Evaluation of optimized parameter values of a distributed runoff–erosion model applied in two different basins

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Abstract A distributed, physically-based, and event oriented runoff–erosion model called WESP (Watershed Erosion Simulation Program) has been used to model the runoff and erosion processes in the micro-basins of the Sumé Experimental Basin by calibrating the parameters of the model with local data. In order to obtain regional estimates of these parameters, the model was applied to the data from an erosion plot in another experimental basin within the same region. Optimum values for the model parameters were obtained utilizing a genetic algorithm named SCE-UA (Shuffled Complex Evolution–University of Arizona). The study shows that the parameter values are close to each other, and regional estimates of the parameters could make the model an efficient predictive tool for ungauged basins in the region.

Key words optimization of parameters; runoff–erosion simulation; WESP model

INTRODUCTION

Predicting runoff and sediment yield in basins is quite a challenging task, and physically-based distributed models seem to be well suited for this purpose. In this context, models based on kinematic wave assumptions have been used widely. Physically-based distributed models have the advantage of taking into account the spatial variability of basin characteristics while considering the fundamental processes involved.

A major problem associated with using physically-based models to predict/estimate erosion processes is the estimation of model parameters that cannot be directly measured in the field. Optimization techniques have been used in the past during the calibration of such erosion models, but it is difficult to assure that the final parameter values are not the result of a local minimum. Thus, robust algorithms are needed in such models. Some of the most robust algorithms used are the evolutionary algorithms, which represent a general form used to describe computer-based problem solving systems that employ computational models of evolutionary processes as key elements in their design and implementation. A variety of evolutionary algorithms have been proposed (e.g. genetic algorithm, evolutionary programming, evolution strategies, classifier systems, and genetic programming). They all share a common conceptual base by simulating the evolution of individual structures via processes of selection, mutation, and reproduction. In the parameter calibration process, the algorithm most used is the genetic algorithm, which is an approach to solving problems that are not yet fully characterized, or too complex to allow full characterization, but for which some analytical evaluation is available. These are problems where a method for obtaining a good solution is unknown, but the relative value of potential solutions can be evaluated by some quantifiable measure. The problems encountered in the optimization process of physically-based erosion models are very much the same. This global and evolutionary optimization procedure has been used in the present investigation, for estimating values for various parameters required by WESP (Lopes, 1987; Lopes & Lane 1988), in two different experimental basins in a semiarid region of Brazil. An attempt also was made to verify the regional applicability of WESP, using the parameters thus obtained.

SUMMARY OF THE WESP MODEL

Lopes (1987) developed a physically-based distributed model called WESP, which computes runoff and sediment yield based on kinematic wave approximations for surface flow due to excess rainfall intensity r_e (m s^{-1}), which is obtained by subtraction of the infiltration rate $f(t)$ from the rainfall intensity I, i.e. $r_e = I - f(t)$. The model was developed for small basins, and is intended to produce both a hydrograph and an accompanying sedigraph. The infiltration process is modelled with the Green-Ampt equation, which can be written in the form of:

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

where K_s is the effective saturated soil hydraulic conductivity (m s^{-1}), $F(t)$ is the cumulative depth of infiltrated water (m), and N_s is the moisture-tension parameter (m). The surface flow is considered to be either the overland flow on planes, or channel flow.

Spatially varied overland flow is considered one-dimensional, and is described by Manning's turbulent flow equation:

$$u = \frac{1}{n} R_H^{2/3} S_f^{1/2} \tag{2}$$

where u is the local mean flow velocity (m s^{-1}), $R_H(x,t)$ is the hydraulic radius (m), S_f is the friction slope, and n is the Manning friction factor. Thus, the local velocity for plane flow can be obtained considering the hydraulic radius equal to the depth of flow ($R_H = h$), and using the kinematic wave approximation resulting in the friction slope being equal to the plane slope ($S_0 = S_f$) as:

$$u = \alpha' h^{m'-1} \tag{3}$$

where h is the depth of flow (m), α' is a parameter related to surface slope and roughness, equal to $(1/n)S_0^{1/2}$, and m' is a geometry parameter whose value is set to 5/3 for wide rectangles.

The equation of continuity for a one-dimensional plane can, then, be written:

$$\frac{\partial h}{\partial t} + \alpha' m' h^{m'-1} \frac{\partial h}{\partial x} = r_e \tag{4}$$

From equations (3) and (4), the overland flow velocity and depth (u, h) can be calculated for a given rainfall excess r_e. The beginning of surface runoff is obtained by determining the ponding time (t_p) for an unsteady rain.

Sediment transport is considered as the erosion rate in the plane, reduced by the deposition rate within the reach. Erosion occurs due to raindrop impact, as well as surface shear. Thus, the continuity equation for sediment transport is expressed as:

$$\frac{\partial (ch)}{\partial t} + \frac{\partial (cuh)}{\partial x} = e_I + e_R - d \tag{5}$$

where c is the sediment concentration in the surface flow (kg m^{-3}), e_I is the rate of sediment erosion due to rainfall impact (kg m^{-2} s^{-1}), e_R is the erosion rate due to shear stress (kg m^{-2} s^{-1}), and d is the rate of sediment deposition (kg m^{-2} s^{-1}). The rate of sediment erosion due to rainfall impact e_I is a function of the rate of detachment by raindrop impact, and the rate of transport of sediment particles by shallow flow, and is expressed:

$$e_I = K_I I r_e \tag{6}$$

where K_I is the soil detachability parameter (kg s m^{-4}). The rate of sediment erosion due to shear stress e_R is expressed by an entrainment rate proportional to a power of the average shear stress acting on the soil surface as:

$$e_R = K_R \tau^{1.5} \tag{7}$$

where K_R is a soil erodibility factor for shear (kg m N$^{-1.5}$ s^{-1}), and τ is the effective shear stress (N m^{-2}), which is given by $\tau = \gamma h S_f$, γ being the specific weight of water (N m^{-3}). Entrainment and sediment transport occur when the erosive forces exceed the resisting forces. Water flowing over the soil surface exerts shear forces on the soil particles that tend to move or entrain them. On a bare soil surface, or in stream beds, the forces that resist erosion due to flowing water depend on the size and the distribution of the sediment particles. For coarse sediments, the forces resisting entrainment are mainly frictional, and depend on the weight of the particles. Finer sediments, that contain appreciable fractions of silt or clay, or both, tend to be cohesive, and resist entrainment mainly due to cohesion rather than friction. Also, in fine sediments, groups of particles (aggregates) get entrained as single units, whereas coarse, non-cohesive sediments are moved as individual particles. Thus, the amount of entrainment is related to the magnitude of the total shear stress as expressed in equation (7), rather than to a "critical" shear stress. Finally, the rate of sediment deposition d in equation (5) is not only the deposition of the particular sediment, per unit area and per unit time, but also represents the rate at which the column of suspended sediment loses solids, per unit time, and is expressed as:

$$d = \varepsilon_p V_s c \tag{8}$$

where ε_p is a coefficient that depends on the sediment and fluid properties, set to 0.5 in the present study, $c(x,t)$ is the plane sediment concentration in transport (kg m^{-3}), and V_s is the particle fall velocity (m s^{-1}).

Channel flow

The concentrated flow in the channels also is described by continuity and momentum equations. The momentum equation can be reduced to the discharge equation with the kinematic wave approximation as:

$$Q = \alpha' A R_H^{m'-1} \tag{9}$$

where Q is the discharge (m^3 s^{-1}), and A is the cross-sectional area of flow (m^2). The continuity equation for channel flow is given by:

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = q_A \tag{10}$$

where q_A is the lateral inflow per unit length of channel. Equations (9) and (10) enable the calculation of channel flow. Since the effect of rainfall impact is negligible in the channel, the continuity equation for sediment is expressed, without the rainfall impact component, by:

$$\frac{\partial AC}{\partial t} + \frac{\partial CQ}{\partial x} = q_s + e_r - d_c \tag{11}$$

where $C(x,t)$ is the sediment concentration in transport in the channel (kg m^{-2}), q_s is the lateral sediment inflow into the channel (kg m^{-1} s^{-1}), d_c is the rate of sediment deposition in the channel (kg m^{-1} s^{-1}), and e_r is the erosion rate of the channel bed material (kg m^{-1} s^{-1}). The components of the net sediment flux for the channel segment are given as follows: the erosion rate of the channel bed material e_r, is obtained from a general equation initially developed for bed-load transport capacity (Croley, 1982; Foster, 1982):

$$e_r = a(\tau - \tau_c)^{1.5} \tag{12}$$

where a is the sediment erodibility parameter, and τ_c is the critical shear stress for sediment entrainment (N m^{-2}), which is given by $\tau_c = \delta(\gamma_s - \gamma)d_s$, where δ is a coefficient, set to 0.047 in the present study, γ_s is the specific weight of sediment (N m^{-3}), and d_s is the mean sediment diameter (m).

The rate of sediment deposition within the channel d_c (kg m^{-1} s^{-1}) in equation (11) is expressed by:

$$d_c = \varepsilon_c T_W V_s C \tag{13}$$

where ε_c is the deposition parameter for channels, considered as unity in the present case based on the study of Einstein (1968), and T_W is the top width of the channel flow (m). From equation (11), sediment transport rate (CQ) can be calculated for overland flow with A and Q obtained from equation (10).

THE SCE-UA METHOD

In general, a good optimization technique is characterized by: (a) global convergence in the presence of multiple regions of attraction; (b) ability to avoid being trapped by small pits and bumps on the objective function surface; (c) robustness in the presence of differing parameter sensitivities and parameter interdependence; (d) non-reliance on the availability of an explicit expression for the objective function or the derivatives; and (e) capacity of handling high-parameter dimensionality.

The SCE-UA method embodies the desirable properties described above and is based on a synthesis of four concepts: (a) combination of deterministic and probabilistic approaches; (b) systematic evolution of a "complex" of points spanning the parameter space, in the direction of global improvement; (c) competitive evolution; and (d) complex shuffling. The synthesis of these elements makes the SCE-UA method effective and robust, and also flexible and efficient. The steps of the SCE-UA method are: (i) randomly generate a sample of *s* points, rank the points according to the order of increasing criterion, and partition of the sample into *p* complexes (communities) with the first point in the first complex, the second point in the second complex and so on; (ii) evolve each complex independently according to the competitive complex evolution (CCE) algorithm based on the Simplex downhill search scheme of Nelder & Mead (1965); (iii) shuffle the complexes; and (iv) check if any of the pre-specified convergence criteria are satisfied, if so stop, otherwise, check the reduction in the number of complexes and continue to evolve. Further details about this method, and a modified version are available in Duan *et al.* (1992) and Santos *et al.* (2003).

THE STUDY AREA

The WESP model has been utilized before to simulate runoff and erosion in the micro-basins of the Sumé Experimental Basin (Santos *et al*., 2003). In order to obtain a regional estimate of the parameters for this model, data from a bare plot in the São João do Cariri Experimental Basin have been used in this study. The plot has an area of 100 m^2 (4.5 m × 22.2 m), and a mean slope equal to 3.8%. This experimental basin is located in a typical semiarid area of Brazil within the same hydrological region of Sumé, with similar climate, soil, and vegetation.

CALIBRATION AND SIMULATIONS

In the WESP model, the basin is represented as a cascade of planes and channels. Among the various parameters involved in the plane and channel processes, the values of some are known, some are adopted, *a priori*, and the rest are determined by calibration. Santos *et al.* (2003) used a representation of 10 elements made up of seven planes and three channels for the micro-basin in the Sumé Experimental Basin. The erosion plot in São João do Cariri would be a single plane.

Selection of SCE-UA algorithm parameters

The SCE-UA method contains many probabilistic and deterministic components that are controlled by various algorithmic parameters. For the method to perform optimally, these parameters must be chosen carefully. The first one is *m*, the number of points in a complex ($m \geq 2$), which should be neither too small, that would make the search an ordinary Simplex procedure, nor too large, to avoid excessive use of computer processing time, when there is no certainty of its effectiveness. The default value of $m = 2n' + 1$ was selected in which n' is the number of parameters to be optimized. For the number of points in a subcomplex q, that have a value greater than or equal to two, and less than or equal to m, the value of $n' + 1$ was selected because it would make the subcomplex a Simplex, which defines a first-order approximation (hyperplane) of the objective function surface and will give a reasonable estimate of the local direction of improvement. The number of consecutive offspring generated by each subcomplex α, whose value must be greater than or equal to one, was set to one, to avoid the search becoming more strongly biased in favour of a local search of the parameter space. The number of evolution steps taken by each complex β (any positive integer value) was set to $2n' + 1$ to avoid a situation in which complexes would be shuffled too frequently if set to too small a value, or to avoid shrinking it into a small cluster, if a large value was used. The number of complexes p, was set to 2, based on the physical nature of the problem, and the minimum number of complexes required in the population $p_{\min}$, which should be a value greater than or equal to one, and less than or equal to p, was set to p because it gave the best overall performance in terms of effectiveness (the ability to locate a global optimum), and efficiency (the speed to locate a global optimum).

Optimization of the model parameters

The parameters whose values are fixed, *a priori*, regardless of location, are the Manning friction factor, which was assumed as 0.02 for planes, and 0.03 for channels, based on the soil type, its grain size composition and surface characteristics, the specific weight of water (9.8 kN m^{-3}), and the specific weight of sediment (2.6×10^4 kN m^{-3}). However, there are some parameters that should be specific to the study area, and should be determined by field tests, such as the saturated soil hydraulic conductivity K_s whose average value was set equal to 5.0 mm h^{-1}, and the mean diameter of the sediment d_s, whose value was assumed to be equal to 0.50 mm. The parameters whose values can not be readily established or measured, need to be determined by calibration, preferably, with an optimization routine.

There are four such parameters in WESP. The first is the soil moisture-tension parameter N_s from equation (1), as well as the remaining three parameters (a, K_R, and K_I) that are related to the erosion process. The first one (a) applies to channel erosion, and the other two (K_R and K_I) to plane erosion. Since there are no universally applicable values for these three erosion parameters, they were optimized using the SCE-UA method. The range in which these parameters could vary was chosen to be a (0.0001–0.1 kg m^2), K_R (0.1–20.0 kg m $N^{-1.5}$ s^{-1}) and K_I (0.1×10^8–100.0×10^8 kg s m^{-4}), based on the recommendation of the author (Lopes, 1987). In the case of an erosion plot, there are only two parameters to be optimized (K_R and K_I). In general, for basins with a large number of plane and channel elements, it would be better to optimize the moisture-tension parameter N_s first, and then in a second stage, optimize the erosion parameters to minimize the relative error in each event. For the micro-basin of the Sumé Experimental Basin, this procedure was adopted as the flow is routed through several elements, and any error in the flows could result in unrealistic erosion values.

In the case of the erosion plots, there being no such risk, all three parameters were optimized at the same time. The optimal values of the parameters for each of the events were obtained by minimizing the combined relative error, shown in equation (14), in which, E_o and E_c are the observed and calculated sediment yields, respectively, in kg, while, L_o and L_c are the observed and calculated runoff depth (mm), respectively.

$$J' = \left| \frac{E_o - E_c}{E_o} \right| + \left| \frac{L_o - L_c}{L_o} \right| \tag{14}$$

RESULTS AND DISCUSSION

For the erosion plot of São João do Cariri, about 50 precipitation events that occurred between March 1999 and June 2002 were individually calibrated for runoff and erosion. For all the events, the starting values of the three parameters were the same, and the optimal values obtained for each event are shown in Table 1. The moisture-tension parameter N_s depends on the antecedent soil moisture conditions, among other things, and hence, varies from event to event, and its mean value can not be considered as a representative parameter value. When more regional data become available, it is likely that a relationship between this parameter and an antecedent precipitation index can be established for different types of soils and vegetative covers. The variations were found to be very similar to those observed in the micro-basin of the Sumé Experimental Basin for about 40 calibrated events. Whereas the range for this parameter at Sumé was 0.002–88.31 mm, with an average value of 13.41 mm, it varied from 0.25 to 75.56 mm with an average value of 12.74 mm for the erosion plot at São João do Cariri. These figures indicate the similarity of the two basins, in terms of runoff processes.

The erosion parameters K_R and K_I also showed similar trends for both Sumé and São João do Cariri. It has been observed that the rainfall impact erosion parameter K_I is relatively insensitive with very high values, and can be conveniently fixed at a single value (Srinivasan *et al.*, 2003). It also can be seen that it varies in a narrow range from about 0.1×10^8 kg s m^{-4} to about 9.5×10^8 kg s m^{-4}, with an average value of 4.01×10^8 kg s m^{-4} (Table 1). In the case of Sumé, the average value was 6.19×10^8 kg s m^{-4}. In spite of being an insensitive parameter in the region, it is of the same order of magnitude, and thus, easily could be represented by a single regional value, for predictive purposes, in ungauged basins of the region.

In the case of the other erosion parameter K_R, the variation also is fairly small, and ranges from about 0.1 to about 5.0 kg m N$^{-1.5}$ s^{-1} with an average value of 1.05 kg m N$^{-1.5}$ s^{-1} (Table 1). In the case of Sumé, it varied from about 0.8 to about 4.2 kg m N$^{-1.5}$ s^{-1} with an average value of 2.53 kg m N$^{-1.5}$ s^{-1}, indicating a fairly large variation between the two basins, in spite of being in the same range and order of magnitude. This parameter applies only to erosion on planes, and is a fairly sensitive one. It has been observed that this soil erodibility parameter is affected by antecedent soil moisture conditions and other physical factors such as the slope (Srinivasan *et al.*, 2003). Hence, it is unlikely that this parameter can be regionally represented by a single value. However, if this parameter can be adequately correlated to such local physical factors as slope, length of ramp, and perhaps, a soil moisture index, it should be possible

Table 1 Simulation results and optimized parameters for erosion plot 1.

Date	N_s (mm)	K_R (kg m $N^{-1.5}$ s^{-1})	K_I (10^8 kg s m^{-4})	E_c (kg)	L_c (mm)
14 March 99	35.22	2.9433	4.2167	0.8561	1.425
18 March 99	6.78	2.5763	4.2450	0.3405	0.870
01 May 99	18.43	0.7812	9.6072	1.0737	1.890
05 May 99	11.18	0.7613	6.0983	0.9084	1.789
14 May 99	7.67	0.8711	6.4914	0.9837	2.037
22 May 99	40.86	4.8994	5.3004	0.1673	0.363
06 June 99	1.73	1.0224	5.0619	0.0923	1.200
24 December 99	0.42	0.1668	1.2587	2.9900	6.600
29 December 99	0.29	2.6864	6.9214	3.9300	3.409
07 January 00	30.98	0.8660	2.1039	19.3700	22.920
16 January 00	6.48	2.8867	1.0084	6.5050	6.600
17 February 00	11.45	0.3849	5.4028	5.1000	9.060
18 February 00	24.10	0.6345	2.2668	0.4250	1.235
01 March 00	4.73	0.1648	1.9191	2.9080	8.070
02 March 00	10.61	0.2215	5.1378	2.0740	3.150
19 March 00	75.56	0.7707	3.1153	7.3010	12.030
29 March 00	7.54	0.3892	6.6924	8.8970	12.180
30 March 00	6.50	1.1233	7.0071	8.9900	10.560
31 March 00	25.34	0.1245	0.7752	7.4100	18.350
08 April 00	9.08	0.3243	2.6291	6.3600	11.870
11 April 00	7.23	0.7531	3.1855	8.4200	8.646
12 April 00	49.61	0.2764	8.1898	17.9400	24.997
25 April 00	6.98	0.4726	6.1734	0.3675	1.350
05 May 00	8.47	0.1154	0.5938	1.0340	10.642
18 May 00	11.44	0.1003	0.1028	0.7253	6.720
26 June 00	4.79	0.2490	1.6061	1.4198	6.683
11 July 00	3.32	0.1060	1.5371	0.5300	6.683
15 July 00	0.99	1.6965	4.2522	0.6940	1.950
08 March 01	30.84	0.4674	0.6308	2.2236	8.610
11 March 01	0.32	0.2678	8.2315	0.8787	4.977
27 March 01	31.88	0.1371	1.1538	8.4524	23.440
02 April 01	0.25	0.9939	6.0894	3.3847	3.663
02 July 01	0.39	2.7643	5.1141	0.0074	0.148
12 August 01	4.89	1.5677	4.8858	0.0025	0.090
22 August 01	1.11	0.1148	3.6278	0.0465	1.413
29 December 01	7.20	0.3577	1.7572	1.9283	4.650
10 January 02	1.90	0.2623	5.7804	1.0118	3.750
05 February 02	2.11	0.7459	1.0499	0.3996	1.350
13 February 02	1.04	1.2079	6.5430	0.2700	0.900
15 February 02	36.22	0.0830	0.1464	7.1582	28.320
04 March 02	10.76	0.9286	2.1581	6.1695	5.100
06 March 02	13.91	0.4187	0.7760	12.7600	32.370
18 March 02	10.03	0.4501	5.5607	1.2947	2.732
10 May 02	1.64	5.0981	3.4319	0.0016	0.020
26 May 02	2.57	3.2629	6.6986	0.0021	0.070
07 June 02	1.05	1.0136	8.0151	0.5113	2.150
Mean values	12.74	1.0546	4.0120	3.5721	7.11

to obtain applicable values for this parameter, within a homogenous hydrological region. The channel erosion parameter *a*, obtained only for Sumé, showed only a very small variation in its range, and essentially would be dependent on the type of soil in the basin. The average value observed in Sumé was 0.053 kg m^2; some additional data, from other basins, would be necessary to confirm whether this can serve as a regional value.

CONCLUSIONS

In order to optimize the parameter values of the process-based distributed runoff–erosion model WESP, a genetic algorithm SCE-UA (Duan *et al.*, 1992) was used. The results show that this evolutionary algorithm is quite robust and efficient. The model parameters were estimated in two different basins and the results show that it is possible to obtain regionally representative values for many of them. It was noted that although the averages may be close in the case of some of the other parameter values, a single representative value may not be regionally applicable. However, by associating the variation of these parameter values with such physical factors as a soil moisture index and/or topographical features, it could be possible to obtain good estimates within homogenous regions. Thus, it would be quite practical to consider using a model like WESP as a predictive tool for estimating runoff and erosion in ungauged basins in the semiarid region of Brazil, as investigated in this study.

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