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Evaluation of an erosion simulation model in a semiarid region of Brazil

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Abstract Runoff and erosion data were collected in an experimental basin during natural rainfall events on plots and microscale basins. A hydrodynamic model was chosen for calibration and simulation, and calibration was carried out for each of the chosen observed events. Two model parameters were related to an antecedent moisture index. The accuracy of the calibrated model and the parameters was tested by applying them to an adjacent microscale basin. The model simulated the runoff values well, even with the estimated parameter values, but the calculated erosion values showed larger variations, underlining the complexity of the erosion process. However, the model could be considered a reasonable tool for obtaining a first estimate of erosion from basins without adequate data but with similar characteristics.

Key words modelling; simulation; semiarid; soil erosion

INTRODUCTION

Predicting runoff and erosion in ungauged drainage basins is one of the most challenging tasks in any location, especially in developing countries where monitoring is carried out in very few basins, either due to the high costs involved or due to the lack of sufficient number of trained personnel in. As planners and regional development authorities need this kind of information for adequate regional planning, ways of estimating runoff and erosion without adequate data even in adjacent basins turns out to be an important task for hydrologists.

An economical and reasonably efficient alternative would be to monitor the major basins with a reliable gauging system, and to create a network of representative experimental basins for predictive purposes in medium and small sized basins (Toebes, 1965). Especially where erosion needs to be estimated, experimental basins seem to be an extremely useful tool in which the response of the experimental units to natural or simulated rainfall could be investigated under various combinations of the major factors involved (Holy, 1965; Vuillaume & Rodier, 1980).

THE EXPERIMENTAL BASIN

To evaluate the influence of natural and human factors on the processes of runoff generation and soil erosion, an experimental basin was established in a representative, semiarid basin in the northeast of Brazil. The basin is located in the municipality of Sumé, where mean annual precipitation is 590 mm and annual class A tank evaporation is about 2900 mm (Cadier *et al.*, 1983). The rainfall in the region is highly irregular and is typically concentrated in about three months between February and May. The soil cover is quite thin, underlain by bedrock. The predominant soil type is "brown non-calcic vertic soil". Soil permeability is only moderate, with the maximum infiltration capacity ranging from 25 to 35 mm h^{-1}. The natural vegetation is mainly bush and small-sized trees. Agricultural activities are carried out during the rainy season, and the natural vegetation is cleared to bare soil in preparing the land.

The experimental basin of Sumé is located on private farmland known as Fazenda Nova within the sub-basin of Umburana (10.7 km^2). This sub-basin lies within the representative basin of Sumé (137 km^2). The erosion and runoff studies were carried out in microscale basins of around 0.5 ha and on standard Wischmeier type erosion plots of 100 m^2, and they were subjected to natural rainfall events only (Cadier *et al.*, 1983).

The field installations consisted of nine erosion plots with different surface covers and slopes, four microscale basins and a weather station. Runoff and sediment yield data from erosion plot number 4 (bare soil with a slope of 7%), and microscale basins 3 and 4 (both cleared of vegetation to a bare soil surface; slopes of 6.8% and 7.0%, respectively) were used to calibrate and validate a process-based model. Further details about the installations and the procedure used for the collection of data may be found in Srinivasan *et al.* (1988) and Cadier *et al.* (1983).

MODEL DESCRIPTION

The model used in this work is a physically-based, distributed and event-oriented model named WESP (Watershed Erosion Simulation Program), which was developed by Lopes (1987) with the objective of simulating runoff and erosion in small semiarid watersheds. This makes WESP particularly suitable for the purposes of this study. The watershed is represented by a set of geometric elements of overland flow planes and channels. The kinematic wave equation is used for routing the spatially-varied unsteady flow over planes and channels. The model uses the Green and Ampt infiltration equation as modified by Mein & Larson (1973) for steady rain, and by Chu (1978) for unsteady rainfall. The infiltration rate f_c [m h^{-1}] at time t is given by:

$$f_c = K_s\left[1+\frac{N_S}{F}\right] \tag{1}$$

$$N_s = (\theta_s - \theta_i)\psi \tag{2}$$

where K_s is the effective soil hydraulic conductivity [m s^{-1}], F is the cumulative depth of infiltrated water [m], N_s is a soil moisture tension parameter [m], t is time [s] measured from the beginning of rainfall, θ_s is the saturated water content [m^3 m^{-3}], θ_i is the initial water content [m^3 m^{-3}], and ψ is the soil suction potential at the wetting front [m].

Upland erosion

The continuity equation for sediment transport by one-dimensional flow on hill slopes is used to describe the sediment movement (Lopes, 1987). It is assumed that soil particles are dislodged and detached by raindrop impact or by overland flow, or by both. Erosion due to raindrop impact is calculated as (Lopes, 1987):

$$e_I = K_i \, i \, r \qquad (3)$$

where K_i is a parameter associated with the soil detachability by rainfall impact [kg s m^{-4}], $i(t)$ is rainfall intensity [m s^{-1}], and $r(x, t)$ is the ratio between rainfall excess rate [m s^{-1}] and rainfall intensity. On the overland flow planes, erosion by flowing water is represented by:

$$e_R = K_r \, \tau^{1.5} \qquad (4)$$

where K_r is a factor for soil detachability by shear stress of flowing water [kg m N$^{-1.5}$ s^{-1}] and $\tau(x, t)$ is the effective mean shear stress [N m^{-2}]. The sediment continuity equation is used to express the sediment transport rate in the reach as a function of concentration, discharge and depth. The equation is solved numerically with a four-point implicit finite-difference scheme to calculate sediment outflow as a function of time and distance. The sediment flux φ [kg m^{-2} s^{-1}] is written as:

$$\varphi = e_i + e_R - d \qquad (5)$$

where d is the deposition rate of the sediment, which is proportional to the concentration.

Channel erosion

In the channel elements, erosion by flowing water is computed as:

$$e_R = a(\tau - \tau_c)^n \quad \text{when} \quad \tau \geq \tau_c \text{ and} \qquad (6)$$

$$e_R = 0 \quad \text{when} \quad \tau < \tau_c \qquad (7)$$

where a is a coefficient for sediment entrainment [kg m^{-2} N$^{-1.5}$ s^{-1}], $\tau(x, t)$ is the average shear stress [N m^{-2}], τ_c is the average critical shear stress for the representative particle size [N m^{-2}], and n is an exponent. The sediment flux is determined by mass balance.

CALIBRATION OF MODEL PARAMETERS

Many of the parameters of WESP can be determined through direct measurement, or obtained from previous investigations in the same experimental area. However, some parameters, such as N_s, K_i, K_r and a in equations (1), (3), (4) and (6), respectively, cannot be measured directly. These parameters need to be estimated or calibrated using existing data. *WESP* allows simulation of runoff and erosion on an event-by-event basis, and requires information about soil moisture at the beginning of each event. This information is incorporated into the soil moisture tension parameter N_s in equation (2), and this parameter must be adjusted or calibrated for each event so that the model may generate a runoff equal to the observed value. The erosion rate depends not only on overland flow but also on the soil resistance, which in turn depends on the soil moisture content. Thus, the parameter K_r depends on the soil moisture conditions at the beginning of the event and this parameter therefore also needs to be calibrated event-by-event. The data from plot 4 were utilized to calibrate the values of N_s, K_i, and K_r for each of the chosen events, so that the calculated values of runoff and erosion came as close as possible to the observed ones.

The data from microscale basin 3 were used for calibration of the channel erosion parameter a and of the overall moisture tension parameter N_s, for the whole micro-scale basin 3, whose geometry was represented by 23 elements of planes and channels. Although WESP produces runoff and erosion data for each of the elements, runoff and sediment yield were measured only at the outlet of the microscale basins. Thus, the erosion parameter of the channel process should be calibrated in conjunction with the plane flow erosion parameters, so that the calculated yield comes closest to the observed value. To simplify this process, the mean value of K_r of 1.786 kg m $N^{-1.5}$ s^{-1}, obtained on the erosion plot 4, was applied to all of the planar elements, based on the similarity of soil and surface characteristics. It was found that no significant variation in the calculated sediment yield of plot 4 occurred when the value of parameter K_i was varied over a wide range. Consequently, K_i was fixed at 5×10^8 kg s m^{-4}, and this value was used for all events. This left only two parameters to be calibrated (N_s and a) at the level of the microscale basins, which enabled calibration by a process of successive trials. In principle, the mean value of N_s from erosion plot 4 could also have been applied to the microscale basin. However, since this parameter represents the overall effect of infiltration on all elements of the basin, it needs to be calibrated event-by-event. It was observed that the values of calibrated parameters varied significantly from event to event for both the erosion plots and the microscale basin. This may be attributed to the influence of other factors that were not explicitly considered in the infiltration equation.

Parameter estimation

Parameter estimation is a methodology usually applied to estimate the values of parameters of a physically based or conceptual model by associating them with some measurable quantities in a basin. In the experimental basin of Sumé, attempts were made to estimate the main parameters of the WESP model. However, a totally satisfactory method to estimate these parameters could not be established. The variation of the parameters seems to indicate a variation in the average condition of the basin between events. In other words, variation of N_s and K_r is due to variation in soil moisture condition at the beginning of each event, and soil moisture conditions depend on the previous rainfall events.

Utilizing a total of 87 rainfall events from erosion plot 4, a relationship between N_s and the *Kohler* antecedent precipitation index (*IH*) was attempted. This index is expressed as:

$$IH_i = K(IH_{i-1} + P_{i-1}) \tag{8}$$

where IH_i is the soil moisture index for day i, P_{i-1} is the total amount of rainfall on the previous day ($i - 1$), and K is a reduction factor which represents the percentage of soil moisture transferred from the previous day to the next day, and is always less than one.

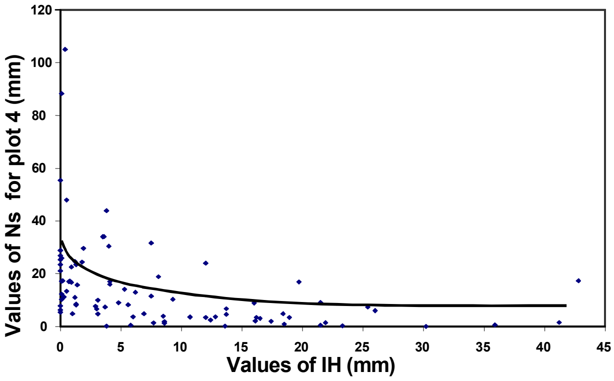

Fig. 1 Relationship between N_s and Kohler Index *IH*.

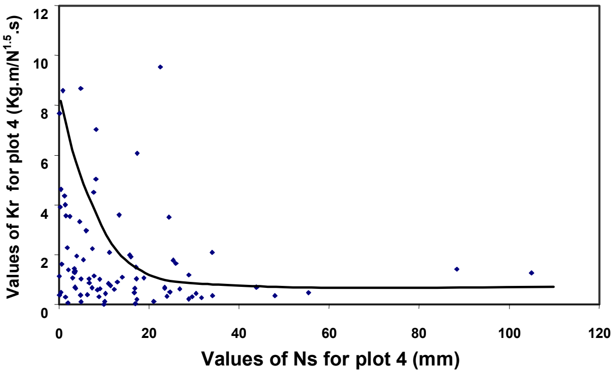

Fig. 2 Relationship between K_r and N_s.

The best possible relationship was obtained with $K = 0.6$, as shown in Fig. 1. When the same procedure was used to relate K_r with IH_i, no relationship was obtained even though a dependence of K_r on N_s was noticeable.

Hydrological modelling inevitably requires simplification. Many processes of runoff generation and soil erosion are interrelated and interdependent but, when represented by simple equations, some of these relationships are neglected, and as a result, simulated results do not always satisfactorily fit the observed data. In addition, there is the problem of parameter interaction. Even though no physical relation between N_s and K_r can be directly implied, there is an apparent influence of soil moisture on both parameters as is shown in Fig. 2.

MODEL VALIDATION

One of the most important applications of modelling erosion and sediment yield is the use of calibrated parameter values in other basins with similar physical and climatic characteristics, but having no data of their own. In other words, using the model as prediction tool for ungauged basins.

The validity of the calibrated model was tested by applying it to the neighbouring microscale basin no. 4, which was represented by 21 plane and channel elements. As parameters were calibrated for each event separately, application of these parameters to corresponding events should produce quite satisfactory runoff and sediment yield values for each of the events. Srinivasan & Galvão (1995) showed that results were excellent in the case of runoff, whereas for sediment yield there were notable deviations from the measured values. In spite of this, the results could be considered satisfactory for obtaining estimates of sediment yields in individual events, as measurements of sediment yield tend to be less precise than runoff measurements.

To verify the regional applicability of the parameters N_s and K_r, the estimated values were used to simulate runoff and erosion in microscale basin 4 for more than 50 events. For this test, N_s and K_r were estimated from Figs 1 and 2, and the channel erosion parameter *a* was the mean value of those obtained during calibration in microscale basin 3. Figures 3 and 4 show the comparison between simulated and observed values of runoff and sediment yield in microscale basin 4.

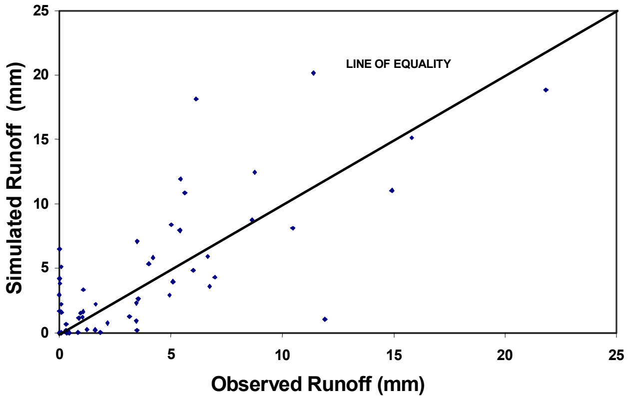

Fig. 3 Simulated and observed runoff in microscale basin 4.

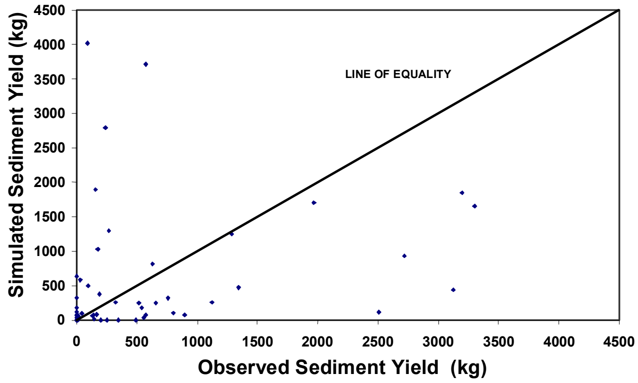

Fig. 4 Simulated and observed sediment yield in microscale basin 4.

DISCUSSION

The calibrated values of N_s, K_r and *a* varied widely between events, since the data used to calibrate the model was collected over a long period of each year (January–June), and many years (1983–1990). There are a number of reasons for this behaviour, such as surface sealing, variations in soil characteristics, and variation of antecedent soil moisture content between events. The parameters of the model could have been better estimated if the influence of these factors could be adequately evaluated and included.

Erosion depends on many factors. Among these, soil moisture and overland flow have an important role (Lal, 1990). Since the infiltration model controls the amount of overland flow, it also controls the sediment yield on both overland flow planes and channel elements. Hence, N_s influences not only overland flow but soil erosion as well, since a higher soil moisture content results in a weaker bond between particles, resulting in increased erodibility. Thus, an inverse relationship exists between N_s and sediment yield.

The validation procedure utilized here to test the applicability of the model in ungauged basins was to apply the estimated parameter values to another, similar basin. The results, as seen in Figs 3 and 4, show that agreement between simulated and observed values is good in the case of runoff, whereas for sediment yield, the differences are large, even though there is a fairly even dispersion around the measured values. The uncertainties involved in the prediction of surface erosion and sediment yield for individual events is large and consequently a wide range of variation in the predicted values is to be expected. Bearing this in mind, one can consider that the use of estimated parameters would provide a first estimate of the sediment yield accurate to within an order of magnitude.

CONCLUSIONS

The studies carried out in the experimental basin of Sumé indicate that the hydrological and erosional processes in the basin are quite complex. The varying soil conditions in the region significantly affect runoff and erosion rates. While there is room for improvement in measurement and modelling techniques, the present study provides support for the idea that process-based models and data from experimental basins can be combined effectively for the purpose of predicting runoff and erosion in ungauged basins. The model tested proved to be quite efficient in the prediction of runoff from individual events, even when the infiltration parameter is estimated purely as a function of an antecedent precipitation index. Further testing with additional data and in other basins would be necessary before the methodology utilized could be considered as generally valid.

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