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Relationship between simulated sediment yield and scale in a semiarid region of Brazil

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Abstract The runoff and sediment yield processes in a representative basin located in the semiarid region of Northeast Brazil (SeNeB) were modelled with the physically based and spatially distributed model SHETRAN. Field data were used to parameterize, test, validate, and simulate the runoff and sediment yields. The model parameters were tested at plot area scales (100 m^2) and then used to simulate larger catchments (0.5 ha–140 km^2) with different grid resolutions. The results achieved at every basin scale and grid size showed that observed runoff and sediment yields were simulated with physically meaningful results. Similar results were produced with different grid size resolutions applied to the larger catchments, but peak discharges, annual volumes, and sediment yields varied with the land use, rainfall regime, and basin area. Simulated sediment yields decreased as basin area increased, and relationships were established for different conditions of land use and rainfall.

Key words scale effect; sediment yield; semiarid; uncertainty

INTRODUCTION

In dry lands, soil erosion is markedly affected by climatic variability, and reduction in plant cover (Williams & Balling, 1996). Sahin & Hall (1996) showed that reduction in vegetative cover may increase the water yield by 17–40 mm. Vegetation provides natural protection against soil erosion. The soil loss rates may range between 0.1 and 60 000 t km^{-2} year^{-1} (Lal, 1993, 1994; Pimentel, 1993; Walling, 1994) depending on the region and climate. Sediment yield decreases as catchment area increases as a result of complex interactions between sources and sinks (Walling & Kleo 1979; Walling, 1983; Julien & Frenette, 1986).

It is important to note that works on the effects of scale in sediment yield modelling, using advanced technology, are scarce. In this study, the physically-based and spatially-distributed model SHETRAN (Ewen *et al.*, 2000) was parameterized and used to simulate the processes of runoff and sediment yield at scales varying from plots (100 m^2), to micro-basins (0.5–1.0 ha), to catchments (10–140 km^2) in the semiarid region of the state of Paraiba, Brazil. Model parameters were tested at the plot scale, upscaled to the larger basins, and the uncertainties evaluated. Simulations considering variations in precipitation and land use were analysed, and relationships between simulated sediment yields and scale established. This paper reports the modelling approaches and their results.

SHORT DESCRIPTION OF SHETRAN

SHETRAN is a physically-based and spatially-distributed model that simulates the major processes of the hydrological cycle. An orthogonal grid network is used to represent the spatial distribution of the processes. The rate of interception is calculated with the equation of Rutter *et al.* (1971/1972). Actual evapotranspiration can alternatively be calculated from a relationship between the ratio of actual to potential evapotranspiration and soil tension (e.g. Feddes *et al.*, 1976). Flow in the unsaturated zone (UZ) is calculated with Richards equation (1931). The equations of Saint Venant (1871) are used for determining overland and channel flows, with flow velocity based on the Manning (1895) equation. Flow in the saturated zone (SZ) is determined with the Boussinesq (1904) equation. Soil erosion consists of soil detachment by rainfall and runoff. Sediment transport is based on the mass conservation equations, and flow transport capacity on the equations of Yalin (1963) and/or Engelund Hansen (1967). Bathurst *et al.* (1995) give details on the model equations.

THE REPRESENTATIVE BASIN OF SUMÉ (RBS)

The representative basin of Sumé (137.4 km^2) is located in the SeNeB (Fig. 1) and has two sub-basins, Umburana (10.7 km^2) and Jatobá (26.8 km^2), where daily flows were observed from 1975 to 1980 (Cadier & Freitas, 1982). Within Umburana, four micro-basins, M1 to M4 (0.5–1.0 ha, ~7% slope), and nine plots, P1–P9 (100 m^2, 4–9% slope), were monitored (flow and sediment) from 1982 to 1988 (Cadier *et al.*, 1983). At these sites, the soils are shallow, with low permeability and two horizons: A (0.1 m; 0.31 m day^{-1}; 50.2% sand, 15.8% clay) and B (0.7 m; 0.03 m day^{-1}; 50.2% sand, 32.5% clay). At specific sites, deeper and more permeable soils (~ 2 m; 8 m day^{-1}) can be found. The vegetation is Caatinga (bushes and typical trees). Annual pan evaporation is 2500 mm. Mean annual precipitation is 600 mm (Cadier, 1996).

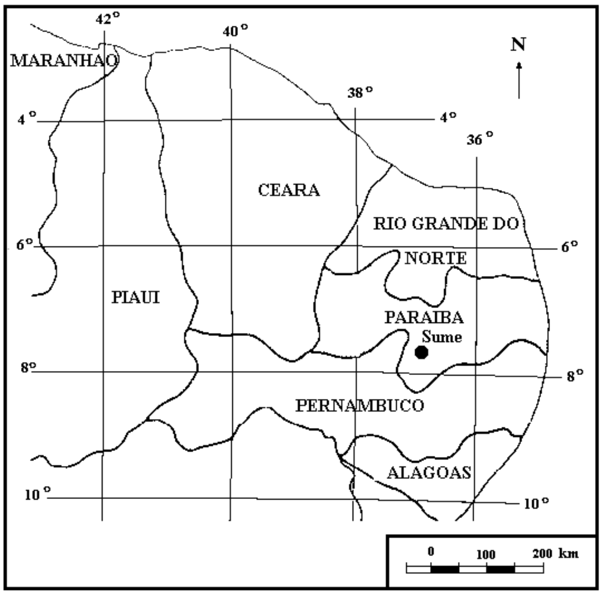

Fig. 1 The Northeast region of Brazil.

MODELLING APPROACH

Model parameters and functions were determined for the catchments, soils, and relevant processes in the semiarid zone of the SeNeB. The SZ was not considered because in the study region, overland flow is mainly hortonian. The catchments were modelled using different grid resolutions. For the plots, a single grid cell was set. Break-point precipitation and daily pan evaporation were taken from observed data (1982–1988 for plots and micro-basins, and 1977 for the RBS). Interception was modelled considering the proportions of ground cover (Cadier *et al.*, 1983) and the canopy parameters of Rutter *et al.* (1971/1972) set according to Jetten (1996). Evapotranspiration was determined by fixing the function between the ratio of actual to potential evapotranspiration and soil tension (Denmead & Shaw, 1962) considering that actual evapotranspiration is zero when the soil tension is at its wilting point and it is at its potential evapotranspiration when the soil tension is at its field capacity. Potential evapotranspiration was set based on data from pan evaporation. The relationship between soil tension and soil moisture was calculated with the equations of Saxton *et al.* (1986). The Brooks & Corey (1964) infiltration parameters (saturated hydraulic conductivity, residual and saturated moisture content, and the Averjanov (1950) exponent) were determined (horizons A and B) based on soil characteristics (e.g. Mualem, 1978; Saxton *et al*, 1986; Rawls & Brakensiek, 1989). The Manning-Strickler roughness coefficients (overland and channel flow) were set based on data in the literature (e.g. Chow, 1959; Woolhiser, 1975; Engman, 1986; Wicks *et al.*, 1992). Soil detachment by rainfall was adjusted by the rainfall erosivity coefficient (Wicks *et al.*, 1992). Detachment by runoff was not taken into account. Surface and channel flow transport capacities were calculated based on Yalin (1963) and Engelund-Hansen (1967), respectively. Table 1(a) shows the baseline parameter values.

BASELINE SIMULATIONS

Simulations were carried out first for the plots P1, P4 and P5, for testing the model parameter values and functions. Next, the parameters tested at the bare plots P1 and P4 were applied to the bare micro-basins M3 and M4, and those tested at the vegetated plot P5 were applied to the vegetated micro-basins M1 and M2. For the larger basins, parameters were defined for vegetated and non-vegetated areas based on an assumed vegetation distribution. Figures 2–4 show some results (Figueiredo, 1998; Figueiredo & Bathurst, 2001). The model explained, on average, about 80% and 50% of the variations between simulated and observed water flow and sediment yields (plots and micro-basins), respectively. For the water discharges at the larger areas, the model explained 67% (Umburana), 76% (Jatobá), and 80% (RBS). Different grid resolutions, used to model a particular catchment, produced similar results; hence, parameter grid scale dependency was not evident. The Manning-Strickler roughness coefficient decreased (50–15 $m^{1/3}$ s^{-1}) as basin area increased because the soil variability (e.g. relief, river network, vegetation, etc.) increased as basin area increased.

Table 1 Parameter values.

Surface	Horizon	h (m)	S_c (mm)	k_c (10^{-5} mm s^{-1})	b_c (-)	K_s (m day^{-1})	θ_s (m^3 m^{-3})	θ_{fc} (m^3 m^{-3})	θ_{wp} (m^3 m^{-3})	θ_r (m^3 m^{-3})	η (-)	$1/n$ (m$^{1/3}$ s^{-1})	k_r (s^{-1} kg^{-1} m^2)	k_f (kg^{-1} m^2 s^{-1})
(a) *Baseline values*														
Bare	A	0.1				0.306	0.448	0.235	0.111	0.075	15	50	11	0
	B	0.7				0.057	0.488	0.289	0.183	0.112	15			
Caatinga	A		0.5	1.7	7.77									
(b) *Bound values (low)*														
Bare	A	0.1				0.633	0.423	0.225	0.092	0.056	15	30	3	0
	B	0.6				0.306	0.474	0.262	0.149	0.098	15	0.5		
Caatinga	A		0.3	1.0	5.55									
(c) *Bound values (high)*														
Bare	A	0.1				0.111	0.467	0.252	0.136	0.091	15	70	20	0
	B	0.9				0.036	0.5	0.317	0.219	0.121	15	1.5		
Caatinga	A		0.7	2.3	13.0									

h: soil depth; S_c: canopy storage capacity; k_c and b_c: canopy drainage parameters; K_s: saturated hydraulic conductivity; θ_s, θ_{fc}, θ_{wp}, θ_r: moisture contents at saturation; field capacity, wilting point and residual; η: Averjanov (1950) exponent; $1/n$: Manning-Strickler coefficient; k_r and k_f: rainfall and runoff erosivity coefficients.

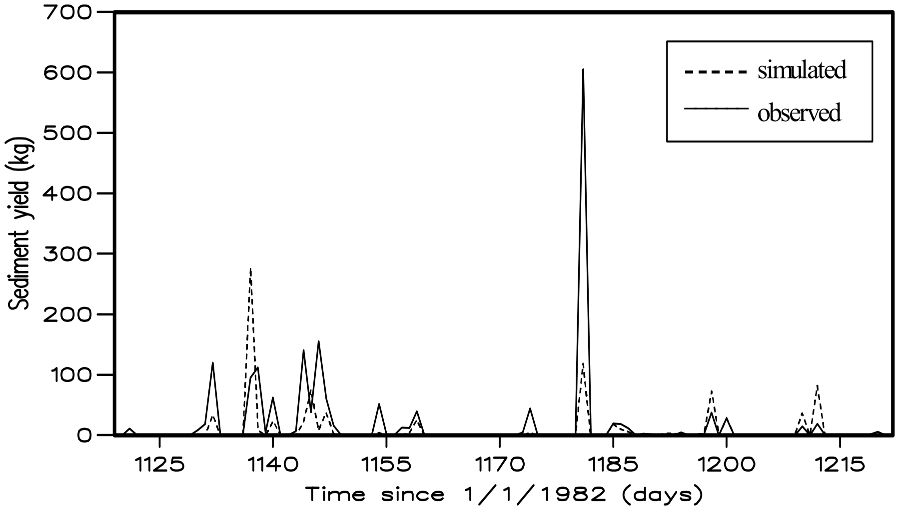

Fig. 2 Sediment yield comparison for Plot P4.

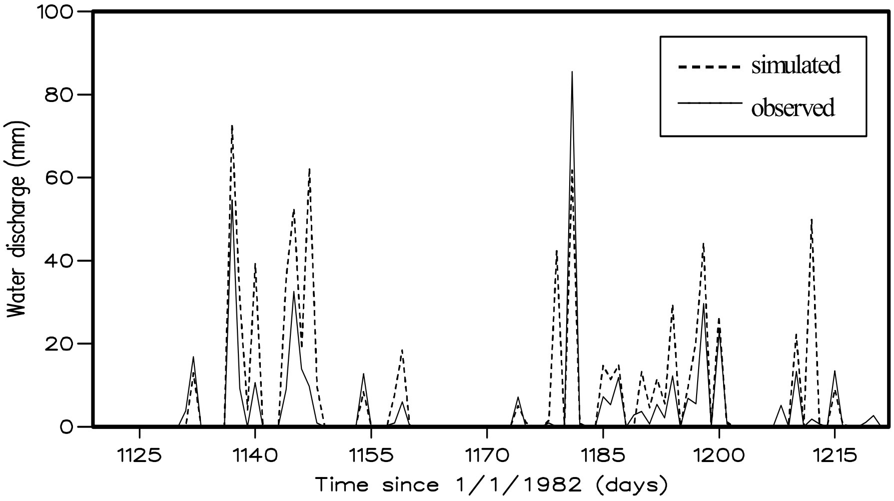

Fig. 3 Flow comparison for Micro-basin M3.

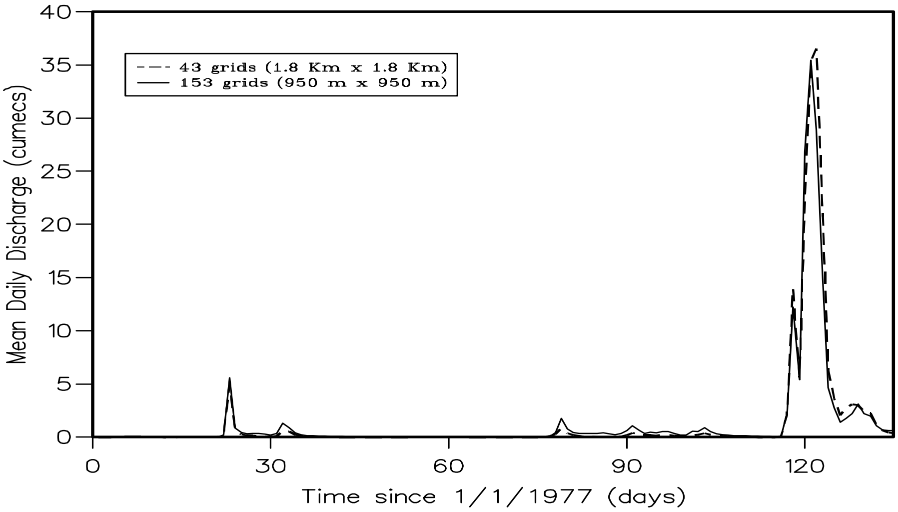

Fig. 4 Simulated flow with different grids (RBS).

OUTPUT BOUND SIMULATIONS

Output bounds of uncertainty were generated using parameter bound values (Table 1(b) and(c)); Fig. 5), determined with the Saxton *et al.* (1986) and Rawls & Brakensiek (1989) equations based on variations in soil characteristics. The model performance was analysed through the containments, which is defined as the percentage of time the observed values fall within overall output bounds (Ewen & Parkin, 1996). The containments were quite reasonable (Figueiredo & Bathurst, 2004) for the observed flow, and sediment yields at the bare plots (>87% and >81%) and micro-basins (>79% and >83%), but decreased for the vegetated areas (33% for the plot P5, 65 and 83% for the micro-basins M1 and M2, respectively). For the larger areas, the containments of daily discharges were 10%, but peak discharges were 100% contained. Figure 6 shows the output bounds for one event observed in Umburana.

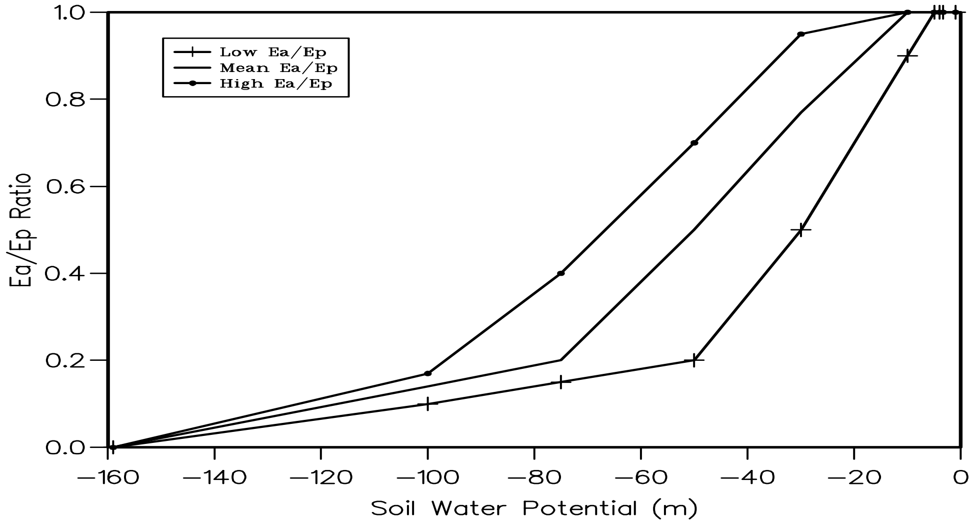

Fig. 5 Function of actual evapotranspiration with bound values.

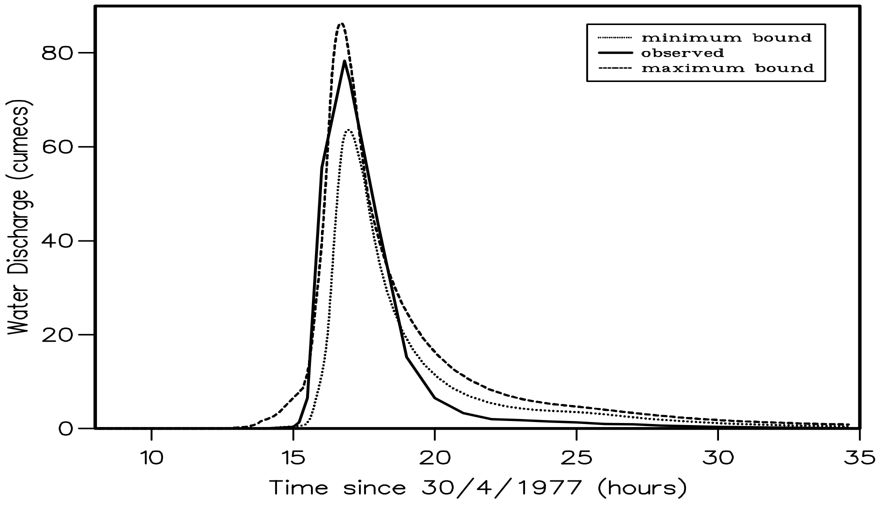

Fig. 6 Output bounds (Umburana).

EFFECTS OF LAND-USE CHANGE AND SCALE ON MODEL OUTPUTS

Five levels of deforestation were fixed (10, 30, 50, 70 and 90% of basin area) and the model applied to plot P4 (100 m^2), micro-basin M4 (4800 m^2), Umburana (10.7 km^2) and RBS (137.4 km^2). Simulations of runoff and sediment yield were realized using the baseline parameter values and annual precipitation data (*P*) varying from 400 to 800 mm (Figueiredo, 1998; Figueiredo & Bathurst, 2002). Annual peak discharges, volumes and sediment yields were affected by the basin area, land use and precipitation. In terms of flow, the largest effects were on the peak discharges, which increased with the level of deforestation and rainfall. In terms of sediment, the erosion rates decreased as basin area increased, but increased as the level of deforestation and precipitation increased. Table 2 shows the simulated annual flow and sediment yields for *P* = 600 mm. Note that when deforestation increased from 50% to 90%, runoff and sediment yield in the RBS increased by 37% (30 mm of water depth) and 85%. Figure 7 shows the relationship between simulated annual sediment yields and basin area, which compare well with those, reported for other areas (e.g. Walling & Kleo, 1979).

Table 2 Simulated annual flow and sediment yield (*P* = 600 mm).

D	Peak discharges [a]				Volumes [b]				Sediment yield (t km^2)			
(%)	P4	M4	Umburana	RBS	P4	M4	Umburana	RBS	P4	M4	Umburana	RBS
90	0.084	4.1	7.3	32.1	13.5	706	1980	14800	2053	1718	247	24
70	0.079	3.7	4.9	30.2	12.2	641	1850	13900	1597	1314	179	18
50	0.071	3.4	5.5	18.6	11.6	583	1740	10800	1136	887	173	13
30	0.071	3.1	4.7	16.3	11.2	540	1790	10100	683	647	144	11
10	0.064	2.7	4.0	11.8	10.8	480	1730	8400	228	401	101	8

[a] in l s^{-1} (P4 and M4) and in 10^3 m^3 s^{-1} (Umburana and RBS).
[b] in m^3 (P4 and M4) and in 10^3 m^3 (Umburana and RBS).
D: deforestation; *P*: annual precipitation.

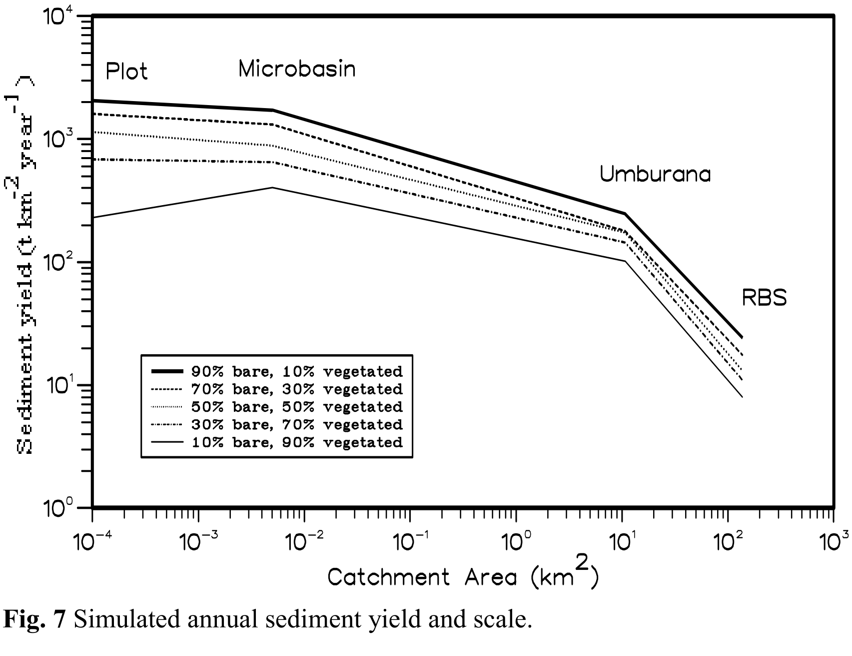

Fig. 7 Simulated annual sediment yield and scale.

CONCLUSIONS

The main conclusions of this work are: (a) parameters of relevant hydrological processes in the SeNeB could be evaluated based on field data, and methods available in the literature; (b) with the evaluated parameter values, the model was capable of representing the observed water discharges and sediment yields in the study area; (c) different resolutions of the grid applied to the larger basins did not highlight any parameter grid scale dependency; (d) peak discharges, annual volumes, and sediment yields increased as rainfall and deforestation increased; and (e) simulated sediment yields decreased as basin area increased.

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