Erosion Prediction in Ungauged Basins: Integrating Methods and Techniques (Proceedings of symposium HS01 held during IUGG2003 at Sapporo, July 2003). IAHS Publ. no. 279, 2003.

Application of a process-based model as a predictive tool for erosion loss in ungauged basins

CELSO AUGUSTO GUIMARÃES SANTOS[1],
VAJAPEYAM S. SRINIVASAN[2] **&**
CARLOS DE OLIVEIRA GALVÃO[2]

1 *Department of Technology for Civil Engineering Constructions, Federal University of Paraíba, 58059-900 João Pessoa, Paraíba, Brazil*
celso@ct.ufpb.br

2 *Department of Civil Engineering, Federal University of Campina Grande, Av. Aprígio Veloso 882, 58109-970 Campina Grande, Paraíba, Brazil*

Abstract In semiarid northeastern Brazil, small and medium sized river basins have no monitoring devices that can help to estimate erosion rates and sediment yields. The Experimental Basin of Sumé was installed in the early 1980s, with four microbasins and nine erosion plots, to help understand the processes involved and to serve as a first step towards finding ways to estimate runoff and erosion in ungauged basins. The dataset collected up until the early 1990s represents a unique and valuable source of information about runoff and erosion in this region. A process-based, event-oriented model (WESP) has been successfully calibrated utilizing the data collected in the experimental basin. The calibrated model and data from erosion plots in the experimental basin were used to obtain an empirical regional soil loss equation of the type proposed by Musgrave. The results seem quite promising, and the proposed method has the potential of being a reliable predictive tool for basins without data in the region.

Key words Brazil; erosion; experimental basin; process-based model; regional relationships; WESP

INTRODUCTION

Erosion of soil and its transport out of the drainage basin are complex processes that depend on factors that can be divided into two groups. The first group would be the climatic regime and the characteristics of individual precipitation events; the second would be the basin characteristics, including topography, soil characteristics and vegetation cover. In order to produce a reliable, predictive tool to estimate soil loss and sediment yield in a basin, a long time series of accurate data, not only of the real amount of soil eroded and transported out of the basin, but also of the diverse variables of the afore mentioned groups, will be necessary. In developing countries in particular, such data are scarce and, more often than not, data from only a few basins must be used for estimating erosion losses from other, ungauged basins. Experimental basins especially installed and equipped for such purposes seem to be a highly practical and economical alternative.

Prediction of possible runoff and erosion in ungauged drainage basins is one of the most challenging tasks anywhere, and especially a very difficult one in developing countries where monitoring and continuous measurements of these quantities are carried out in very few basins. This is due to the very high costs involved and the lack of personnel trained in sufficient numbers. As planners and regional development authorities need this information for adequate regional planning, developing means for estimation of runoff and erosion losses in basins without adequate data turns out to be an important task for hydrologists.

Frequently, especially in developing countries, basins with a reliable and long-term database are rare, and in such cases the problem of prediction of future basin responses becomes very tough and the degree of uncertainty associated with transposed empirical models would be extremely high. An economical and reasonably efficient alternative would be to monitor the major basins with a reliable gauging system, and create a network of representative, experimental basins for predictive purposes for medium and small-sized basins. Experimental basins seem to be extremely useful tools with which the response of the experimental units to natural or simulated rainfall could be investigated under various combinations of the major factors involved, especially where erosion losses need to be estimated. Such an experimental basin was instrumented in the semiarid region of the northeast of Brazil to investigate the relative influences of various factors—principally those of vegetation cover, slope, and land management—over the processes of runoff generation and erosion under field conditions. An appropriate process-based model, tested and calibrated with the data, could be either directly or indirectly used to estimate runoff and erosion loss from plots and basins without measured historical data. This paper presents the details of such data collected in the basin, as well as the results obtained with a process-based distributed model called WESP (Lopes, 1987) that is calibrated and used as a simulation tool. Utilizing synthetic data from such simulations, an empirical equation was developed as a predictive tool for erosion loss from ungauged areas.

The following sections present some details regarding the experimental installations, the runoff-erosion model, synthetic data generation, calibration of a Musgrave-type empirical equation with observed and synthetic data in the erosion plots and, finally, a comparative evaluation between values predicted by the developed equation and observed on erosion plots with different types of vegetation.

EXPERIMENTAL PLOTS

The experimental erosion plots were installed in the Experimental Basin of Sumé, which has been operated 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 on runoff, erosion and sediment yield produced by rainfall in a natural environment (Cadier *et al.*, 1983). The erosion plots were 100 m^2, with a 4.55 m width and 22.5 m length. Their mean slope, surface cover and year of installation are given in Table 1. To permit comparison of results from different slopes, the same conditions of surface treatment and type of vegetation were maintained on the following pairs of plots: 1 and 4, 2 and 3, and 5 and 9. Four microbasins with areas of around 5000 m^2 were also instrumented in this experimental basin, of which two were maintained with a bare soil surface and two with the native vegetation known as *caatinga*. The soil in this area is classified as a “brown non calcic-vertic” soil, which is a typical soil in the semiarid regions of northeastern Brazil.

Table 1 Characteristics of the erosion plots.

Plot no.	Mean slope (%)	Vegetation cover	Year of installation
1	3.8	Bare soil	1982
2	3.9	Dead vegetation cover	1982
3	7.2	Dead vegetation cover	1982
4	7.0	Bare soil	1982
5	9.5	Native vegetation (*caatinga*)	1982
6	4.0	Cactus (downslope tillage)	1983
7	4.0	Cactus (contoured tillage)	1983
8	4.0	Bare and cultivated soil	1986
9	4.0	New native vegetation (since 1981)	1986

On the bare plots (plots 1 and 4), the vegetation was always removed when it reached 5 cm in height. The plots with a mulched vegetation cover (plots 2 and 3) had their vegetation cut when it reached about 20 to 25 cm height, but the cut vegetation was not removed and was left as mulch on the plots. Plot 8 was constantly kept free of any vegetation and the soil was regularly cultivated (ploughed), whereas plots 6 and 7, with cactus planting, were cleared of weeds when they reached around 5 cm in height. Plot 5, with undisturbed native vegetation, and plot 9, in which native vegetation had been allowed to regrow for at least 5 years, received no operative interventions since 1981.

Based on the experience from a previous investigation (Santos *et al.*, 1994), several storm events between 1987 and 1988 were selected for study. The relationship between observed runoff depth L_o and observed rainfall depth R_o is shown in Figs 1(a) and 1(b) for the plots with and without vegetation cover, respectively. It can be seen that, despite the similar tendencies between the two cases, there is a clear reduction in runoff and more events with runoff depths of less than 0.1 mm on the plots with a vegetation cover.

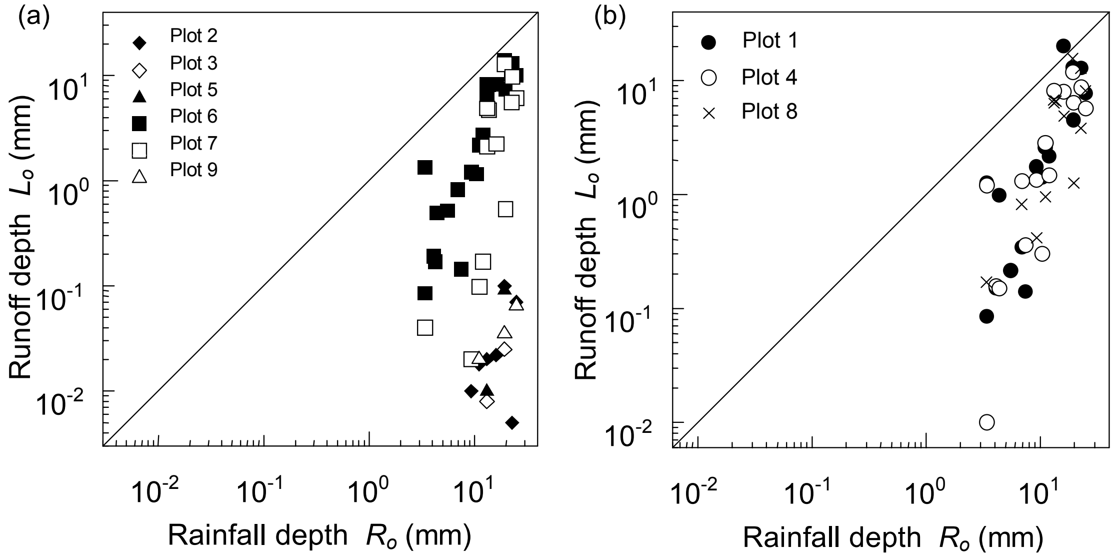

Fig. 1 Relationship between observed runoff L_o and observed rainfall R_o for the plots with (a) vegetation cover, (b) bare surface.

THE RUNOFF-EROSION MODEL

The Watershed Erosion Simulation Program (WESP) (Lopes, 1987), developed to simulate the hydrological and erosional response of small basins, was chosen for application in the present investigation as it had already been tested with success in the semiarid region of northeastern Brazil (Santos *et al.*, 1994). The model, being process-based, offers the possibility of success under a large range of conditions, and helps in understanding the influence of the various factors that affect runoff and soil erosion. The model uses the Green-Ampt equation as modified by Mein & Larson (1973) to calculate infiltration during steady rain. This equation was further extended by Chu (1978) to determine the beginning of rainfall excess during unsteady rainfall. Overland flow caused by rainfall excess is considered to be one-dimensional, and the equation for flow velocity on the planes is computed using the kinematic wave approximation and Manning's equation for mean velocity.

Net sediment transport over a plane is calculated as the difference between the erosion rate and the deposition rate on the plane. Erosion occurs due to raindrop impact and surface shear. The sediment continuity equation is used to express the sediment transport rate in the reach as a function of concentration, discharge and flow depth. The equation is solved numerically with a four-point implicit finite-difference scheme to calculate sediment flux as a function of time and distance.

To simulate runoff and erosion on a plane, three principal parameters that characterize field conditions must be known. They are: (a) the moisture tension parameter of the soil, N_s; (b) the soil erodibility parameter due to raindrop impact, K_I; and (c) the soil erodibility parameter due to shear stress, K_R. The erodibility parameters for the bare soil surface in the experimental basin have been determined in an earlier study (Santos *et al.*, 1994), and these values were utilized in the simulations.

PROPOSED REGIONAL EROSION EQUATION

Musgrave (1947) synthesized the results of analysing soil-loss measurements for some 40 000 storms occurring on small plots in the United States of America, and expressed the rate of soil loss E with the following relationship:

$$E = \alpha L^{\beta_1} I^{\beta_2} S_0^{\beta_3} \tag{1}$$

where α is the inherent erodibility of the soil and a cover parameter, L, is the slope length, S_0 is the slope, I is the rainfall intensity and β_1, β_2 and β_3 are exponents that must be determined from field data. As this empirical equation considers all the major factors that affect erosion, as verified by observations in the experimental basin, this equation was adopted as the regional erosion equation for the semiarid region of Sumé.

To determine the exponents β_1, β_2 and β_3 and the parameter α of this equation, it would be necessary to have a large amount of data for the study area, covering a wide range of the variables involved. Such a task may be impossible in many regions, and the time and cost of collecting such field data may even be prohibitive in developing countries. To simplify this task, generating synthetic data using a calibrated process-based model like WESP may be a feasible and sound alternative. The procedure utilized for the region of Sumé is described here.

SYNTHETIC DATA

The synthetic data were generated using several rainfall intensities on hypothetical plots of unit width with lengths of 30, 100 and 300 m and slopes of 4, 10 and 20%, constituting a set of nine plots. The rainfall intensities applied on these plots were 10, 20 and 50 mm h^{-1}, and the sediment yields for each plot were computed with the WESP model. Santos *et al.* (1994) determined the mean values of the parameters K_I and K_R to be 5.1×10^8 kg s m^{-4} and 2.1 kg m $N^{-1.5}$ s^{-1}, respectively. These values were obtained by calibrating the model to a microbasin in the Sumé Experimental Basin, with an area of 0.48 ha, a mean slope of 7.1%, bare soil and a mean sediment diameter of 0.50 mm.

For the calculation of infiltration, saturated soil conditions were assumed, which amounts to the infiltration rate being set equal to the saturated hydraulic conductivity (5 mm h^{-1}) and the moisture tension parameter N_s equal to zero. One other parameter that should be mentioned here is the Manning roughness factor n, assumed to be equal to 0.02, based on soil type, sediment size and surface characteristics.

Once the plot dimensions, rainfall intensities and erosion parameters were chosen, the WESP program was utilized to determine the sediment yield E. Figure 2 presents the simulated values of erosion as a function of plot length, rainfall intensity and slope, respectively.

RESULTS AND DISCUSSION

The WESP model calculates erosion as a function of surface flow, and hence to utilize the synthetic data, the rainfall intensity in equation (1) was substituted by the rainfall excess rate r_e, being equal to the difference between rainfall intensity and saturated hydraulic conductivity. The exponents β_1, β_2 and β_3 in equation (1) would correspond to the slopes of the lines in Figs 2 (a), (b), and (c), respectively. Thus, the final form of

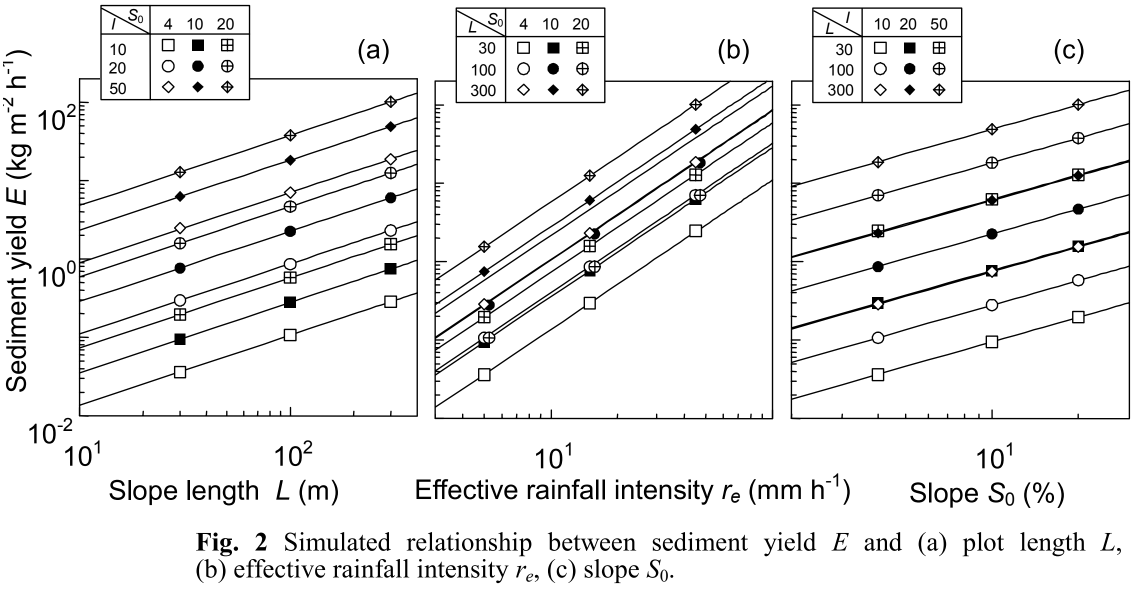

Fig. 2 Simulated relationship between sediment yield E and (a) plot length L, (b) effective rainfall intensity r_e, (c) slope S_0.

the proposed regional erosion equation becomes:

$$E = 1.91 \times 10^{-5} L^{0.9} r_e^{1.91} S_0^{1.04} \tag{2}$$

where E is in kg m^{-2} h^{-1}, L in m, S_0 in percent, and r_e is the effective rainfall intensity in mm h^{-1} given by $r_e = I - K_s$, in which the final infiltration rate or effective soil hydraulic conductivity K_s = 5 mm h^{-1}. In an alternative form, equation (2) may also be expressed in terms of the total rainfall intensity I (mm h^{-1}) as:

$$E = 1.19 \times 10^{-6} L^{0.9} I^{2.59} S_0^{1.04} \tag{3}$$

Equation (3), however, must be used with caution, as there is an implication that the infiltration rate is constant and equal to the saturated hydraulic conductivity.

Erosion rates given by equations (2) and (3) would be valid for bare soil surfaces only, and to utilize them for other surface covers, an appropriate value of the coefficient α in equation (1) must be used. In order to determine the values of α for other than the bare soil surfaces, erosion data from the 100 m^2 plots with different vegetation covers in the experimental basin were used.

Figure 3(a) shows the observed erosion rate on the bare plots 1, 4, and 8, compared to the values calculated by equation (2) using synthetic data. The agreement is reasonably good, and the dispersion around the estimated values is quite even. The dispersion around the lines can be explained by the fact that equation (2) assumes a uniform effective rainfall equal to the mean intensity, whereas variations in rainfall intensity cause variations in sediment yield in practice. It can be observed that the steepest slope of plot 4 (7%) results in high erosion rates compared to plot 1 (3.8%). The erosion rate on plot 8 (4%) is as high as on plot 4. Thus, the increased availability of sediment due to ploughing seems to have the same effect as the increase in slope from 4 to 7%.

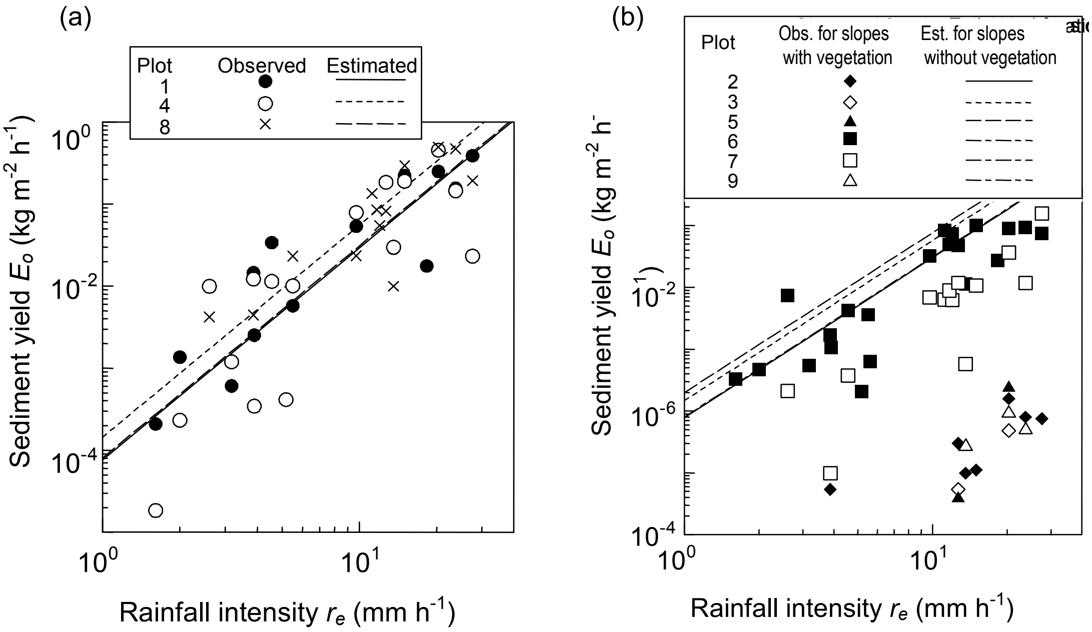

Fig. 3 Relationship between observed sediment yield E_o and effective rainfall intensity r_e for the plots with (a) bare surface, (b) vegetation cover.

Figure 3(b) shows the observed rates of erosion on the vegetated plots along with the estimated values of erosion on these plots if they were bare. Thus, for each of the observations, the value of coefficient α was calculated by comparing the observed and estimated values for a bare surface from equation (2). The calculated values of α for each of the plots are shown in Fig. (4). As one would expect, this value varied for each of the surface covers, and the value of 1.19×10^{-6} in equation (3) corresponds almost exactly to the mean value for the bare plots 1, 4 and 8.

The mean values of α for vegetated plots could be established by taking the average values for each surface cover type. Thus, the approximate values obtained for α were 10^{-10}, 3×10^{-10}, 8×10^{-8} and 5×10^{-7} for undisturbed or regrown native vegetation, mulching with dead vegetation cover, cactus on contour planting and cactus planted down the slope, respectively.

As seen from Figs 3(a) and 3(b), as well as from the values of α, it appears that erosion rates increase sharply when the soil is unprotected because of the absence of vegetation, whereas natural vegetation (*caatinga*) or a mulch cover provide very effective protection.

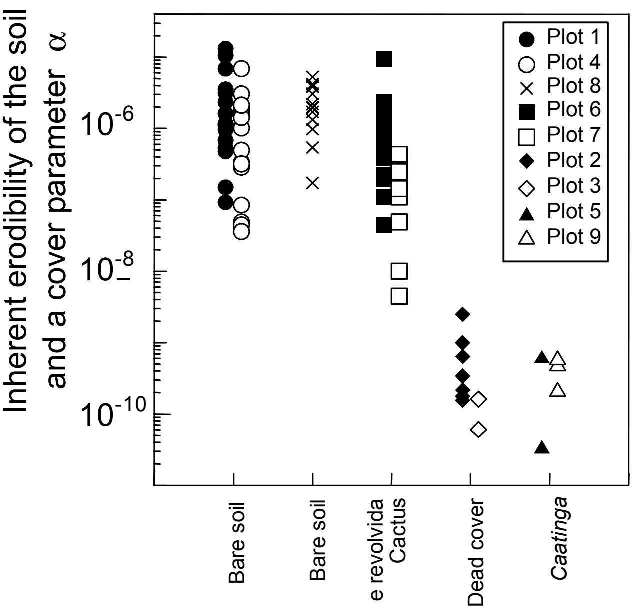

Fig. 4 Relationship between inherent erodibility of soil α, and the type of vegetation cover and soil cultivation.

CONCLUSIONS

Combining field data and synthetic data generated by a calibrated process-based model seems to be a cost-effective and feasible approach for developing a regional erosion equation similar to that of Musgrave (1947). Such an equation takes into account the major factors that affect sediment production, namely length, slope, rainfall intensity and surface cover. A process-based model is best suited for such purposes as its parameters are not only physically meaningful, but also the extrapolation of results for other situations, hypothetical or otherwise, would be more certain.

The combination of WESP (Lopes, 1987) and data collected in the Sumé experimental basin has resulted in the generation of a regional erosion equation that could be applied to ungauged areas to obtain estimates of the rates of sediment production during individual precipitation events, and of the total yield during a given period. Equation (2), with appropriate values of α for the type of vegetation or surface cover, seems to yield satisfactory results for the semiarid region investigated.

Acknowledgements The initial field installations at Sumé were realized by SUDENE and ORSTOM (France), whereas the operation of the basin was carried out by the research group of the Federal University of Campina Grande (UFCG), formerly Campus II of the Federal University of Paraíba (UFPB). The authors thank Dr Vicente L. Lopes of the University of Arizona for providing WESP. The National Council for Scientific and Technological Development (CNPq) supported this research.

REFERENCES

Cadier, E.; Freitas, B. J. & Leprun, J. C. (1983) *Bacia Experimental de Sumé, instalação e primeiros resultados*. (Experimental Basin of Sumé, installation and first results) (in Portuguese). SUDENE Recife, Brazil, Série Hidrologia, vol. 16.

Chu, S. T. (1978) Infiltration during an unsteady rain. *Water Resour. Res.* **14**(3), 461–466.

Lopes, V. L. (1987) A numerical model of watershed erosion and sediment yield. PhD Thesis, University of Arizona, Tucson, Arizona, USA.

Mein, R. G. & Larson, C. L. (1973) Modeling infiltration during a steady rain. *Water Resour. Res.* **9**(2), 384–394.

Musgrave, G. W. (1947) The quantitative evaluation of factors in water erosion: a first approximation. *J. Soil Water Conserv.* **2**(3), 133–138.

Santos, C. A. G., Suzuki, K., Watanabe, M. & Srinivasan, V. S. (1994) Optimization of coefficients in runoff-erosion modeling by Standardized Powell method. *J. Hydrosci. Hydraul. Engng, JSCE* **12**(1), 67–78.