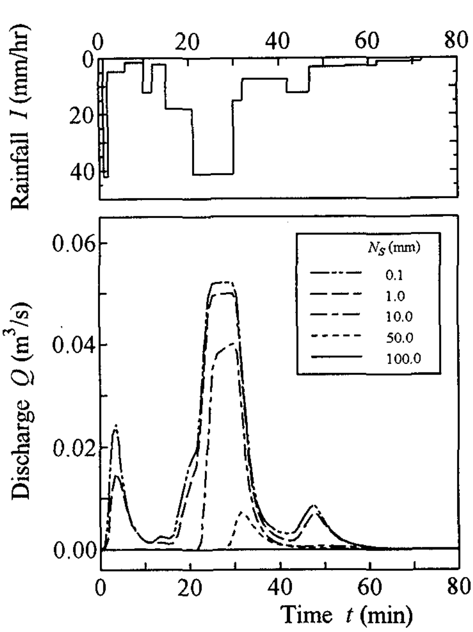

Fig.9 Hydrograph and hyetograph for event No. 11 with different N_s.

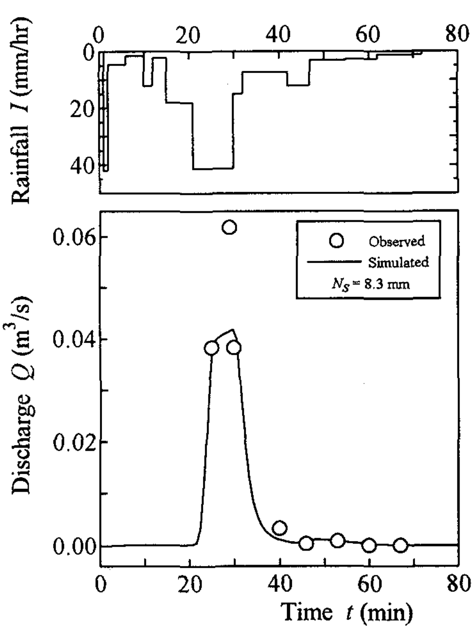

Fig.10 Hydrograph and hyetograph for event No. 11.

7. INFLUENCE OF N_s VALUES ON HYDROGRAPH

The influence of N_s values on the hydrographs have been discussed by Santos et al. [16].

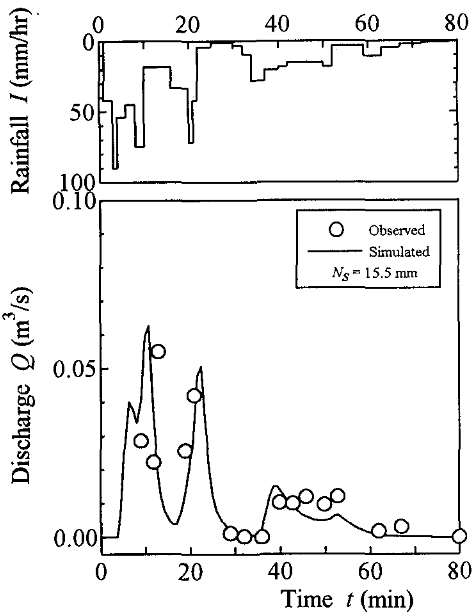

Fig.11 Hydrograph and hyetograph for event No. 16.

Figure 9 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 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 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.10**. 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 10 to **14** 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 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

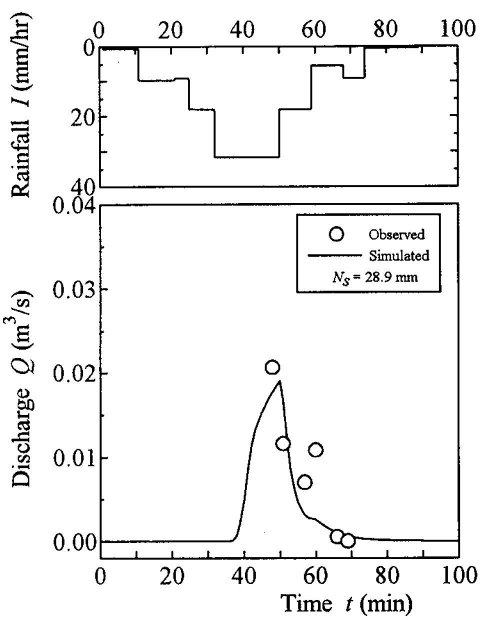

Fig.12 Hydrograph and hyetograph for event No. 4.

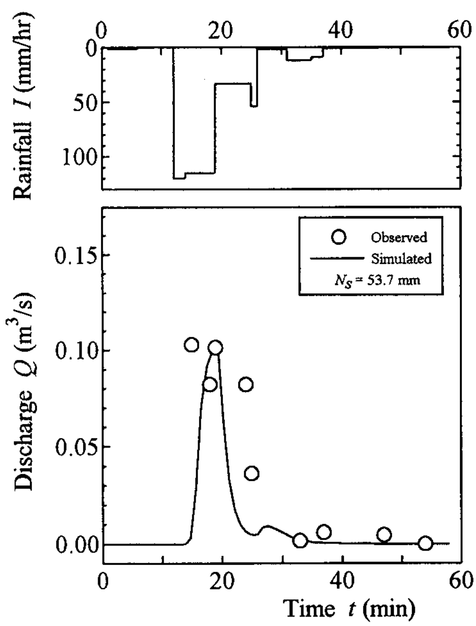

Fig.13 Hydrograph and hyetograph for event No. 13.

previous rainfall, the simulated hydrographs seem to follow the observed data very well for the simple hydrograph as shown in **Fig.10** as well as for complex rainfall patterns as shown in **Fig.11**. On the other hand, the simulated hydrographs for

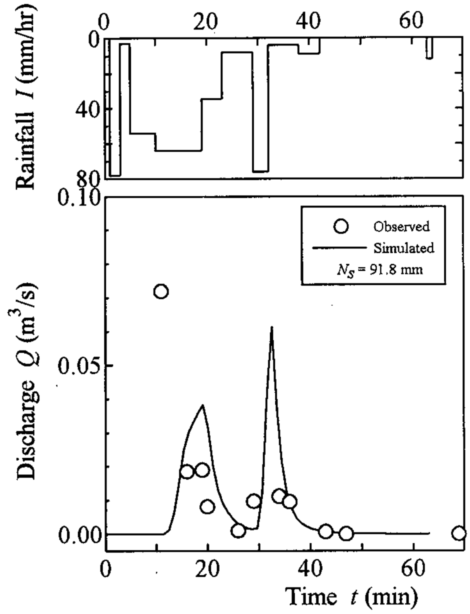

Fig.14 Hydrograph and hyetograph for event No. 8.

large values of N_S do not follow the variation of the observed discharge data well as shown in **Figs.13** and **14**. More accurate consideration of the N_S values for dry conditions of soil is needed. In addition, as it is seen in **Fig.6**, the N_S value can also range from near zero up to 60 mm when the number of dry days D is very small.

8. CONCLUSIONS

The runoff-erosion process, using data obtained from an experimental watershed in the semiarid region of Brazil, was studied. The obtained conclusions are summarized below.

1) Runoff discharge in the field test basin in Brazil is very small for the total rainfall depths less than approximately 10 mm due to the large infiltration, but the runoff coefficient ranges from 0.2 to 0.7 for the rainfall depths more than 10 mm.

2) Sediment yield from the basin is directly connected with the runoff discharge and is approximately 5% of the total runoff discharges in weight.

3) Runoff-erosion modeling based on the kinematic wave approximation both for the overland flow and the channel flow can give a good estimation of the runoff discharge and sediment yield from the basin for the total rainfall

depths more than 10 mm with appropriate values of the parameters in the model.

4) Further study was needed for the reasonable determination of the parameters in the runoff-erosion model, especially for the events with small amount of rainfall and with preceding rainfall.

5) Standardized Powell method for finding the minimum of a nonlinear function with many variables was applied for the optimization of parameters in a runoff-erosion modeling, and it has proved to be useful for the optimization of the four parameters in the runoff-erosion modeling.

6) The channel erosion parameter a, the soil detachability factor K_R, and sediment entrainment parameter by rainfall impact K_I are obtained as constant for almost all rainfall events in the test basin, e.g., a = 0.015 kg·m^2/N$^{1.5}$·s, K_R = 2.2 kg·m/N$^{1.5}$·s, K_I = 4.0x10^8 kg·s/m^4.

7) 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 $N_S \approx 90$ mm for $D > 50$ days, and N_S varies from 0 to 60 mm within few antecedent days without rainfall.

8) Parameters, except for the moisture-tension parameter N_S, in runoff-erosion model optimized by the Standardized Powell method change with the scale of the elements for the data of runoff and sediment yield observed in the test field. In this particular case, a large total number of modeled elements, which leads to precise division of the basin into small elements, does not always give better simulation results. Although the medium scale of elements gave the best results among the three configurations of division of the basin, even the simplest division with 4 elements appears to give acceptable simulation results.

9) Generally, the simulated hydrograph and the observed discharge data from the test field 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 with short duration from the previous rainfall, the simulated hydrographs appear to follow the observed data very well for the simple hydrograph, and for complex rainfall patterns as well. On the other hand, the simulated hydrographs for large values of N_S do not follow the variation of the observed discharge data well. More accurate consideration of the N_S values for dry conditions of soil is needed. In addition, the N_S value can also range from near zero up to 60 mm when the number of days D is very small.

ACKNOWLEDGMENT: The field work reported in this paper was carried out by UFPB (Brazil), SUDENE (Brazil) and ORSTOM (France). The authors would like also to thank Dr. Lopes of the University of Arizona for developing the kinematic model used in this work.

REFERENCES

1) Onstad, C.A. and Foster, G.R.: Erosion modeling on a watershed. *TRANSACTIONS of the ASAE* 18(2): pp.288-292, 1975.

2) Curtis, D.C.: A deterministic urban storm water and sediment discharge model. In: *Proc. of National Symposium on Urban Hydrology, Hydraulics, and Sediment Control.* University of Kentucky. Lexington, KY. pp.151-162, 1976.

3) Smith, R.E.: Field test of a distributed watershed erosion/ sedimentation model. In: Soil Erosion: Prediction and Control. Special Publication No. 21. *Soil Conservation Society of America.* Ankeny, IA, pp.201-209, 1977.

4) Beasley, D.B. ANSWERS: *A mathematical model for simulating the effects of land use and management on water quality.* Ph.D. Thesis, Purdue University, West Lafayette, IN, 1977.

5) Cardier, E. and Freitas, B.J.: *Bacia Representativa de Sumé, primeira estimativa dos recursos de água* (Representative Basin of Sumé, first estimation of the water resources) (in Portuguese), Recife, Pernambuco, Brazil, SUDENE, 1982.

6) Lopes, V.L.: *A numerical model of watershed erosion and sediment yield,* Ph.D. Thesis, University of Arizona, Tucson, Arizona, USA, 1987.

7) Green, W.H. and Ampt, G.A.: Studies on soil physics, I. The flow of air and water through soils. *Journal Agr. Sci.*, 4(1), pp.1-24, 1911.

8) Brakensiek, D.L. and Rawls, W.J.: Agricultural management effects on soil water processes. Part II: Green and Ampt parameters for crusting soils. *Trans. Am. Soc. Eng.*, 26(6), pp.1753-1757, 1983.

9) Srinivasan, V.S., Santos, C., Suzuki, K. and Watanabe, M.: Sediment yield observed in a small experimental basin and its simulation by runoff-erosion modeling, *Annual Journal of Hydraulic Engineering*, JSCE Vol. 37, pp.717-722, 1993.

10) Santos, C.A.G., Suzuki, K., Watanabe, M. and Srinivasan, V.S.: Optimization of coefficients in runoff-erosion modeling by Standardized Powell Method, *Journal of Hydroscience and Hydraulic Engineering*, JSCE, Vol. 12, No. 1, pp.67-78, 1994.

11) Santos, C.A.G., Srinivasan, V.S., Suzuki, K. and Watanabe, M.: Otimização dos parâmetros de um modelo hidrodinâmico de erosão pelo método de Powell, *XI Simpósio Brasileiro de Recursos Hídricos e II Simpósio de Hidráulica e Recursos Hídricos dos Países de Língua Oficial Portuguesa*, pp.167-171, 1995 (in Portuguese).
12) Powell, M.J.D.: An efficient method for finding the minimum of a function of several variables without calculating derivatives, *The Computer Journal*, Vol. 7, pp.155-162, 1964.
13) Nagai, A. and Kadoya, M.: Numerical experiments on optimum identification of series tanks model for runoff analysis, *DPRI Annuals 22 B-2*, Kyoto Univ., pp.209-224, 1979 (in Japanese).
14) Nagai, A. and Kadoya, M.: Optimization techniques for parameter identification of runoff models, *DPRI Annuals 23 B-2*, Kyoto Univ., pp.239-247, 1980 (in Japanese).
15) Santos, C.A.G., Suzuki, K., Watanabe, M. and Srinivasan, V.S.: Scale effects of basin elements on coefficients in runoff-erosion modeling, *Annual Journal of Hydraulic Engineering*, JSCE Vol. 38, pp.83-88, 1994.
16) Santos, C.A.G., Suzuki, K., Watanabe, M., Azuma, M. and Srinivasan, V.S.: Influence of initial infiltration on runoff hydrographs from a test field in a semiarid region of northeastern Brazil, *Annual Journal of Hydraulic Engineering*, JSCE Vol. 41, pp.203-208, 1997.

(Received May 28, 1997)

ブラジルの試験地流域における豪雨による土砂生産とその降雨流出-土壌侵食モデルによる解析

セウソ A. G. サントス・渡辺政広・鈴木幸一・ヴァジャペヤム S. シリニヴァサン

ブラジルの典型的な半乾燥地域における降雨流出-土壌侵食の過程を，キネマティック・モデルを用いてモデル化している．はじめに，降雨・土砂流出データを解析し，SP 法を用いてモデルの最適化を行っている．また，流域のモデリングの精粗がモデル・パラメータに及ぼす影響について，３種の流域モデリングを行って検討している．次に，流出を予測する上でキネマティック・モデルは有用な手段となってきているが，これを用いて降雨流出-土壌侵食の過程をモデル化する場合，降雨期間中の浸透の評価が重要となってくる．そこで，初期浸透能および降雨波形の違いが流出ハイドログラフに及ぼす影響を検討すると共に，本モデルにおいて最適化されるべきモデル・パラメータの一つである土壌水分吸引係数と前期無降雨日数との関係についても検討を進めている．