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Modelling spatio-temporal patterns of sediment yield and connectivity in a semi-arid catchment with the WASA-SED model

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Abstract Rainfall–runoff induced soil erosion causes important environmental degradation by reducing soil fertility and impacting on water availability as a consequence of sediment deposition in surface reservoirs used for water supply, particularly in semi-arid areas. However, erosion models developed on experimental plots cannot be directly applied to estimate sediment yield at the catchment scale, since sediment redistribution is also controlled by the transport conditions along the landscape. In particular, representation of landscape connectivity relating to sediment transfer from upslope areas to the river network is required. In this study, the WASA-SED model is used to assess the spatial and temporal patterns of water and sediment connectivity for a semi-arid meso-scale catchment (933 km^2) in Brazil. It is shown how spatial and temporal patterns of sediment connectivity within the catchment change as a function of landscape and event characteristics. This explains the nonlinear catchment response in terms of sediment yield at the outlet.

Key words sediment yield; watershed connectivity; catchment scale; semi-arid; WASA-SED model

Modélisation des patrons spatio-temporels de la connectivité et de la production de sédiments dans un bassin versant semi-aride à l'aide du modèle WASA-SED

Résumé L'érosion des sols induite par le ruissellement cause d'importantes dégradations de l'environnement en réduisant la fertilité des sols et en ayant un impact sur la disponibilité de l'eau suite au dépôt de sédiments dans les réservoirs, particulièrement dans les régions semi-arides. Cependant, des modèles d'érosion développés pour des parcelles expérimentales ne peuvent pas être appliqués à l'évaluation de la production de sédiments à l'échelle des bassins hydrographiques, parce que la redistribution des sédiments est aussi contrôlée par les conditions de transport dans le paysage. En particulier il est nécessaire de représenter la connectivité du paysage en relation avec le transfert des sédiments des versants vers le réseau hydrographique. Dans cette étude, on utilise le modèle WASA-SED pour évaluer les patrons spatio-temporels de la connectivité de l'eau et des sédiments dans un bassin versant semi-aride de méso-échelle (933 km^2) au Brésil. Les résultats montrent comment les patrons spatio-temporels de la connectivité des sédiments dans le bassin versant changent en fonction des caractéristiques du paysage et des événements. Ceci explique la réponse non-linéaire du bassin versant en termes de production de sédiments à l'exutoire.

Mots clefs production des sédiments; connectivité; échelle du basin versant; semi-aride; modèle WASA-SED

INTRODUCTION

Rainfall–runoff induced erosion is recognized as an important factor of environmental degradation. In semi-arid regions, such as the Brazilian Northeast, soil detachment is particularly pronounced as a consequence of high rainfall rates and soil exposure due to the sparse vegetation (Megnounif *et al.*, 2007), with the transport conditions being the limiting factor for sediment yield. Detachment and transport of the top soil layers result in loss of nutrients that were available to the vegetation. Consequently, an enrichment of nutrients and accelerated eutrophication in surface water bodies occurs (Lindenschmidt

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et al., 2004). Also, nutrient enrichment in water bodies is more intense in dry regions, where water scarcity reduces dilution capacity. In addition, erosion and sediment transport have an adverse impact on water availability in Northeast Brazil, where most of the water for human supply is stored in manmade surface reservoirs (de Araújo *et al.*, 2004; Güntner *et al.*, 2004). Sediment deposition in reservoirs leads to the reduction of their storage capacity and thus of the reliability of water supply (de Araújo *et al.*, 2006).

Despite the importance of erosion and sediment transport processes, published studies have not reached a conclusive methodology for estimating sediment yield at different spatial scales. This is due to the nonlinearity of the above-mentioned processes with scale, and the large number of governing factors (Aksoy & Kavvas, 2005). At the catchment scale, sediment yield is controlled not only by well-known erosion factors (such as soil and vegetation properties, slope length, slope angle) and event- and landscape-characteristics controlling runoff generation (such as soil moisture content, infiltration rates), but it is also strongly affected by the transport conditions along the flow pathways. In this respect, natural (alluvial fans, riparian zones) and artificial (terraces, dams) geomorphic features may act as barriers to the sediment transport, thus breaking the connectivity of the catchment (Fryirs *et al.*, 2007a).

We refer to catchment connectivity as the degree to which sediment generation on the hillslopes is connected to the river network by overland flow. The shape of a hillslope itself may enhance (convex shape) or reduce (concave shape) sediment delivery from the upslope regions to the channels (Kinnell, 2008). Desmet & Govers (1995) confirmed the major influence of topography on erosion and deposition patterns. Beuselinck *et al.* (2000) agreed that topography is a controlling factor for sediment deposition, even though they recognized the importance of vegetation barriers on filtering the transported sediment. Also, Cammeraat (2002) showed the importance of biological factors, such as vegetation patterns and soil biological activity, on sediment transport, in particular at small scales, and Lesschen *et al.* (2009) demonstrated the influence of vegetation patches and agricultural terraces on hydrological and sediment transport connectivity. Nonetheless, the features affecting catchment connectivity act in different ways to retain the eroded sediment, ranging from a partial retention to full blocking. The breaking of such barriers may occur at time scales which vary from the event scale to thousands of years (Fryirs *et al.*, 2007a).

In semi-arid Northeast Brazil, the large number of reservoirs (up to one small dam per 8 km^2) acts as an efficient barrier to retain sediment (Mamede, 2008). Similar findings are discussed for a dryland agricultural region in Australia (Callow & Smettem, 2009). In addition, since Hortonian-type flow is the predominant runoff process at the hillslope scale, there is a high probability that the overland flow generated in upper areas re-infiltrates, at least partly, in a downstream location (Güntner & Bronstert, 2004), thus representing a break in catchment connectivity.

Therefore, an accurate estimation of sediment export at the catchment scale depends not only on a reliable estimation of gross erosion at a smaller scale, but also on how well the connectivity of the landscape can be described at the larger scales. Sediment Delivery Ratio (SDR, see Walling, 1983) equations have been used to estimate catchment-scale sediment yield, but the lumped nature of those equations does not allow a spatially-distributed interpretation of connectivity. Aksoy & Kavvas (2005) cite some physically-based models (EUROSEM and WEPP, for example), which overcome this limitation and are able to simulate sediment fluxes on an event basis. Nonetheless, the substantial amount of input data for such models makes their applicability to large watersheds impractical, unless the governing equations are upscaled, as in WEHY model (Kavvas *et al.*, 2004, 2006). As a consequence, watershed-scale estimations of sediment yield in a spatially-distributed manner have been carried out with semi-distributed models such as SWAT (Chen & Mackay, 2004), or pixel-based models such as WATEM/SEDEM (Verstraeten *et al.*, 2007; de Vente *et al.*, 2008). Also, the temporal patterns of sediment delivery have been assessed, as reported by de Araújo (2007). Regarding connectivity of sediment transport, quantitative studies have estimated sediment delivery from hillslopes to the river network (Verstraeten *et al.*, 2007) and assessed the role of sinks of water and sediment on overall catchment connectivity (Lesschen *et al.*, 2009). Qualitative analysis of the role of the landscape on catchment connectivity for sediment transport has also been performed (Fryirs *et al.*, 2007a,b). Other studies, such as in Bracken & Croke (2007), focused on the factors that influence hydrological connectivity.

The objective of this study is to assess the spatial and temporal distribution of sediment yield and connectivity within a meso-scale catchment in the semi-arid Northeast of Brazil and to evaluate the influence of connectivity patterns on sediment yield at the catchment outlet. The analysis was based on model simulations with a deterministic, semi-distributed model for real-world and fictitious rainfall events.

STUDY AREA

The study was carried out in the Benguê catchment, located in the semi-arid Northeast of Brazil in the Federal State of Ceará (Fig. 1). The Benguê catchment drains an area of 933 km^2 controlled by the Benguê Reservoir, which has a storage capacity of 19.6 hm^3 and is mainly used for human water supply and to keep the Umbuzeiro River perennial downstream of the dam.

As described by de Araújo & Piedra (2009), the climate is tropical semi-arid ("BS", according to the Köppen classification), with a mean annual potential evaporation of 2500 mm (Class A Pan measurements) and mean annual rainfall of 560 mm. The rainfall regime presents high intra- and inter-annual variability; the rainy season comprises the period from January to May, which is responsible for over 80% of annual rainfall, 46% occurring during the months of March and April. Rainfall is mostly convective and concentrated in a few, high intensity events. Such characteristics produce mainly Hortonian type surface runoff. Mean annual temperature is 26°C, ranging from 24°C in June to 28°C in November and mean annual relative humidity is 62%. Geomorphologically, the area is situated in a transition zone, with occurrence of the Sertões unit (hinterland–crystalline complex) in the central and eastern sectors and the Altos Planaltos Sedimentares (high sedimentary plateaus) at the western and southern borders. The Sertões unit is characterized by shallow soils with high clay content and a significant amount of rock fragments, whilst in the high sedimentary plateaus the soils tend to be deeper and highly permeable (Creutzfeldt, 2006). These characteristics define the runoff spatial pattern, with higher runoff coefficients on the region coincident with the Sertões unit, and high infiltration rates on the Altos Planaltos Sedimentares.

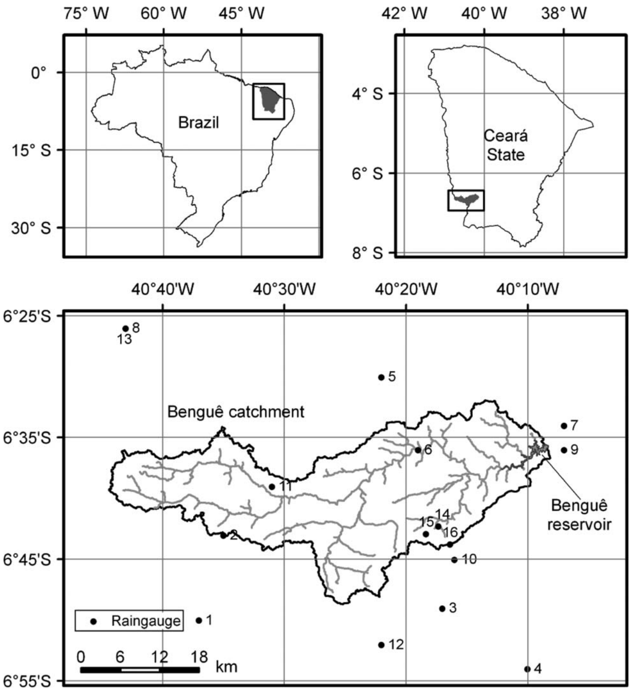

Fig. 1 Location of the Benguê catchment.

The catchment is located in a rural area with low population density (6.4 inhabitants per km^2) and large unexploited areas. The main economic activities are agriculture, with a predominance of beans and maize, as well as goat farming. The predominant vegetation type is *Caatinga*, a deciduous dry woodland with xerophytic species. It is composed of a mixture of trees, bushes and cacti, with heights that vary from 3 to 7 metres. Due to recurrent droughts and a lack of important groundwater resources, the construction of dams has been the main means to supply water in the region. In the Federal State of Ceará, over 90% of the drinking water derives from surface reservoirs (de Araújo *et al.*, 2004). Reservoir siltation by sediment inflow reduces the State's water storage volume by almost 2% per decade (de Araújo *et al.*, 2003). In the Benguê catchment, Mamede (2008) identified 121 reservoirs with surface areas varying from 150 to 830 000 m^2.

MODELLING APPROACH

To simulate sediment yield and connectivity in the semi-arid Northeast of Brazil, the WASA-SED model (Model of Water Availability in Semi-Arid Environments with a Sediment Dynamics Component) (Güntner, 2002; Güntner & Bronstert, 2004; Güntner *et al.*, 2004; Mamede *et al.*, 2006; Bronstert *et al.*, 2007; Mamede, 2008; Mueller *et al.*, 2008) was used. WASA-SED is a semi-distributed, deterministic model for continuous simulation of water and sediment fluxes. It is composed of process-oriented conceptual approaches, and has been included in an integrated modelling framework (Krol *et al.*, 2006).

The main features of WASA-SED relate to: the model's applicability to large areas (for instance, Güntner, 2002, simulated the entire Brazilian states of Ceará and Piauí, an area of 398 000 km^2); and the

Simulation of specific semi-arid characteristics, such as Hortonian type flow, runoff re-infiltration at downstream positions and a dense network of surface reservoirs, for which a cascade method is used. As WASA-SED is not a grid-based distributed model, it adopts a catena-based, hierarchical discretization of the study area into modelling units at five scale levels to account for the spatial variability of landscape characteristics and their influence on runoff generation (see Güntner, 2002; Güntner & Bronstert, 2004).

On the one hand, the multi-scale scheme for landscape discretization adopted in WASA-SED captures the variability of landscape characteristics, making possible an explicit simulation of runoff re-infiltration and lateral redistribution. These processes are particularly pronounced in semi-arid environments and strongly affect hydrological connectivity. On the other hand, the aggregation of modelling units in various levels to represent coarser-scale spatial units allows the simulation of large river basins with reduced parameterization and computation efforts.

Surface reservoirs, which play an important role in the hydrological response of catchments, are also simulated in WASA-SED. Due to the large density of such structures and the associated high data and computational demand, small reservoirs are grouped in size classes and only one representative reservoir of each class is simulated. A cascade scheme is then adopted, and outflow of a reservoir class is distributed among the classes of larger size reservoirs. Simulation is performed individually for the strategic reservoirs, i.e. those implemented by the government for water supply throughout long-term (2–4 year) droughts, with storage capacities usually greater than 30 hm^3.

Within the sediment component, erosion caused by rainfall/runoff and sediment transport are simulated at the terrain component scale in WASA-SED. The approach is based on the USLE equation (Wischmeier & Smith, 1978) coupled with the transport capacity equation proposed by Everaert (1991). Initially, the USLE is applied to estimate daily net erosion:

$$E = (\mathrm{EI} \cdot K \cdot L \cdot S \cdot C \cdot P \cdot \mathrm{ROKF}) \cdot A \qquad (1)$$

In equation (1), E is erosion (t d^{-1}), EI is the rainfall erosivity factor (MJ mm ha^{-1} h^{-1} d^{-1}), K is the soil erodibility factor (t h MJ^{-1} mm^{-1}), L is the slope length factor (-), S is the slope factor (-), C is the vegetation and crop management factor (-), P is the erosion control practice factor (-), ROKF is the coarse fragment factor (-) and A is the area (ha) of the terrain component. The sediment transport capacity according to Everaert (1991) is then computed:

$$\text{if } D_{50} \leq 150\ \mu\text{m}: q_s = 3.67 \cdot 10^{-2}\, \Omega^{1.07} D_{50}^{0.47} W \qquad (2)$$

$$\text{if } D_{50} > 150\ \mu\text{m}: q_s = 1.38 \cdot \Omega^{1.75} D_{50}^{-0.56} W \qquad (3)$$

where q_s is the solid discharge (t d^{-1}), Ω is the effective stream power (kg$^{1.5}$ s$^{-4.5}$ m$^{-2/3}$) computed within the hydrological routines of WASA-SED, D_{50} is the median particle diameter (µm) estimated from the particle size distribution of the eroded soils, and W is the width of the terrain component (m). The effective stream power is given by:

$$\Omega = (\rho g q s)^{1.5} \big/ d^{2/3} \qquad (4)$$

where ρ is the density of water (kg m^{-3}), g is the gravitational acceleration (m s^{-2}), q is the overland flow rate per width unit (m^3 s^{-1} m^{-1}), s is the slope (-) of the terrain component (TC) and d is the flow depth (m).

Net erosion added to the sediment coming from an upper TC (SED$_{\mathrm{in}}$) is then compared to the maximum sediment load (see, for instance, scheme in Haan *et al.*, 1994, p. 242) based on the sediment transport capacity (equations 2 and 3), and sediment yield (SY) of a TC is computed as:

$$\mathrm{SY} = \min(E + \mathrm{SED}_{\mathrm{in}}; q_s) \qquad (5)$$

Similar to the downslope partitioning scheme for surface runoff described by Güntner & Bronstert (2004), sediment that leaves a TC is partitioned into a fraction that is routed to the next TC downslope and a fraction that reaches the river directly, representing the soil particles carried through preferential flow paths, such as rills and gullies. Sediment leaving a TC, which is routed on the next TC downslope (SED$_{\mathrm{in},i+1}$ in t d^{-1}), is computed based on the areal fraction of the current TC according to equation (6):

$$\mathrm{SED}_{\mathrm{in},i+1} = \mathrm{SY}_i \left[1 - \left(\alpha_i \Big/ \sum_{n=i}^{n\mathrm{TC}} \alpha_n \right) \right] \qquad (6)$$

In equation (6) i and i+1 are the indices of the current and the next downslope TCs respectively, α is the areal fraction of a TC and nTC is the number of terrain components in the current landscape unit. The remaining fraction is transferred directly to the river network. For the assessment of connectivity on sediment transport, the deposition rate is used as an indicator. Expressing the changes on sediment yield caused by the transport conditions, the deposition rate relates inversely to connectivity, i.e. high deposition indicates low connectivity. In WASA-SED, the deposition rate (DEP) is computed at the scale of terrain component as follows:

$$\mathrm{DEP}_i = 1 - \left[\mathrm{SY}_i / \left(\mathrm{SED}_{\mathrm{in},i} + E_i\right)\right] \tag{7}$$

Total sediment load of a sub-basin is then routed through the reservoir cascade. Sediment budget within reservoirs is estimated based on the overflow rate concept (see Mamede, 2008). For a full description of the erosion and sediment transport processes in the hillslope, river and reservoir modules of the WASA-SED model see Mueller *et al.* (2008).

Model parameterization

The first parameterization step of the Benguê catchment consisted of delineating the hydrological modelling units, i.e. sub-basins, landscape units and their discretization into terrain components, using a semi-automated algorithm presented by Francke *et al.* (2008). Topographic features were derived from a digital elevation model with 15-m resolution, generated from ASTER images by Creutzfeldt (2006). Land cover was assessed from classification of satellite images (ASTER and CBERS) conducted by Creutzfeldt (2006), whereas soil information was obtained from the RADAM-BRASIL soil map (1981). Daily rainfall data were obtained for the sub-basin units by inverse-distance interpolation of data from 16 raingauges. Gauges 1–13 (see location in Fig. 1) are monitored by the Ceará Foundation of Meteorology and Water Resources (FUNCEME), whereas gauges 14–16 are monitored by the Federal University of Ceará at the Aiuaba Experimental Watershed. Table 1 presents characteristics of the raingauges and information about annual rainfall. Other daily climate data (air temperature, humidity and shortwave radiation) were obtained from the FUNCEME database for the stations of Assaré (40 km southeast of the Benguê Reservoir) and Tauá (65 km north of the study catchment).

Concerning the USLE factors, the rainfall erosivity factor (EI, in MJ mm ha^{-1} h^{-1} d^{-1}) was computed according to Williams & Arnold (1997) as follows:

$$\mathrm{EI} = R\,[12.1 + 8.9(\log_{10} r - 0.434)]\,I_{30}/100 \tag{8}$$

where R is the daily rainfall (mm), r is an estimate (assuming an exponential distribution of rainfall rate over time) of the peak rainfall intensity (mm h^{-1}) given by $r = -2R\cdot\ln(1-\alpha_{30}\}$, α_{30} is the maximum fraction of 30-min rainfall compared to the daily amount (or (1/ 2 h) $(I_{30})/R$) and I_{30} is the maximum 30-min rainfall intensity (mm h^{-1}). Since sub-daily rainfall is not recorded in the regular raingauges located in the

Table 1 Characteristics of the 16 raingauges in the study area.

Raingauge	Data resolution	Time series (years)	Rainy days per year*	Annual rainfall (mm)			
				Mean	Max.	Min.	CV
1	24 h	69	33	676	2058	248	0.44
2	24 h	18	32	603	929	326	0.31
3	24 h	25	30	635	1211	239	0.35
4	24 h	37	38	779	1557	421	0.34
5	24 h	28	28	580	1436	286	0.46
6	24 h	33	22	533	1273	173	0.48
7	24 h	66	28	546	1285	136	0.39
8	24 h	20	30	634	1240	285	0.37
9	24 h	13	25	500	852	205	0.35
10	24 h	6	20	528	843	302	0.37
11	24 h	7	29	592	894	402	0.29
12	24 h	6	23	490	926	270	0.50
13	24 h	7	24	624	1074	321	0.38
14	5 min	5	30	725	1066	516	0.30
15	5 min	2	24	507	519	495	0.03
16	5 min	3	29	598	684	551	0.12

*Days with rain ≥ 5 mm.

Benguê catchment, a relationship between daily rainfall and I_{30} was established for Raingauge 14 (Fig. 2), which measures rainfall in 5-min intervals. This relationship was then used to estimate I_{30} based on daily rainfall for the other stations. Figure 3 presents, for Raingauge 14, the relationship between the EI factor calculated with measured I_{30} and that calculated with I_{30} intensities estimated by the adjustment previously mentioned. It can be observed that the derived equation provides a good fit, and variability in the estimation of EI should be compensated in the long run since no bias is observed.

The soil erodibility, slope length, slope gradient and coarse fragment factors were estimated according to the equations proposed by Williams & Arnold (1997). The vegetation and crop management factor (*C*) was assigned to each of the 12 land-cover classes as mapped by Creutzfeldt (2006). The *C* values were both estimated in the field, on the basis of vegetation cover, and derived from published studies. The erosion control practice factor was set to one, since no protection against erosion was observed in the field. The ranges of the USLE factors *K*, combined *LS* (at the landscape unit, i.e. hillslope, scale) and *C* are presented in Table 2.

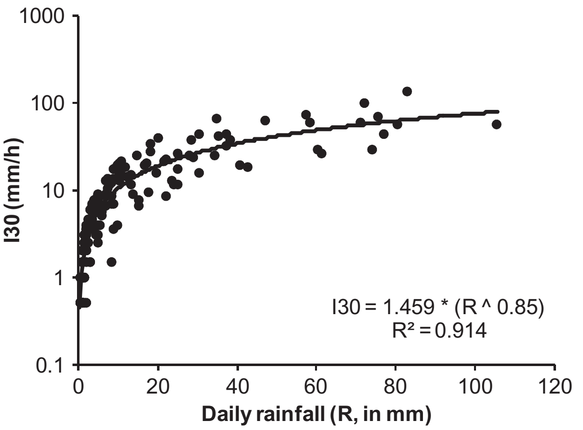

Fig. 2 Plot of I_{30} *versus* daily rainfall, *R*, for Raingauge 14.

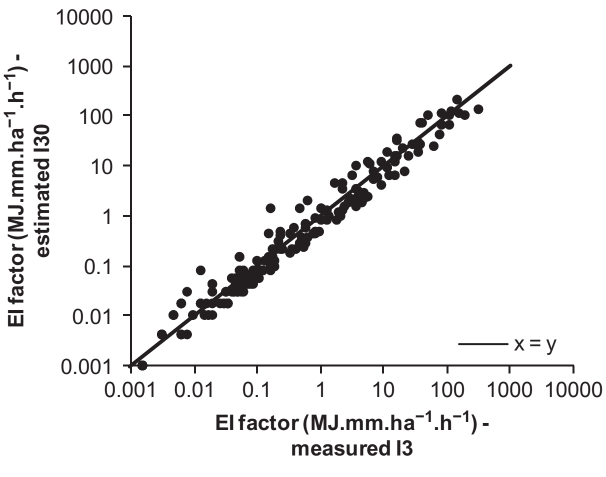

Fig. 3 The EI factor with measured and estimated I_{30} intensity for Raingauge 14.

Table 2 Ranges of values of the USLE factors *K* (t h MJ^{-1} mm^{-1}), combined *LS* (-) and *C* (-) in the Benguê catchment.

USLE factor	Average	Median	Maximum	Minimum
K	0.025	0.025	0.033	0.015
Combined *LS*	0.631	0.498	1.483	0.277
C	0.067	0.039	0.297	0.004

The soil erodibility factor (*K*) showed low variability in the Benguê catchment, and thus should not represent a main source of uncertainty in the parameterization. Concerning the *LS* factor, despite the wider range of values, identification of the landscape units was carried out with a semi-automated algorithm (Francke *et al.*, 2008) and based on a 15-m resolution DEM, reducing the uncertainties. The vegetation factor (*C*), which was mapped using satellite images, has a wider range. In addition to the difficulties in estimating a *C* factor to each class (measured in the field as a function of vegetation density and taken from publications), imagery classification for mapping the vegetation types is also problematic. The temporal and spatial variability of the vegetation characteristics in deciduous forests represented another source of uncertainty in the determination of the vegetation and crop management factor.

RESULTS AND DISCUSSION

For the assessment of sediment yield and connectivity patterns within the Benguê catchment, two simulation experiments were carried out with the WASA-SED model running on a daily basis. First, the model was run using real climate data for the period 2001–2008. However, given the variation of daily rainfall volumes and the irregular sequence of wet and dry periods in the real-world data, the first simulation may not be the most appropriate means to clearly separate the effects of changing catchment connectivity on sediment yield from those related to rainfall variability. Therefore, a second simulation was carried out assuming 30 days of constant rainfall intensity (20 mm d^{-1}), totalling 600 mm within a month. In the year 2004, for instance, a total rainfall depth of 520 mm was observed within a 25-day period, which makes the second simulation realistic.

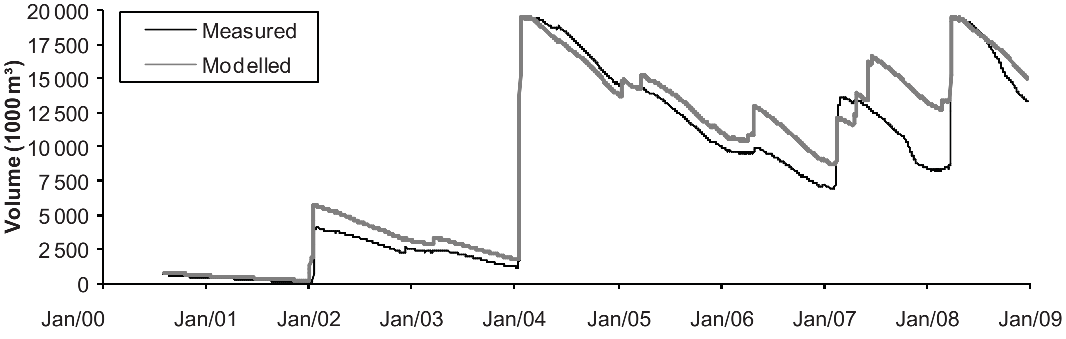

Fig. 4 Measured and modelled (WASA-SED) water volume in the Benguê Reservoir.

Model performance

In the absence of direct discharge measurements, the assessment of the WASA-SED model performance for the hydrological simulation was made by comparing measured and modelled reservoir water volume (Fig. 4). It can be observed that the model is able to represent total runoff that is generated in the watershed, with a 0.918 NSE (efficiency coefficient, Nash & Sutcliffe, 1970) for measured and modelled water volume in the Benguê Reservoir.

With regard to the validation of sediment budget estimations, Walling (2005) reports the difficulty of obtaining spatially distributed information on suspended sediment using traditional monitoring techniques, and highlights the importance of sediment fingerprinting techniques for the identification of source areas. Radionuclides, in particular caesium-137, have been used with success for this purpose (for instance Walling *et al*., 2003). However, due to the size of the study area, which demands much financial and staff input, and the lack of previous estimations of soil redistribution, assessment of model performance was only possible at the catchment outlet. Sediment concentration and river discharge measurements were performed during 34 monitoring campaigns in 2007 and 2008. For the analysis of suspended sediment concentrations, water samples were collected manually two times per day for river discharges less than 2 m^3/s. In addition, a water level-based sampler (10-cm intervals) was used on the rising limb of higher magnitude hydrographs. From the observations, sediment yield was estimated for the monitored events at the catchment outlet and a sediment rating curve was built. It should be noted that measured sediment yield ranges from 0.2 to 1200.0 t d^{-1}, while modelled values are as high as 9000 t d^{-1}. In 2007 and 2008, sediment inflow to the Benguê Reservoir measured during the monitoring campaigns corresponds to 8% of the total load estimated for that period.

The rating curve, in association with daily runoff estimations based on reservoir water level, was used to generate a series of daily sediment inflow to the reservoir. Yearly averaged sediment yield was estimated from that series for the years 2003 to 2008 as 13.6 t km^{-2} $year^{-1}$, whereas WASA-SED simulations indicate 11.5 t km^{-2} $year^{-1}$ for that same period. Sediment yield in the study area is much lower than the average for the region (400 t km^{-2} $year^{-1}$) due to high infiltration rates and the good preservation status of the vegetation (de Araújo & Piedra, 2009). Figure 5 illustrates daily sediment yield *vs* daily river discharge data for both modelled (2001–2008) and measured (specific events in 2007 and 2008) events.

Figure 5 indicates high dispersion of daily sediment yield data (varying by up to two orders of magnitude for the same runoff volume) especially for lower runoff amounts, which can be attributed to the

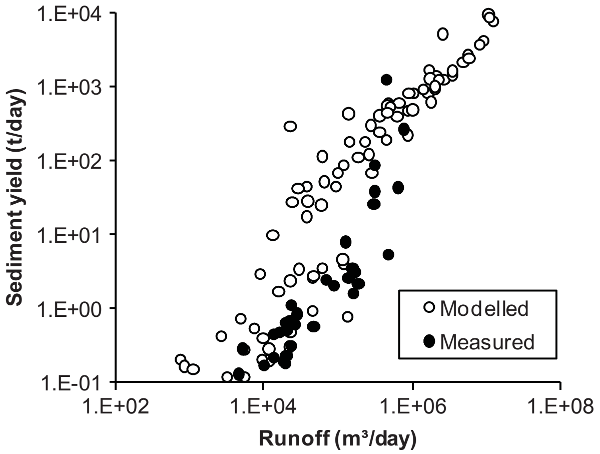

Fig. 5 Daily sediment yield *vs* runoff for both modelled (2001–2008) and measured (2007–2008) events at the Benguê catchment outlet upstream of the reservoir.

variable degree of the influence of subsurface flow on the total runoff. Variability of sediment yield is considerably reduced for larger runoff volumes, which are less influenced by subsurface water contributions. For such events, larger areas of the catchment contribute to the overall sediment yield due to higher connectivity and, therefore, sediment transfer to the catchment outlet is more uniform. This characteristic makes the model estimations more reliable for high runoff events, which are responsible for most of the sediment generated (in this simulation, the ten largest events produce over 70% of total sediment yield). Although the measured data do not cover the full range of simulated runoff volumes, there is a good indication that the modelling approach adopted in WASA-SED is able to predict sediment yield on a daily basis within the order of magnitude of observed values, especially for the largest events. This is particularly remarkable in view of the complexity of the erosion and sediment transport processes involved in this comparison, including sediment transfer from upslope areas to the river network, sediment deposition on its pathways and retention in small reservoirs.

Spatial patterns of connectivity

For the 2001–2008 period, the simulation of the Benguê catchment with the WASA-SED model showed that the fraction of sediment reaching the catchment outlet (sediment delivery ratio) corresponded to 25% of the total erosion estimated with USLE. Sediment retention in surface reservoirs accounted for 18% of the eroded amount, whilst 57% was deposited along the landscape in areas with reduced sediment transport capacity, which represented the main sediment sink. In relation to the amount of sediment reaching the river network, 42% was retained in the 121 surface reservoirs present in the catchment. Even though some higher percentages of retention have been reported in previous studies (de Araújo *et al*., 2003), one must recall that reservoirs in the Benguê catchment are small (65% with storage capacities < 25 000 m^3) and that the 8-year simulation period included an exceptionally rainy year (2004, with 1020 mm annual rainfall compared to a mean of 560 mm, and had a 22-year recurrence time), producing frequent reservoir overflow, and thus, sediment release from the reservoirs. In addition, the area controlled by those reservoirs corresponds to only 45% of the catchment, i.e. 55% of the Benguê catchment area drains directly to the outlet (Mamede, 2008).

According to the model results, the year 2004 alone was responsible for 65% of total runoff in the simulation period. Similarly, most of the sediment generation occurred in 2004 (57%). Due to the predominance of runoff and sediment yield in the wet season of 2004, the evaluation of spatial patterns of connectivity along the landscape was focused on this period. Figure 6 illustrates the simulated response within the Benguê catchment from 10 January to 9 February 2004. Based on the simulation, two days with similar runoff volumes but very different sediment yield were taken for the assessment of connectivity: 21 January (event one), close to the onset of the wet period (165 mm antecedent rainfall in the previous 15 days), and 28 January (event two) (346 mm antecedent rainfall in the previous 15 days).

The results presented in Fig. 6 indicate that a daily rainfall depth of 63 mm on 21 January generated 10.6 hm^3 of runoff, whereas a runoff volume of 9.1 hm^3 (85% of that of event one) was simulated for

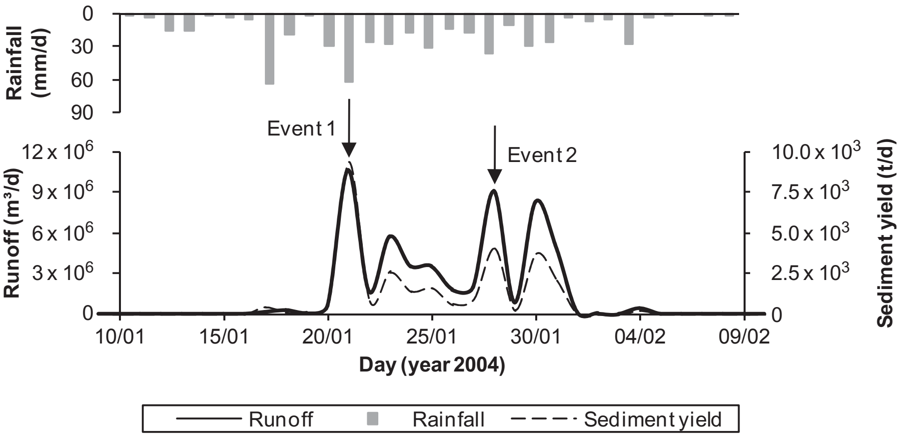

Fig. 6 Benguê catchment response to measured rainfall, as simulated by WASA-SED.

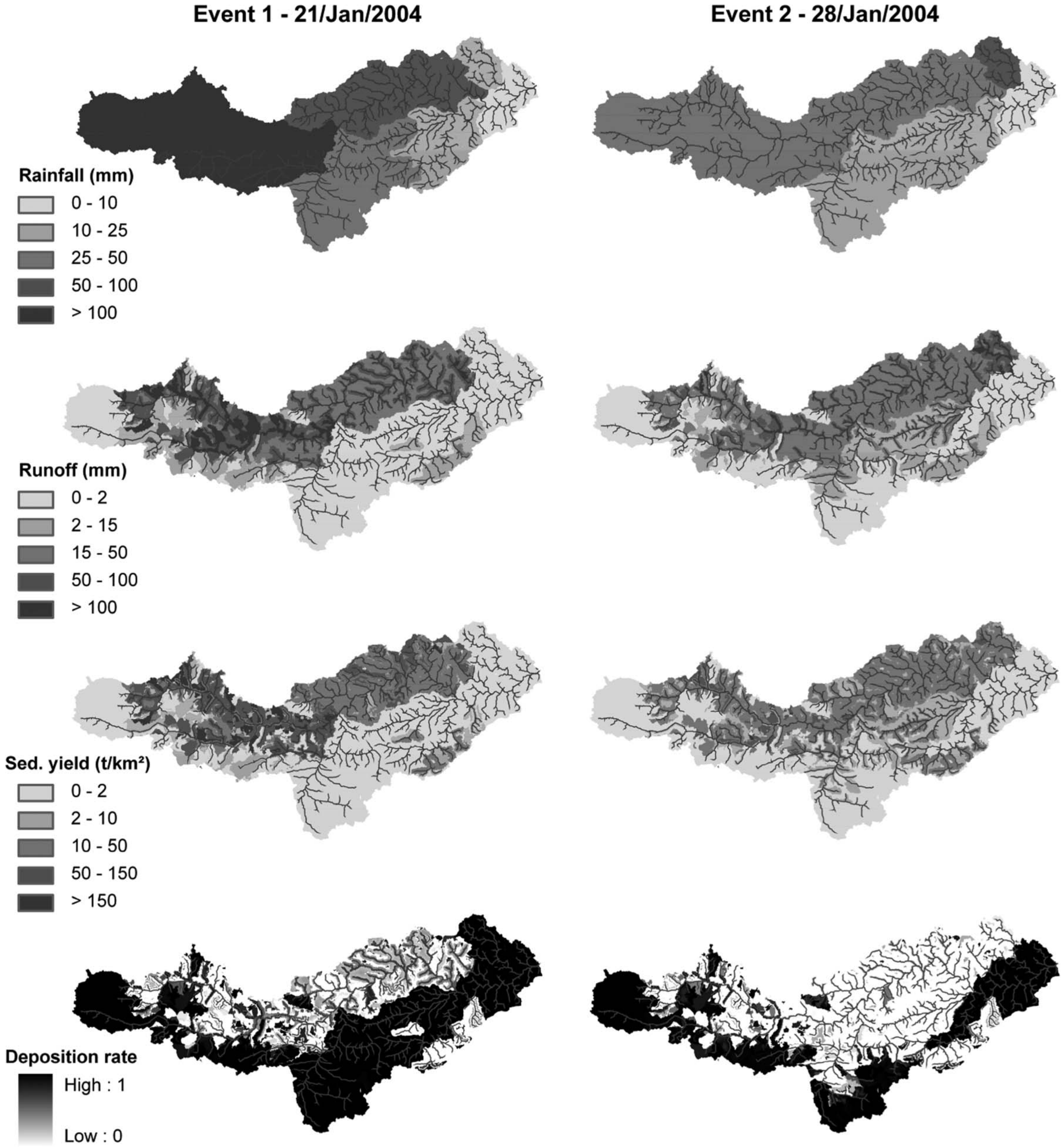

Fig. 7 Spatial patterns of rainfall, runoff, sediment yield and sediment deposition in the Benguê catchment for 21 January 2004 (left) and 28 January 2004 (right).

the event of 28 January with 37 mm daily rainfall (58% of the rainfall on event one). A closer look at the spatial pattern of rainfall (Fig. 7) indicates that not only rainfall magnitude, but also its spatial variability, were very different during these events: high rainfall variability was observed on event one, whilst a more uniform pattern occurred on event two.

Due to the different rainfall input and soil moisture content, the modelled runoff showed very different spatial patterns. For the 21 January rainfall event, most of the runoff which reached the catchment outlet was generated in the northwestern part of the catchment, where rainfall depth was higher. The rest of the catchment contributed with very low runoff volumes. During event two, runoff was generated in a more equally distributed way throughout the catchment. Despite the lower rainfall amount of event two, high antecedent soil moisture content caused higher runoff generation, lower re-infiltration losses and thus higher catchment connectivity for water fluxes, resulting in overall higher runoff/rainfall rates.

Even though the estimations of total runoff volume were similar for the two events analysed, simulated sediment yield differed greatly, with more than 9000 t reaching the catchment outlet on 21 January against approximately 4000 t on 28 January. The nonlinearity between sediment yield and runoff can be explained by the spatial pattern of sediment generation. The model results indicate that large amounts of sediment generated by the first event originated from the region with high rainfall magnitude, where most runoff was generated (Fig. 7). In that area, low sediment deposition indicates that the catchment was well connected to the river network. For the second event, runoff was equally generated across the catchment at intermediate intensities, and no areas with very high sediment generation were indicated by the modelling. Instead, sediment was generated at lower rates but contributed in a more uniform way to total sediment yield, since the terrain components and hillslopes were thoroughly connected to the river network due to the antecedent soil moisture, according to the simulations. Figure 7 shows low deposition rates over a larger area for the later event. Exceptions were the southern and western fringes of the catchment, which belong to the sedimentary plateaus, where the soils present high permeability, and an area close to the catchment outlet, where soils are deep. In areas with such characteristics, the model tends to generate low runoff and sediment even after a sequence of rainy days.

Temporal pattern of connectivity

The temporal evolution of connectivity in the Benguê catchment was studied in greater detail for the model experiment with fictitious data, assuming a constant daily rainfall of 20 mm during 30 consecutive days. This rainfall volume is consistent with field observations for 2004, when a mean daily rainfall of 21 mm was recorded during a period of 25 consecutive days (11 January–4 February, Fig. 6). Other climatic data (temperature, humidity, radiation) were taken from the observed time series in the 30-day wet period from 11 January–9 February 2004. In the simulation, an antecedent dry period of 60 days was admitted in order to establish adequate initial conditions at the beginning of the rainy period. Since daily rainfall was kept constant in time and space for the experiment, any change of connectivity in the simulation results should be a function of landscape characteristics and varying soil moisture patterns only.

Figure 8 shows the temporal evolution of runoff and sediment yield at the catchment outlet. Due to the initially dry conditions, runoff and sediment yield at the catchment outlet commence around five days after rainfall began. As the soil moisture content increased after the first days with rain, runoff was initially generated at low rates and rapidly increased after the 15th day. Around the 25th day, soil moisture and its spatial distribution reached nearly equilibrium wet conditions, which corresponded to water saturation in areas with shallow soils. Accordingly, runoff generation was close to a stationary behaviour. A very similar temporal behaviour was observed for sediment yield.

Sediment yield increased as the soil moisture content rose during the rainy period, whereas deposition rates were reduced (Fig. 9). Larger areas of the catchment became connected and contributed to the overall sediment yield, as runoff was enhanced and,

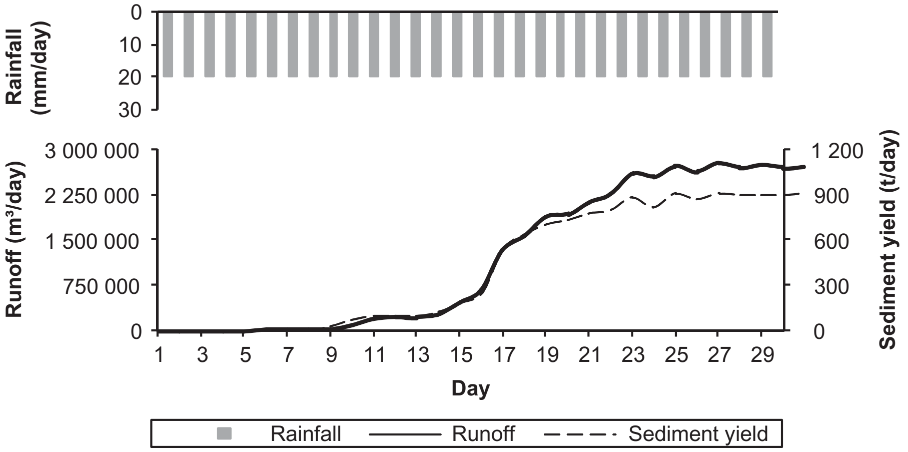

Fig. 8 Temporal evolution of simulated runoff and sediment yield at the outlet of Benguê catchment for the modelling experiment with fictitious data.

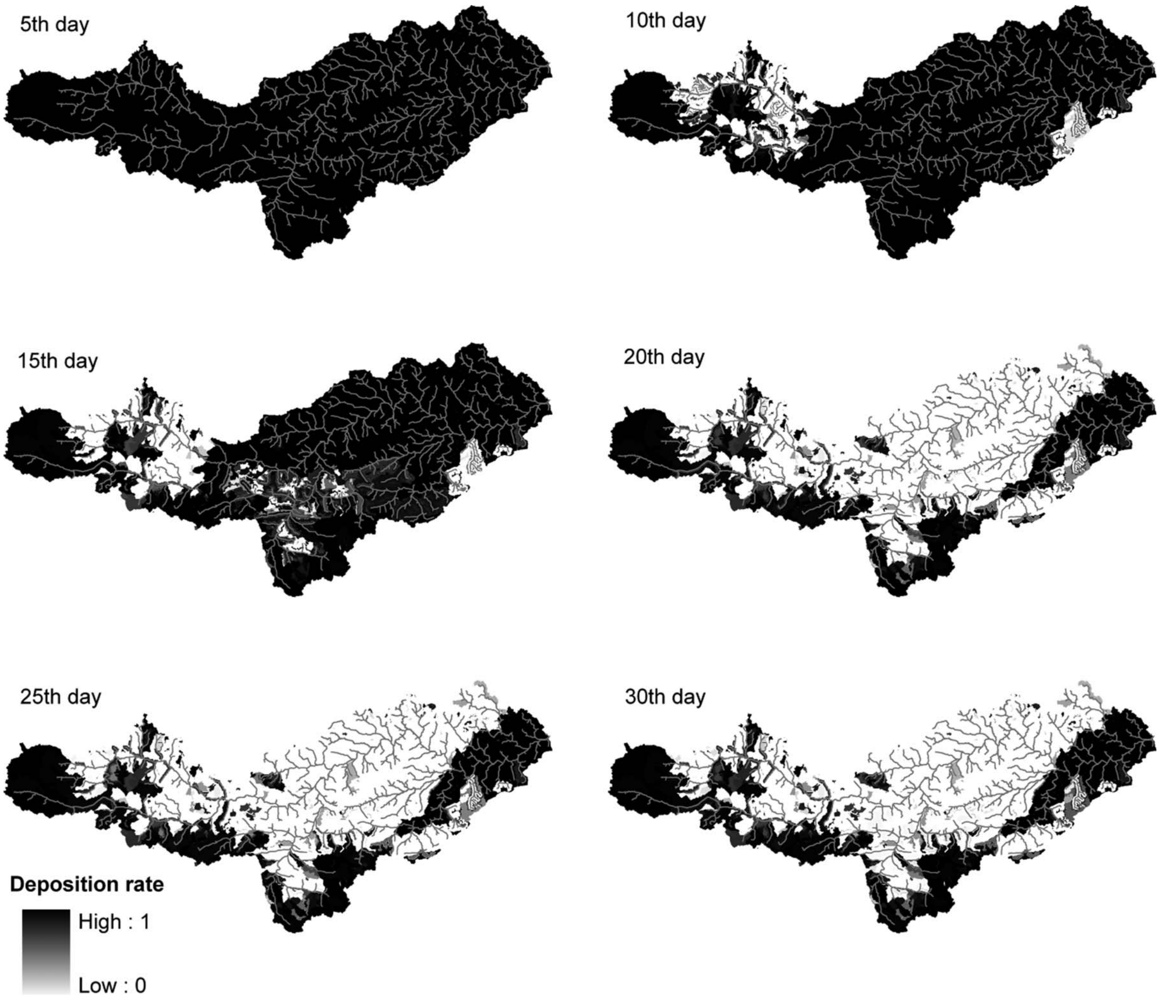

Fig. 9 Deposition rates in the Benguê catchment, given the occurrence of 20 mm daily rainfall during 30 days.

consequently, the landscape became less efficient in retaining the sediment generated upslope.

As occurred in the simulation with real climatic data, a large area in the northwestern part was the first to be connected, indicating that not only rainfall depth but also physical characteristics of the catchment were responsible for this pattern. In that region, soils are shallow (around 0.7 m thick above the crystalline bedrock basement), and therefore easily saturated, producing high connectivity. In the central and northeastern regions, which became connected on the 20th day, soils are also shallow, but the permeability is lower. There, saturation occurred some days later, and even though some excess rainfall was simulated between the 10th and the 15th day, runoff sustained the transport of only small fractions of the eroded sediment. On the western-, eastern- and southernmost borders, there is a predominance of deeper soils (2 m thickness, on average) below which there is no bedrock basement, so allowing deeper infiltration. There, connectivity continued to be very low even after large rainfall inputs. At a finer spatial scale, the main factors influencing connectivity can also be assessed. For instance, a relation between deposition (low connectivity) and low slopes can be noticed for individual toposequences. As a general tendency at the hillslope scale, higher deposition was indicated by the model on highlands and valley bottoms, where slope gradients are usually lower. Temporal variation of sediment transport efficiency indicates that, at larger scales, regional characteristics, such as soil type, may be useful in predicting connectivity patterns. At finer scales, variability of local characteristics (position within the toposequence, slope gradient) seems to play a more important role on sediment transport.

CONCLUSIONS

Simulations performed with the WASA-SED model and measured sediment yield at the Benguê catchment outlet suggest the validity of the model results, even though no validation was performed in a distributed manner due to the catchment size and lack of data. The spatial discretization within a hierarchical approach, used in the model, allows for the upscaling of erosion processes from a terrain component scale (10^{-1} km^2) to the catchment scale (10^3 km^2). This is possible due to the simulation of processes such as lateral redistribution and re-infiltration of water, resulting in the explicit simulation of sediment deposition along the landscape and suppressing the use of a lumped sediment delivery ratio (SDR) approach. As demonstrated by Verstraeten *et al.* (2007), spatially distributed modelling of sediment transport is essential to represent the variability of sediment delivery processes within a catchment, so enabling the identification of major contributing areas. The main advantage of the approach used here is its applicability to large areas of up to 10^5 km^2 (Güntner, 2002). Another advantage is the consideration of characteristics specific to semi-arid regions (Hortonian type flow, re-infiltration, and simulation of dense reservoirs networks), which are particularly important in the present work.

The model indicates the high sensitivity of watershed connectivity to topography and soil characteristics, as already addressed by other researchers (e.g. Verstraeten, 2006; Bracken & Croke, 2007; Fryirs *et al*., 2007a). This seems to be a key factor affecting connectivity in the study area, since sediment yield was well estimated even though other features, such as vegetation barriers and soil biological activity, were not considered in the model approach. Thus, it seems that the latter factors, indicated by Cammeraat (2002, 2004) and Puigdefabregas *et al*. (1999) as influencing connectivity at the plot scale, may play a secondary role at the catchment scale. In fact, measurements in southeastern Spain (Puigdefabregas *et al.*, 1999) indicated that connectivity at the hillslope scale is mostly influenced by water transfer, which is highly dependent on soil characteristics and topography.

According to the results for the Benguê catchment, the spatial pattern of connectivity in semi-arid environments seems to be closely related not only to rainfall, but also to the water content in the soil. Even though Hortonian flow type is predominant in such environments (Cammeraat, 2004; Güntner & Bronstert, 2004; Bracken & Croke, 2007), shallow soils above a crystalline basement may produce runoff due to saturation. This process has been reproduced by the model in the experiment with fictitious rainfall data, in which connectivity showed high spatial variability which was related to the soil depth, despite the constant rainfall in space and time.

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