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Evaluation of a physically-based model to simulate the runoff and erosion processes in a semiarid region of Brazil

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Abstract: A physically-based distributed model called *Catchment Hydrology Distributed Model*—CHDM, developed by Lopes (1995), was tested in an experimental basin, located in a representative semiarid region in northeastern Brazil. This model is a refinement of an earlier model, WESP, which has been found to simulate infiltration, runoff, and erosion processes well, in one dimension, within small-sized basins. Different from WESP, which is based on a simple mass balance that does not take into account the limiting transport capacity of flow, CHDM has a built in choice of six different transport capacity relationships. The model was evaluated utilizing the runoff and erosion data collected for natural rainfall events in the Sumé Experimental Basin, where erosion plots of 100 m^2 and micro-basins of about 0.5 ha were installed. The model proved to be consistent and useful for runoff and erosion prediction in the semiarid region of Brazil.

Key words physically-based models; runoff, semiarid region; soil erosion

INTRODUCTION

In order to simulate hydrological processes in a given basin several types of computational models have been proposed, developed, and applied to a variety of catchments over the past decades (Singh, 1995). Models are based on assumptions and a set of equations arranged in a certain fashion, which allows the simulation of hydrological processes. Among these, physically-based models have been successfully applied to assess the hydrologic responses in basins and to estimate the resultant runoff and sediment yield for a given rainfall event.

The equations intrinsic to physically-based models attempt to represent hydrological processes as closely as possible to the physical reality, making them a suitable tool to investigate the effect of catchment changes due to human activities or to climatic changes. However, their results are only as reliable as the model assumptions, inputs and parameter estimates. The quantification of runoff and sediment yield is a very important step in the management of the scarce water and soil resources of a semiarid region.

Because of the uncertainties involved in representing the actual runoff–erosion process, and also due to the large number of variables that govern the phenomenon, the development or identification of an appropriate model is very important, and is only possible when sufficient amounts of field-derived data are available. An event-oriented, physically-based, and distributed model, WESP (Lopes, 1987), has been successfully applied in a representative, semiarid region of Brazil to simulate the rainfall–runoff–erosion process (Srinivasan *et al.*, 2003). However, this model does not consider the limiting capacity of flow for transporting sediments. In order to overcome this deficiency, another model called CHDM (Catchment Hydrology Distributed Model; Lopes, 1995), which is an improvement over the WESP model, was developed. The CHDM incorporates six well-known sediment transport equations, which can optionally be used to limit the sediment production by erosion, based on maximum transport capacity.

THE CHDM MODEL

The CHDM (Lopes, 1995) is a physically-based, event-oriented, and distributed model that calculates runoff and sediment yield in small watersheds from a single rainfall event. The watershed is represented by a sequence of discrete planes and channel elements with planes contributing either laterally, or at the start of the channel elements. Each plane or channel element may be characterized by their unique parameters. The kinematic wave equations are used to describe the unsteady one-dimensional (1-D) overland flow as well as the channel flow.

Infiltration process

The infiltration process in the model is based on the Green and Ampt equation (1911):

$$f_c = K_s\left[1+\frac{G\phi(S_{\max}-S_i)}{F}\right] \tag{1}$$

where ϕ is the soil porosity, $S_{\max}$ is the maximum relative saturation, S_i is initial relative saturation, K_s is the saturated hydraulic conductivity (m s^{-1}), G is the effective value of the capillary head (m), and F is the cumulative infiltration (m). The initial relative saturation (S_i) is limited at the lower end by the value for residual saturation (S_r). Conceptually, the parameter G is a soil characteristic, and does not incorporate the effect of initial water content which is treated independently. The infiltration is also considered to occur during recession.

Upland and channel erosion processes

The mass balance equation for sediment transport in 1-D flow on hillslope and in channels is used to describe the sediment dynamics in the form (Bennett, 1974):

$$\frac{\partial}{\partial t}(C_s\, A)+\frac{\partial}{\partial x}(C_s\, Q)=e(x,t)+q_s\,(x,t) \tag{2}$$

where C_s is sediment concentration (kg m^{-3}), A is the cross-sectional area of flow (m^2), Q is the water discharge rate (m^3 s^{-1}), e is sediment flux into the flow (kg m^{-1} s^{-1}) due to erosion, and q_s is the lateral sediment inflow rate for channels (kg m^{-1} s^{-1}).

Erosion on planes

The erosion $e(x,t)$ for plane elements is assumed to be composed of two major components: soil particle entrainment by raindrop impact on bare soil (d_i), and erosion due to shear stress or deposition due to gravity (d_f). These are expressed as follows:

$$d_i = C_f \exp(-C_h h) ir \qquad \text{for } q>0 \tag{3}$$

where C_f and C_h are the erosion coefficients due to the raindrop impact. The CHDM assumes that for any given surface flow condition (velocity, depth, slope, etc.), there is an equilibrium concentration of sediments that can be carried, if the flow is steady, and:

$$d_f = C_g(C_{mx} - C_s)A \tag{4}$$

where C_{mx} is the sediment concentration at equilibrium transport capacity, $C_s = C(x,t)$ is the actual local sediment concentration, and C_g is a transfer rate coefficient for entrainment (s^{-1}) that must be estimated or calibrated. Alternatively, C_g is a function of the relative fall velocity of median size particles when deposition is occurring, i.e. when C_s exceeds C_{mx}.

Channel erosion

The general approach to sediment transport simulation for channels is nearly the same as for upland areas. The major difference in the equations is that entrainment by raindrop impact (d_i) is neglected in channel flow, and the term $q_s(x,t)$ representing lateral sediment inflows becomes a major sediment contributor. The total mass of sediment transported by the flow shall be less than or equal to the transport capacity of the flow, depending on the available supply. This can be calculated from any of the six equations (Meyer & Wischmeier, Yang, Bagnold, Ackers & White, Yalin and Engelund & Hansen) available in CHDM (Lopes, 1995). While the transport limit applies to surface flow as well, the model permits the choice of different equations with surface-flow and channel-flow conditions.

THE STUDY AREA

The data used in this study are from the Sumé Experimental Basin in Paraiba State, Brazil, located in the Sumé Representative Basin, which is typical of a large representative region of northeastern Brazil (Srinivasan & Galvão, 2003). The Experimental Basin was in operation from 1983 to 2001 during which runoff and sediment yields were obtained for many rainfall events, in erosion plots of 100 m^2 and micro-basins with areas ranging from 0.5 to 1 ha. Typical characteristics for the area are: erratic rainfall, a thin soil cover of the brown-non-calcic vertic type, and sparse vegetation. Data from two erosion plots, P1 and P4 (bare soil with a slope of 3.8 and 7%, respectively), and two micro-basins M3 (0.52 ha) and M4 (0.48 ha) (bare soil with a slope of 6.8 and 7%, respectively), were used for estimating parameters that could not be obtained otherwise, and for verification of the CHDM.

MODEL APPLICATION AND PARAMETER ESTIMATION

The CHDM model requires that the basin be represented geometrically by a set of plane and channel elements. In the present study, M3 was represented by 23 elements (16 planes and seven channels), and the M4 by 21 elements (17 planes and four channels). Each of the elements is characterized by a set of parameters; most of them based on physical characteristics, and others have to be either estimated or calibrated. In CHDM, parameters that need to be estimated or calibrated include: Manning's roughness parameter (n), saturated hydraulic conductivity (K_s), effective capillary head (G), initial relative saturation (S_i), maximum relative saturation ($S_{\max}$), transfer rate coefficient (C_g), erosion coefficients due to the raindrop impact (C_f and C_h), and some coefficients that are specific to the selected sediment-transport equations.

Based on the literature and previous modeling experience (Srinivasan & Galvao, 1995), Manning's roughness was fixed at 0.02 for planes and 0.03 for channels. Further, CHDM has a built in table that suggests values for K_s, G, and $S_{\max}$, according to the soil texture. According to Srinivasan *et al.* (2003), the soil texture in the basin is of the sandy-clay-loam type which led to the following values: $K_s = 4.3$ mm, $G = 263$ mm, and $S_{\max} = 0.83$. The values for S_i, C_g, C_f and C_h must be provided at the beginning of every simulation, and were estimated through a calibration process.

Parameter calibration

Parameter calibration was carried out by trial and error, such that the values for the parameters were adjusted until the calculated values of runoff and erosion were close enough to the observed values for each event. Since erosion is strongly dependent on the amount of runoff, the S_i parameter, which affects infiltration and hence, runoff, must be calibrated prior to estimating the erosion parameters. To determine the sediment transport equation best suited for the planes, CHDM was applied to plots P1 and P4, using a pool of more than 100 events. While the parameter C_g was calibrated for each of the events, the values of C_f and C_h were fixed at the limits suggested by Lopes (1995) at, $C_f = 100$ and $C_h = 300$; these values were maintained for all the planes.

In the case of erosion in plots P1 and P4, the Meyer & Wischmeier and Yalin equations appeared to provide the best results, whereas the other four were unsatisfactory. The coefficients of determination R^2 for calculated and observed sediment yields in the two cases were 0.89 and 0.86, respectively. In the case of the Meyer & Wischmeier equation, a coefficient has to be determined, and based on some initial trials, its value was fixed at 0.002.

For channel flow, a value for C_g is required. In order to obtain the best estimate of this parameter for the channel elements, data from the M3 micro-basin were utilized. Thirty events that occurred between 1984 and 1989, representing small, medium, and large runoff were selected. First, the value of S_i was optimized for each event to obtain a simulated runoff that was as close as possible to the observed one. Next, utilizing the mean value of C_g (0.02) obtained from the erosion plots for the plane elements, a channel element value for this parameter was optimized for each event by forcing the calculated sediment yields to come as close as possible to the measured values. Since the value of this parameter for planes had been fixed at the mean value of 0.02, this parameter had to be varied substantially, within the suggested range (Lopes, 1995) between the events, to obtain reasonably close calculated and observed sediment

Table 1 Values of runoff and sediment yield (observed and calculated in micro-basins M3 and M4).

No.	Date	S_i	Micro-basin M3				Micro-basin M4			
	dd/mm/yyyy		*OR* (mm)	*OE* (kg)	*CR* (mm)	*CE* (kg)	*OR* (mm)	*OE* (kg)	*CR* (mm)	*CE* (kg)
1	03/4/1984	0.810	3.22	191.22	3.26	197.27	0.84	5.48	3.19	247.56
2	21/2/1985	0.815	0.93	20.83	0.91	36.08	0.30	0.33	0.86	49.85
3	03/4/1985	0.810	2.81	119.78	2.69	215.35	2.14	257.04	2.65	277.58
4	24/4/1985	0.829	13.32	441.81	13.60	1556.68	11.90	1669.32	12.24	1626.46
5	03/5/1985	0.700	1.11	190.95	1.06	74.00	0.16	116.64	1.01	88.96
6	04/5/1985	0.823	2.67	622.15	2.22	134.97	1.44	412.80	2.53	212.15
7	05/6/1985	0.642	4.60	606.32	4.65	435.62	3.50	630.24	4.63	522.71
8	12/6/1985	0.710	3.24	284.10	3.28	291.14	4.21	95.52	3.26	353.61
9	03/3/1986	0.822	1.14	68.82	1.15	79.50	0.40	8.49	1.15	95.77
10	04/3/1986	0.080	2.49	160.68	2.62	317.85	5.58	162.24	3.92	504.97
11	05/3/1986	0.745	4.97	218.35	4.97	505.20	4.01	141.61	4.95	575.17
12	10/4/1986	0.720	8.60	1288.84	8.48	846.04	5.64	268.20	9.56	1171.23
13	15/4/1986	0.780	1.35	65.45	1.25	77.05	0.94	43.31	1.31	106.57
14	22/4/1986	0.810	4.22	342.94	3.49	318.29	3.45	144.80	4.18	467.19
15	2/5/1987	0.360	2.31	1214.52	2.28	172.72	1.07	154.65	2.31	223.28
16	28/6/1987	0.070	1.21	544.59	1.39	61.41	0.23	18.06	1.13	62.28
17	02/3/1988	0.758	4.64	571.51	4.76	476.19	1.62	323.08	4.80	487.42
18	09/3/1988	0.009	3.39	448.01	3.45	438.92	5.99	191.40	3.70	455.27
19	14/3/1988	0.773	5.67	1875.53	5.73	725.06	6.14	1967.82	6.18	798.76
20	19/3/1988	0.730	1.69	580.07	1.54	150.56	1.24	575.60	1.52	146.82
21	24/3/1988	0.630	13.52	4019.04	13.59	2242.88	8.78	2716.36	11.75	1884.40
22	05/4/1988	0.680	10.60	3615.40	10.60	1531.05	10.47	3299.76	10.68	1543.04
23	08/4/1988	0.600	7.23	1286.65	7.24	992.19	5.02	1340.66	6.81	875.09
24	20/4/1988	0.810	1.81	441.75	1.86	193.24	1.61	556.52	2.01	193.54
25	30/4/1988	0.520	5.36	887.39	5.37	687.68	5.40	631.80	5.44	672.50
26	06/5/1988	0.580	7.82	910.36	7.85	1019.35	6.66	657.62	8.27	981.23
27	23/6/1988	0.362	14.36	3278.87	14.58	2264.87	13.66	2666.56	14.11	2112.61
28	01/3/1989	0.600	6.75	941.85	6.96	938.07	6.98	1123.13	7.98	1073.18
29	22/3/1989	0.750	20.60	2699.88	20.66	2362.67	18.53	2820.22	21.52	3277.83
30	16/4/1989	0.619	27.97	4397.26	27.83	4274.66	26.73	5706.67	28.77	4889.13

Si: initial relative saturation; *OR*: observed runoff; *OE*: observed erosion; *CR*: calculated runoff; *CE*: calculated erosion.

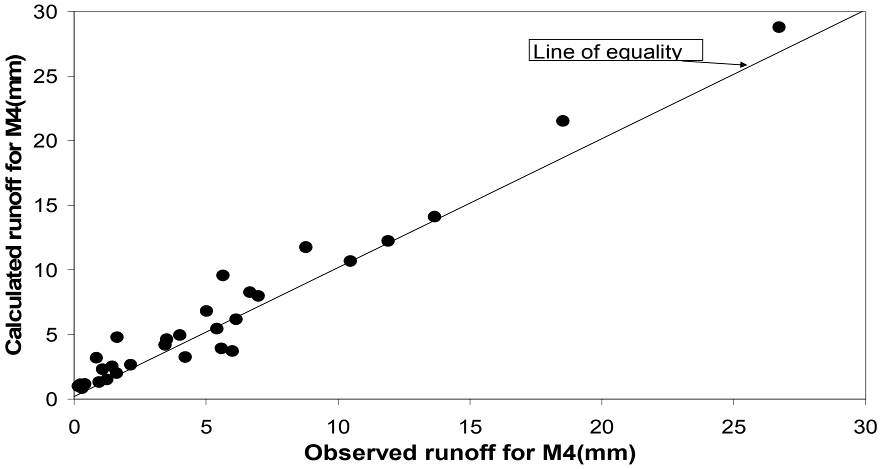

Fig. 1 A comparison between observed and calculated runoff for micro-basin M4.

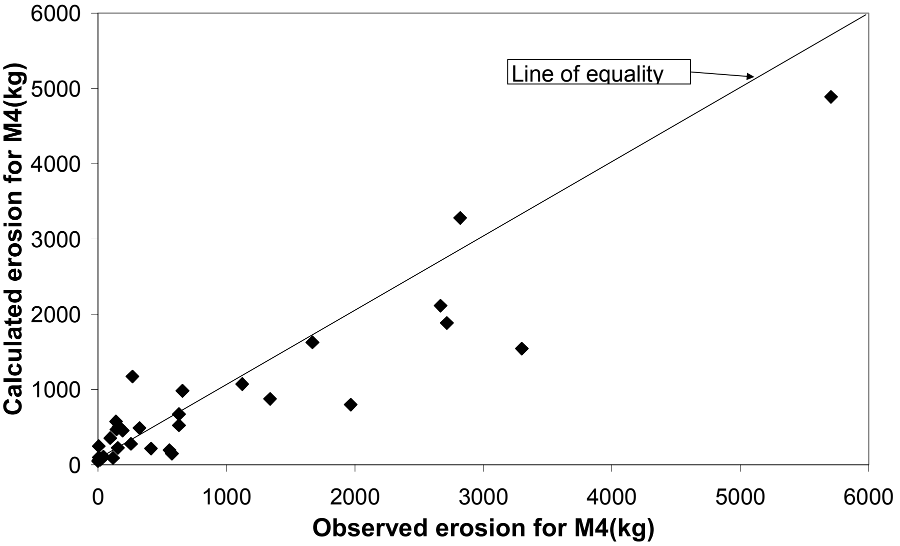

Fig. 2 A comparison between observed and calculated sediment yield for micro-basin M4.

yields. The Yang's transport equation provided the best results for channels, whereas the Meyer & Wischmeier and Yalin equations resulted in highly exaggerated channel erosion. A mean value of 0.08 for C_g appeared to produce the best results for channels. Once all the mean values for the requisite parameters had been established, all the events were simulated again. A comparison of the observed and the simulated values of runoff and sediment yield for M3 are shown in Table 1. The R^2 values for the calculated runoff and sediment yields were 0.99 and 0.77, respectively.

Model validation

Several alternatives are possible for validating a model (Ewing & Parkin, 1996). Here, the proxy-catchment test was applied, and consisted of using the calibrated parameters for one basin in another one. Since initial soil saturation is an important parameter, and varies from event to event, it is necessary that similar conditions exist in both the proxy and calibrated catchments. Thus, micro-basin M4, located within the Experimental Basin and close to M3, was an ideal choice. In order to test the calibrated model, the same 30 events utilized in M3 were simulated in M4. For these events, the values of S_i that were obtained in M3 (event by event) were utilized. The erosion parameters were the mean values obtained in M3. Thus, runoff and sediment yield were calculated for all the events, and the measured and calculated values compared (Table 1). The R^2 values for calculated runoff and sediment yields were 0.95 and 0.85, respectively (Figs 1 and 2).

RESULTS AND DISCUSSION

The 30 events used for parameter calibration and estimation are spread over several years and include dry, wet, and very wet years. These changes were reflected in the values of S_i and C_g, which varied over a wide range. As an event-based model, CHDM does not carry forward the antecedent soil water condition between events, and thus, requires a value of S_i to be established at the beginning of each event. For some events, S_i reached either the minimum (residual saturation) or the maximum limit (close to saturation), without being able to simulate the observed runoff. Effects such as the sealing of surface pores that prevent continued infiltration, and preferential flow paths along cracks and vegetation that drain at a rate higher than the uniform rate calculated by the model, seem to be the most probable causes for these situations. Further, the assumptions of a homogeneous soil layer with a uniform advance of the wetting front, with ponding at the surface when runoff begins, are not fully valid and these effects sometimes generate unrealistic variations in S_i. However, in most cases, the model was able to predict the runoff values quite satisfactorily.

The strong influence of the initial soil saturation parameter S_i can be seen from the simulated runoff values in the M4 micro-basin. In this case, the same values of the parameter that were obtained from each of the events in M3 were utilized in the calculation of the resulting runoff in M4. In spite of this, most of the simulated runoff values for M4 were slightly higher than the observed ones, indicating that the local soil saturation in this basin is a bit lower than that of M3. However, the very high R^2 (0.95) between calculated and observed runoff seems to attest to the similarities in the hydrological processes at work in both cases.

In simulating slope and channel erosion and sediment yield, the model proved to be quite sensitive to the value selected for the erosion parameters $C_{g.}$ It can be seen from Table 1 that the sediment yields calculated using the mean value for this parameter, for all the M3 calibration events, deviated substantially from the measured values, even though individually during calibration, it was possible to obtain values close to the measured ones. However, the validity of this mean value, as a reasonable representative one, was borne out in the simulations of the events in M4, a neighbouring micro-basin with similar physical and soil characteristics. The R^2 between simulated and measured sediment yields was 0.85, even higher than the 0.77 obtained for M3.

The option of selecting one of the six transport capacity equations built into the CHDM model appears quite helpful. It is well known that various transport capacity equations can produce highly variable results. Hence, it is possible that for a given set of field conditions, where the theoretical assumptions of the model are never completely satisfied, one of the equations may prove to be significantly better than the others. In the present case, only Yang′s equation provided satisfactory results for channel transport. For sediment transport on the plane slopes, either Yalin’s or Meyer & Wischmeier (also known as the tractive force equation) equations were found adequate. The WESP model (Lopes, 1987), which also has been tested in the region (Srinivasan *et al.*, 2003), does not consider the limiting capacity of flow for transporting sediments. Hence, it would be more applicable for situations in which the sediment yield from a basin is supply-rather than flow-limited. Since CHDM takes this aspect into account, it appears to be more versatile than WESP.

It can be seen from Table 1 that the M3 and M4 micro-basins can generate sediment yields that are distinctively different, or quite similar. M3 and M4 are located near each other, and have almost the same area and similar physical conditions. The slight variation in topography between the two cannot explain the large differences that are seen, in some cases. This underlines the complexity of the erosion process itself, and the problems involved in using simplified models to simulate it. The difficulties involved in correctly measuring sediment yield cannot be understated either. In the present study, the sediment yield was obtained by measuring the average sediment concentration from various samples, and any small error in the value of the concentration could result in a large difference in the yield, when multiplied by the runoff volume (see Srinivasan *et al.*, 1988; Srinivasan & Galvão, 2003 for details regarding the sampling procedure). Under such circumstances, the results obtained from the CHDM model appear more than satisfactory.

CONCLUSIONS

A physically-based runoff–erosion model, CHDM (Lopes, 1995), has been tested with data from two micro-basins in a semiarid region of Brazil. Model parameters were established based on observations in one basin, and subsequently used to satisfactorily simulate runoff and erosion in the other one. The model proved useful as a predictive tool for estimating runoff and sediment yields from small basins. The model allows the selection of one of six different transport capacity equations; this proved to be very useful during calibration, and in establishing an appropriate range for various input parameters. The model is sensitive to relatively small changes in the values for various input parameters; hence, it may be difficult to obtain accurate estimates of runoff and sediment yield from individual events using representative or single parameter values. The performance of the model also needs to be tested in larger basins to evaluate possible scale effects.

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