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Sediment Yield Observed in a Small Experimental Basin and its Simulation by Runoff-Erosion Modeling

by

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Abstract

Sediment yield from a small test field with the area of 5200m^2 in a typically semi-arid region of the north-east of Brazil has been observed for several rainfall events in 1987 and 1988. And the sediment yield is proved to increase remarkably when the total rainfall depth in a continuous rainfall event exceeds 10mm. Sediment yield is directly connected with runoff discharge and is about 5% of the total runoff, and it is well estimated with a runoff-erosion process modeling for rainfall events of the total depth more than 10mm.
Keywords: runoff-erosion, sediment yield, field observation

1. Introduction

The sediment yield phenomenon is generally divided into two categories, sheet erosion by overland flows and sediment transport in river channels. This means that information concerning to the amount and type of precipitation and the movement of water is necessary before the sediment movement is modeled. Many types of sediment yield models have been discussed with the mathematical formulation of the pertinent processes [1), 2)]. But, construction of a runoff-erosion process modeling requires more attention to calibrate and verify the model with observed data. An experimental basin was installed near Sume in the semi-arid region of Paraiba in the north-east of Brazil to obtain sediment yield data from a natural field. The region of Sume lies within a large zone of frequent draughts known as the polygon of draughts in Brazil. The rainfall is irregular and is concentrated in about three months of the year. The soil cover of the test basin is relatively thin, underlain by bed rock and the native vegetation is slashed and burned for cultivation. The installation of the test basin is intended to know the effect of these activities on surface runoff and land erosion. In this paper, the observed data are presented and simulated with a physically-based, event-oriented, numerical model for soil erosion and sediment transport which is summarized by Lopes [3)], in which basin parameters in the model are determined.

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2. Test Field and Observed Data

1) Test basin

An experimental basin is installed for the measurement of sediment yield from the basin by a series of rainfall in the semi-arid region of the north-east of Brazil. Brown non calcic "vertic" soil covers more than 85% of the basin and this soil is typical of most of the semi-arid regions [4]. Figs. 1 and 2 show the topography of the experimental field which is one of sub basins of Umburana River, and one of the test basins which have been studied by Srinivasan since 1982. The basin with a mean slope of 7.1% has no vegetation with bare soil and its area and perimeter are $5200m^2$ and 302m, respectively. At the outlet (point A in Fig. 1) of the 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 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. A recording rain gauge was installed close to the basin to provide the necessary precipitation data.

2) Modeling of the basin

The test basin in Fig. 2 will be divided into 10 elements as shown in Fig. 3 for the runoff-erosion modeling explained in the next chapter. Overland flows are assumed in the elements No. 1, 2, 3, 5, 6, 8 and No. 9, and channel flows in the elements No. 4, 7 and No. 10. The definition of planes were based on soil, slopes and surface cover characteristics. 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

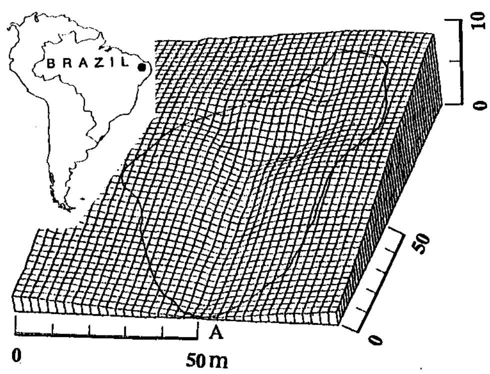

Fig. 1 Aeroview of test basin.

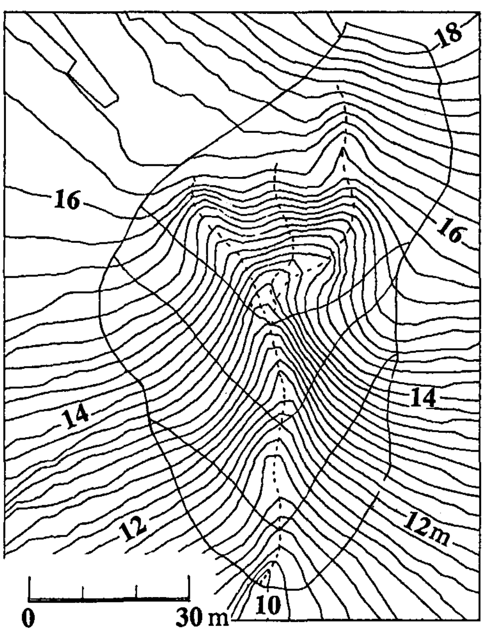

Fig. 2 Topography of test basin.

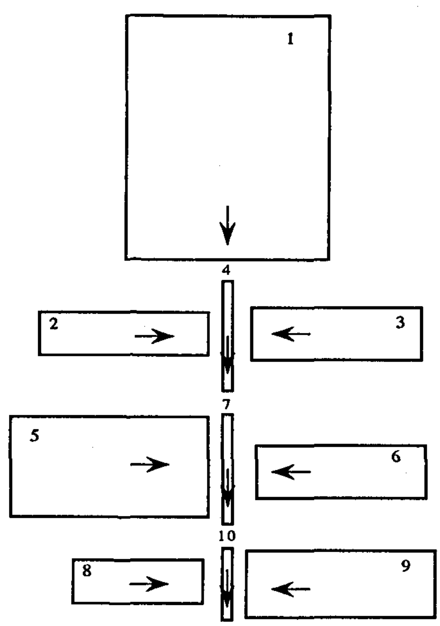

Fig. 3 Modeling of test basin.

and lengths of flow paths for each plane element. Dimensions of the model elements are given in Table 1. The shape of the cross section of channel elements is assumed to be triangular and the lateral slopes are given in the table.

3) Observed data

Rainfall intensity and flow discharge have been measured every minute for 21 events of continuous rainfalls from 1987 to 1988, and the total sediment discharges have been measured at the end of every continuous rainfall. Fig. 4 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 that total rainfall depth is less than about 10mm because of large infiltration capacity of the soil and large evaporation in the semi-arid area. 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. The maximum average rainfall intensity in 30 minutes as the parameter used later in Fig. 7 is proved to describe well the exceptional data. Runoff coefficient for the total rainfall depth more than 10mm ranges widely from about 0.2

Table 1 Dimensions of modeled elements.

Element	Area (m^2)	Length (m)	Width (m)	Slope	Lateral Slope
1	2166.66	41.18	52.60	0.0896	-
2	349.12	34.87	10.02	0.0936	-
3	434.45	34.67	12.52	0.0998	-
4	-	23.04	-	0.0554	0.25 :1
5	931.36	41.33	22.54	0.0806	-
6	447.00	35.67	12.52	0.0903	-
7	-	23.04	-	0.0466	0.25 :1
8	278.85	27.85	10.02	0.0791	-
9	592.56	39.43	15.03	0.0878	-
10	-	16.53	-	0.0665	0.25 :1

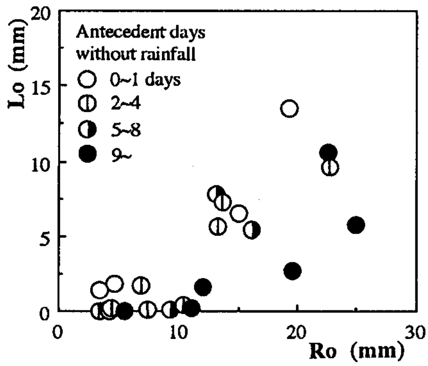

Fig. 4 Total rainfall depth R_0 and runoff depth L_0.

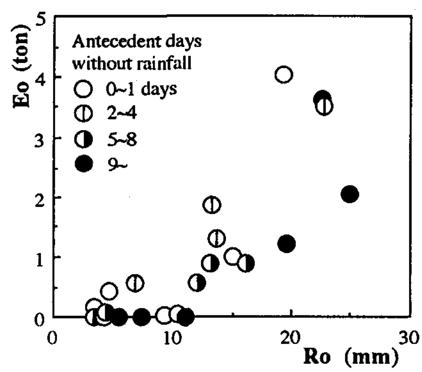

Fig.5 Total rainfall depth R_0 and sediment yield E_0.

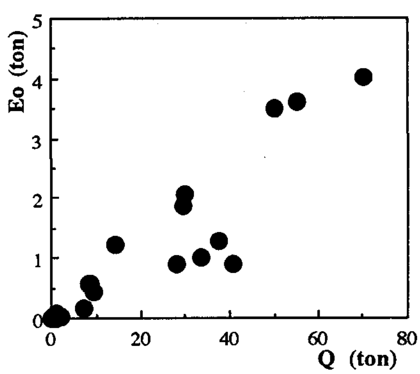

Fig.6 Total flow discharge Q and sediment yield E_0.

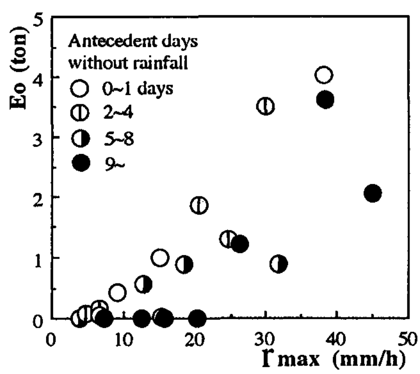

Fig.7 Total sediment yield E_0 and maximum average rainfall intensity in 30 minutes.

to 0.7, depending on the antecedent days without rainfall and characteristics of the rainfall intensity and duration. Fig. 5 shows the relationship between total rainfall and total sediment yield. Sediment yield is also negligible for the total rainfall less than about 10mm, but soil seems to be actively eroded when the total rainfall becomes more than 10mm. Sediment discharge is to be directly connected with the runoff discharge rather than the rainfall depth as shown in Fig. 6. From this figure, the sediment yield from the test basin can be roughly estimated as 5% of the total runoff discharges in weight. This large rate of sediment production is due to the steep slopes without vegetation as well as the soil fragility. Fig. 7 shows the relationship between total sediment yield and maximum average rainfall intensity with a rainfall duration of 30 minutes. The total sediment yield seems to depend on the rainfall intensity as well as the total rainfall depth.

3. Runoff-Erosion Modeling

1) Surface runoff

Erosion of land surface soil and sediment transport are caused by overland flows and channel flows as shown in Fig. 8. These flows are usually analyzed based on the kinematic wave approximation.

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

$$\frac{\partial h}{\partial t}+\frac{\partial (uh)}{\partial x}=r \quad (1), \qquad u=\alpha h^{m-1} \quad (2)$$

where h is the local flow depth, u is the local mean flow velocity, r is the lateral inflow rate per unit area, t is the time, x is the distance in the flow direction and α, m are constants. The lateral inflow rate r(x,t) in Eq.(1) is given by the rainfall intensity i(t) and the infiltration rate f(t) as follows:

$$r=i-f \quad (3), \qquad f(t)=\frac{dF}{dt}=K_s\left(1+\frac{N_s}{F(t)}\right) \quad (4)$$

where F(t) is the cumulative depth of infiltrated water, N_s is the soil moisture-tension parameter and K_s is the saturated hydraulic conductivity. Eq.(2) can be substituted into Eq.(1) to yield:

$$\frac{\partial h}{\partial t}+\alpha m h^{m-1}\frac{\partial h}{\partial x}=r \quad (5)$$

which is conditioned by h(0,t) = 0 for $t \geq 0$ and h(x,0)=0 for $x \geq 0$.

For the channel flow, the basic equation corresponding to Eq.(1) is:

$$\frac{\partial A}{\partial t}+\frac{dQ}{dA}\frac{\partial A}{\partial x}=q_A \quad (6)$$

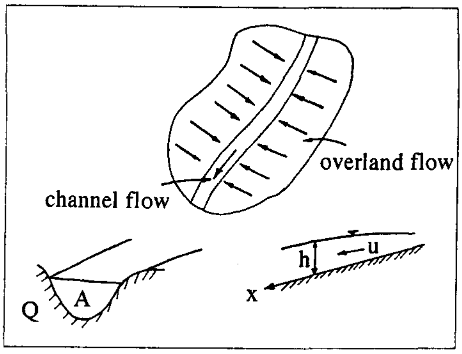

Fig.8 Definitions.

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 and $Q(0,t) = Q_o(t)$ for $t \geq 0$, Q(x,0) = 0 for $x \geq 0$. Equation corresponding to Eq.(2) is also derived with the kinematic approximation:

$$Q=\alpha A R_H^{m-1}=\frac{\alpha A^m}{S^{m-1}} \quad (7)$$

where R is the hydraulic radius and S is the wetted perimeter.

2) Erosion-deposition

Sediment continuity equation of the overland flow is given by:

$$\frac{\partial (ch)}{\partial t}+\frac{\partial (cq)}{\partial x}=e_L-d_L \quad (8)$$

where c is the concentration of sediment in transport, $e_L(x,t)$ is the rate of sediment entrainment by bed shear stress, d_L is the rate of sediment deposition, and the rate of sediment entrainment by rainfall impact is neglected. When $\tau(x,t)$ is the average effective bed shear stress and w_o is the particle fall velocity, e_L and d_L are assumed to be given as follows, respectively:

$$e_L = \gamma \tau^n \quad (9), \qquad d_L = \beta w_o c \quad (10)$$

where γ is a soil detachability factor for shear stress and β is a coefficient depending on the soil and fluid properties. The continuity equation for sediment transport with the concentration C in one-dimensional flow in a single channel element is :

$$\frac{\partial(AC)}{\partial t} + \frac{\partial(CQ)}{\partial x} = e_R + q_s - d_R \qquad (11)$$

where e_R is the rate of sediment entrainment by channel flow, q_s is the lateral sediment inflow from adjacent flow planes and d_R is the rate of sediment deposition. d_R is assumed to be given by the same form as d_L expressed by Eq.(10), and e_R is given by:

$$e_R = a(\tau - \tau_c)^n \quad \text{for } \tau \geq \tau_c, \qquad e_R = 0 \quad \text{for } \tau < \tau_c \qquad (12)$$

where a and n are coefficients. The average shear stress $\tau(x,t)$ is given by $\tau = \rho gRI$ and the average critical shear stress τ_c for the representative particle size d is expressed by $\tau_c = \delta(\sigma - \rho)gd$, where I is the friction slope, g is the acceleration due to gravity, δ is a constant and σ, ρ are the densities of sediment and water, respectively.

3) Parameters in the model

There are many parameters to be given in the above mentioned model. Some of them may be assumed to be universal. But, parameters such as moisture-tension parameter N_s and saturated hydraulic conductivity K_s in Eq. (4) should be given for the specific basin under consideration. The infiltration is essential in this semi-arid area when the preceding rainfall is small as considered here. K_s and N_s are determined as K_s = 5.0 mm/h and N_s = 40mm for convenience with reference to the previous work[5] about test basins near this basin , where the preceding rainfall is assumed to be zero and N_s is constant. Manning's N in α is 0.020 for the plane and 0.030 for the channel, and a coefficient for sediment deposition β is 0.50 for the plane and 1.0 for the channel. Channel erosion parameter a = 0.014 ($kg{\cdot}m^2/N^{1.5}{\cdot}s$) and parameter for sediment entrainment by bed shear stress of overland flow γ = 2.17 ($kg{\cdot}m/N^{1.5}{\cdot}s$) are also given by the previous work. The sand over the land surface consists of a sand mixture with mean diameter of 0.5mm and the standard deviation of the grain size is 6.0, but the representative diameter of the sand d is assumed to be 0.5mm. Other parameters are given as follows: m = 5/3, n = 3/2, δ = 0.047.

4) Calculation procedure

In the calculation u and h for the overland flow are calculated first with Eq. (5), from which q_A in Eq. (8) can be given, and Q and A are calculated. Then c and C can be calculated with Eq. (9) and Eq. (10), respectively. Finite difference scheme is used for the calculation. Time increment Δt and distance increment Δx should satisfy the following C.F.L. condition: $\Delta t/\Delta x < 1/(\alpha m h^{m-1})$.

4. Results and Discussions

Fig. 9 shows the comparison between observed runoff depth L_o and calculated one L_c, where the calculated runoff depths for small rainfalls for 11 events in 21 events are zero because of the overestimated infiltration, whose data do not appear in the figure. The observed runoff depths for more than 10mm seem to be well simulated by the calculation, although they can not be calculated for very small rainfall events. This is also the case for the relationship between observed total sediment yields E_o and calculated ones E_c as shown in Fig. 10.

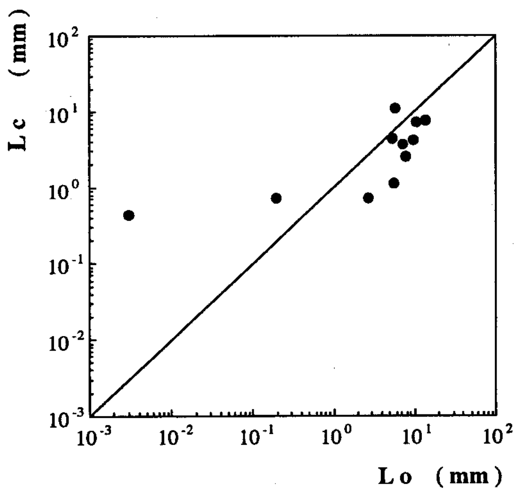

Fig.9 Observed total runoff depth L_o and calculated one L_c.

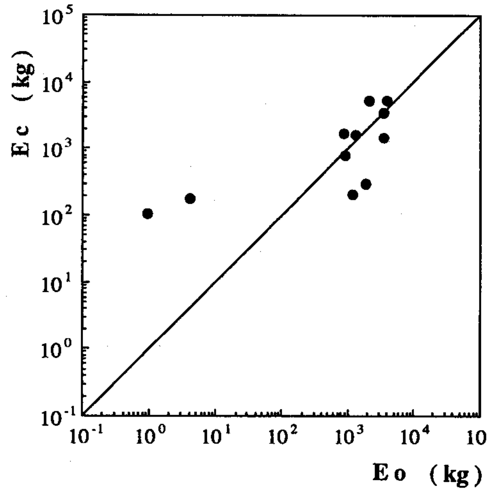

Fig.10 Observed total sediment yield E_o and calculated one E_c.

5. Conclusions

Observed data about sediment yield from a natural basin in the semi-arid area of the north-east of Brazil are discussed for several rainfall events and the following conclusions are obtained:

1) Runoff discharge in the basin is very small for the total rainfall depths less than about 10mm because of the large infiltration, but the runoff coefficient ranges from 0.2 to 0.7 for the rainfall more than 10mm, depending mainly on the antecedent days without rainfall and the feature of the rainfall intensity and duration.

2) Sediment yield is directly connected with the runoff discharge and is about 5% of the total runoff.

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

Further study is 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.

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