

Temporal variability of rainfall in a semiarid environment in Brazil and its effect on sediment transport processes

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Received: 23 January 2013 / Accepted: 7 November 2013 / Published online: 26 November 2013
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Abstract

Purpose The temporal variabilities of both soil erosion by water and sediment redistribution in watersheds are directly related to rainfall characteristics. The purpose of this work was to assess the temporal pattern of rainfall in a semiarid watershed in Brazil and explain how this feature controls soil erosion and sediment yield.

Materials and methods Daily and 5-min rainfall records were used to assess the temporal pattern down to the sub-hourly scale. To study the effect of the rainfall on sediment processes, erosivity and sediment yield at the Aiuaba (12 km²) and Benguê (933 km²) watersheds, Brazil were determined. Erosivity was calculated based on the rainfall kinetic energy method, while sediment yield was estimated from sediment rating curves and daily water discharge measurements.

Results and discussion A large portion of annual rainfall is restricted to a few rain events and strong concentration in the sub-daily scale occurs, producing high erosivity. The temporal concentration of erosivity is greater than that of rainfall; the 10th percentile of the highest magnitude events encompasses 51% of the precipitation, but 80% of the erosivity. The temporal concentration of sediment yield is more pronounced; 88 and 98% of the sediment yield for the Aiuaba and Benguê watersheds, respectively, are within the 10th percentile of events.

Conclusions The strong temporal concentration of precipitation causes events with high intensity and erosivity, thus allowing for soil detachment. Nonetheless, the low runoff rates limit downstream sediment transport. Such behavior

produces a much higher temporal concentration of sediment yield, which reaches its maximal after a sequence of rainy days, when hydrological connectivity is enhanced and the sediments are propagated throughout the entire transport-limited system.

Keywords Brazil · Rainfall regime · Sediment yield · Semiarid · Soil erosion

1 Introduction

Soil erosion by water and the transference of sediment among different landscape compartments are recognized as major environmental degradation processes, and knowledge about their spatial and temporal distribution is essential for the management of watersheds and the conservation of natural resources. Features such as topography, soil type, and land use are employed as indicators of the spatial variability of soil redistribution (e.g., Bahadur 2009; López-Vicente et al. 2011; Slimane et al. 2013), and empirical methods such as the Universal Soil Loss Equation (USLE; Wischmeier and Smith 1978) have been largely used to map soil erosion susceptibility based on the combined effect of those factors.

On the other hand, the temporal variability of erosion in the short-time scale (i.e., from hours to a few years) is mainly driven by the precipitation regime and its influence on erosivity since the other relevant factors vary at much lower rates, and thus, can be assumed to be constant (or slightly variable) over this time scale. Moreover, the temporal variability of rainfall has a considerable effect on hydrological behavior (Obled et al. 1994; Smith et al. 2004; Arnaud et al. 2011), which will strongly influence the transport capacity of soil particles (Huang et al. 2013) and the sediment yield. Lima Neto et al. (2011) demonstrated the importance of the temporal variation of erosivity on the sediment cascade. The authors proposed an equation to assess the retention rate of sediments in reservoirs, and the only temporal variable was the erosivity.

Responsible editor: Jorge Enoch Furquim Wemeck Lima

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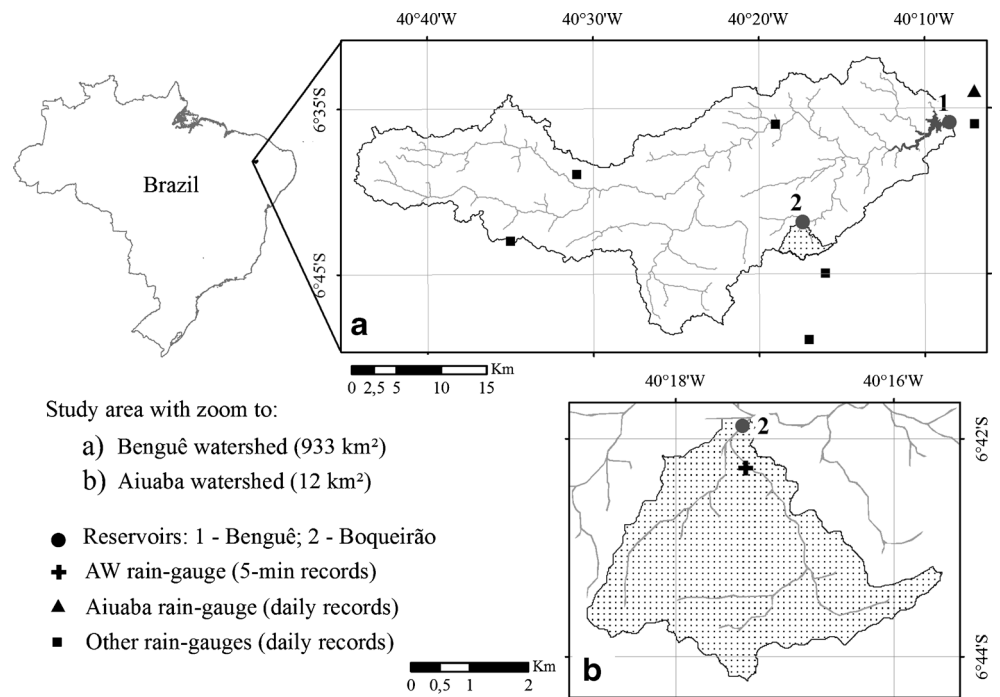
The equation was proved valid for reservoirs of different sizes (range, 1×10^4 to 1×10^8 m³) in the Brazilian semiarid environment, indicating that the joint effect of the remaining factors controlling sediment yield can be assumed to be invariant at the time scale of up to a few years.

According to Torrico (1974), the Brazilian semiarid region is characterized by a strong concentration of precipitation in the sub-daily scale with significant portions of the rainfall events occurring in short intervals. Torrico's study of rainstorms covered the entire Brazilian territory and suggests that the northeast of the country is the region with the strongest temporal concentration; up to 48 and 15% of daily precipitation occurs in 1 h and 6 min intervals, respectively. In this context, the objective of this study is to assess the temporal variability of the rainfall in the Aiuaba Experimental Area, Brazil, and explain how this temporal pattern controls soil erosion and sediment yield. Knowledge about the temporal pattern of sedimentological processes is crucial for the adoption of measures to reduce the impacts both with respect to their local (e.g., soil loss) and downstream (e.g., siltation of rivers and reservoirs) effects (e.g., Haregeweyn et al. 2012; Slimane et al. 2013). In addition, understanding of the time scale occurrence of the dominant processes is required for adequate representation in hydrological models.

2 Study area

The study was conducted at the Aiuaba Experimental Area (AEA) in the semiarid northeast of Brazil (Fig. 1). The site is composed of two nested watersheds:

Fig. 1 Location map of the study area Aiuaba watershed, Brazil

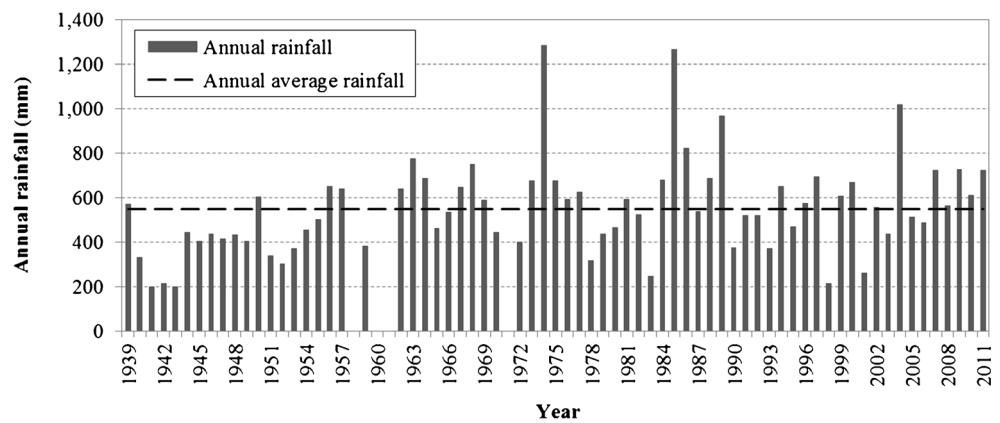


- The Benguê Watershed (BW–933 km²) whose outlet is the Benguê reservoir (2×10^7 m³); and
- The Aiuaba Watershed (AW–12 km²) whose outlet is the Boqueirão reservoir (6×10^4 m³).

The study area is in one of the driest regions in the country with an average annual rainfall of 549 mm characterized by high interannual variability of rainfall with coefficient of variation of 0.40 and 1.20 for annual rainfall and runoff, respectively. Soils in the region are shallow (1 m depth above the crystalline bedrock) with high clay contents and a significant amount of rock fragments. In the west and south borders of the Benguê watershed, high sedimentary plateaus occur, with deeper and highly permeable soils. Detailed information about the AEA can be found elsewhere (e.g., de Araújo and Piedra 2009; Pinheiro et al. 2013; de Araújo and Medeiros 2013). The annual rainfall time series of the Aiuaba rain gauge (Fig. 2) indicates the occurrence of years (e.g., 1974 and 1985) with precipitation above 1,200 mm (i.e., more than twice the average) or as low as 200 mm. Figure 2 also indicates sequences of years with total rainfall below the average such as in the 1940s, the first half of the 1950s, the period between the years 1978 and 1983, and in the 1990s. Frischkorn et al. (2003) argue that, statistically, there is the occurrence of a severe drought in the region in every decade.

Regarding the intra-annual variability, rainfall in Aiuaba is concentrated on a well-defined rainy season, from January to May, in which 84% of the annual precipitation occurs. In the three wettest months (February to April), the precipitation corresponds to 61% of the total annual average. Figure 3 shows the monthly median rainfall, as well as its amplitude

Fig. 2 Time series of annual rainfall in Aiuaba (years with no values correspond to missing data)



in the period from 1939 to 2011. In Fig. 3, a wide range of monthly precipitation in the rainy season can be observed with months in which rainfall is of the same order of magnitude as the total expected for the entire year (March 1960 with 548 mm), as well as months with zero precipitation even in the period characterized as rainy (e.g., February of 1989 and 2002 and April of 1998). It is not unusual that daily events equal or exceed 100 mm in Aiuaba (as on 27th February 2004 with 105 mm), which may represent 20% of annual rainfall and over 40% of annual erosivity.

3 Material and methods

The analysis of the temporal variability of rainfall in Aiuaba was based on daily records from 1939 to 2011 (station equipped with a Ville de Paris rain gauge; Funceme—Meteorological and Water Resources Foundation of Ceará 2012) complemented by precipitation data with 5 min intervals registered by a tipping-bucket rain gauge at the Aiuaba watershed since 2003 by the Research Group of Hydro-Sedimentology of the Semiárid—HIDROSED (www.hidroсед.ufc.br).

To assess the rainfall variability, coefficients indicating its concentration at the daily, hourly, and sub-hourly scales were proposed. The ratio of the day with the highest precipitation

(RDP), the ratio of the hour with the highest precipitation (RHP), and the ratio of the 30-min interval with the highest precipitation (RSHP) are the respective values normalized by the annual rainfall. These coefficients were calculated for each year of the series, comprising the period from 1939 to 2011 for the RDP and the period from 2004 to 2011 for the RHP and RSHP due to availability of the sub-daily data.

To assess erosion and sediment yield, a period of 6 years (2004–2009) was considered. Rainfall erosivity rates ($E_{I_{30}}$ in megajoules millimeter per hectare per hour) were estimated with the method proposed by Wischmeier and Smith (1978) for the USLE and modified by Foster et al. (1981), which is based on the rain kinetic energy [Eqs. (1) and (2)].

$$e = 0.119 + 0.0873 \log_{10} I \quad (1)$$

$$E = e \cdot P \quad (2)$$

Where e is the rainfall kinetic energy (megajoules per hectare per millimeter), I is the rainfall intensity (millimeters per hour), E is the total kinetic energy of the rain event (megajoule per hectare), and P is the water depth of the rain event (millimeter). The rainfall erosivity index $E_{I_{30}}$ (megajoules millimeter per hectare per hour) is the product of the kinetic energy of the rain event and the maximum 30 min intensity (I_{30} in millimeters per hour) during the respective event. The index was calculated for all rainy days of the period 2004–2009 using the AW rain gauge data.

Daily sediment yields at the Aiuaba (12 km²) and Benguê (933 km²) scales were estimated from sediment rating curves (daily water discharges versus sediment yield) at river sections upstream of the Boqueirão and Benguê reservoirs. To build the sediment rating curves, specific events were monitored upstream of the reservoirs regarding river discharges (current meter discharge measurements) and suspended sediment concentrations (SSC). For the analysis of SSC, a water level-based sampler (10 cm intervals) was used on the rising limb of hydrographs, and water samples were collected manually

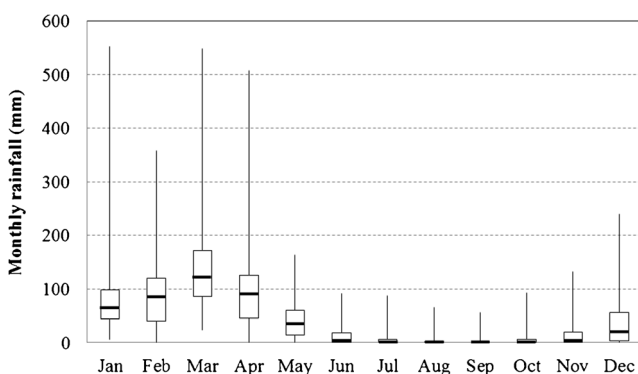


Fig. 3 Monthly rainfall in Aiuaba, with indication of the median, first, and third quartiles, minimum and maximum values (period 1939–2011)

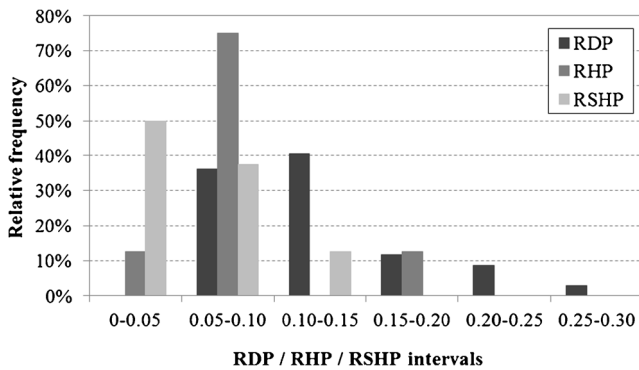


Fig. 4 Relative frequency of the ratios of the day (RDP), hour (RHP), and 30-min (RSHP) intervals with the highest rainfall in Aiuaba

two times per day for low river discharges not captured by the sampler (as described by Medeiros et al. 2010). The sediment rating curves upstream of the Boqueirão and Benguê reservoirs were built with 14 and 33 measured events and presented good fits with R^2 values of 0.93 and 0.82, respectively.

Estimation of daily sediment yield over the period 2004–2009 was based on the abovementioned rating curves and the daily water inflow to the reservoirs assessed by means of a water balance simulation (Eqs. (3)–(5), de Araújo et al. 2006).

$$dV(t)/dt = Q_{in}(t) - Q_{out}(t) \tag{3}$$

$$Q_{in} = Q_R + Q_P + Q_G \tag{4}$$

$$Q_{out} = Q_E + Q_I + Q_O + Q_W \tag{5}$$

Where V (cubic meter) is the water volume in the reservoir at time t (day); Q_{in} is the summation of all input discharges (the river inflow to the reservoir, Q_R ; direct precipitation on the lake, Q_P ; groundwater recharge, Q_G) and Q_{out} the summation of all output discharges (evaporation loss, Q_E ;

infiltration, Q_I ; weir outflow, Q_O ; withdrawal, Q_W) with all discharges computed in cubic meters per day.

Groundwater recharge and infiltration were not taken into account since $Q_G \approx Q_I$ in the study area (de Araújo et al. 2006), whereas withdrawal is known for both reservoirs. Q_P and Q_E were estimated from rainfall measured at the AW and Aiuaba rain gauges (see Fig. 1) and evaporation (class A pan) measurements in the vicinity of the Boqueirão reservoir. Hourly and daily water level measurements at the Boqueirão and Benguê reservoirs, respectively, enabled the estimation of the stored water volumes and the weir outflows; thus, river inflow to the reservoirs (Q_R) could be computed.

Furthermore, an assessment was undertaken to determine the importance of the most prominent events in terms of erosivity and sediment yield relative to the totals estimated for the study period. An analysis on how the temporal distribution of the rainfall influences erosivity and sediment yield in the study region was also carried out.

4 Results and discussion

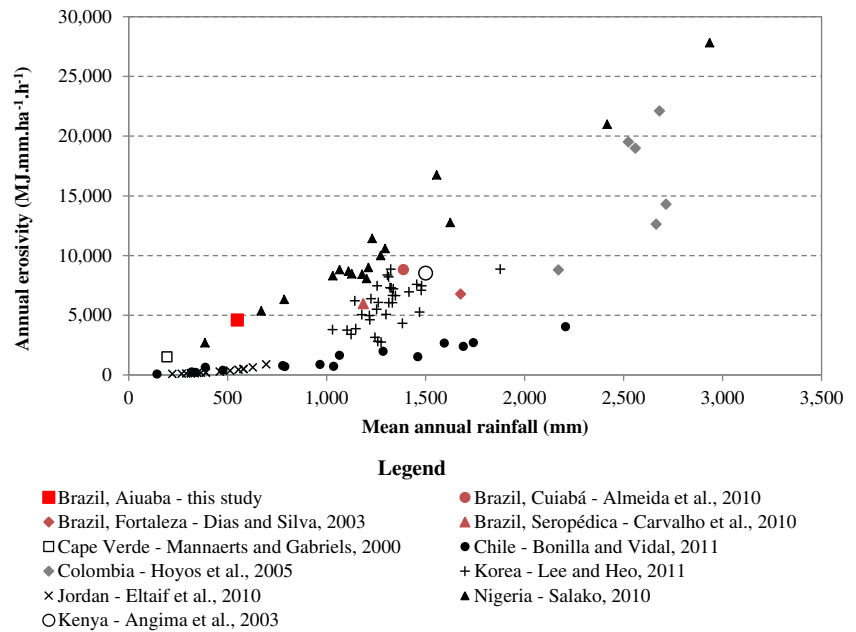
Daily records from Aiuaba indicate that rainfall is temporally concentrated not only in some months of the year but also mainly in a few rainfall events; in the period 1939–2011, on average, there were only 42 days with precipitation per year. Considering solely daily rainfall exceeding 12 mm, below which there is no occurrence of runoff in the Aiuaba watershed (Figueiredo 2011), there is an average of only 15 days per year with precipitation capable of generating runoff in that watershed. Frequently in Aiuaba (77% of the years of the series), the wettest day contains 5 to 15% of all annual rainfall (Fig. 4). It is also observed that in the ninth percentile of the years, the wettest day represents to up to 25% of the annual total, and in the third percentile of the years, almost a third of the total rainfall occurs on a single day. As highlighted by Sun

Table 1 Annual values of rainfall, erosivity, runoff, and sediment yield in the study area

Variable	Year								
	2004	2005	2006	2007	2008	2009	2010	2011	
Rainfall (mm)	1,002	518	561	739	733	743	449	598	
Erosivity (MJ mm ha ⁻¹ h ⁻¹)	5,808	6,506	4,880	5,338	4,756	3,719	2,456	3,334	
Aiuaba Experimental Watershed (12 km ²)									
Runoff (mm)	16.3	5.0	1.7	2.7	3.9	1.1	4.0	14.5	
Runoff coeff. (%) ^a	1.6	1.0	0.3	0.4	0.5	0.1	0.9	2.4	
Sediment yield (t km ⁻²)	6.14	1.67	0.30	0.62	1.08	0.22	1.51	10.34	
Benguê watershed (933 km ²)									
Runoff (mm)	23.4	0.7	0.9	7.3	13.6	8.6	3.1	13.9	
Runoff coeff. (%) ^a	2.3	0.1	0.2	1.0	1.9	1.2	0.7	2.3	
Sediment yield (t km ⁻²)	5.68	0.02	0.02	0.63	6.02	0.69	0.09	2.70	

^a Based on the spatial average of precipitation calculated from available data of rain gauges located within and in the vicinity of the watersheds

Fig. 5 Erosivity indices versus annual rainfall for different locations in Brazil and the world



et al. (2006), a limited number of rainy days contributing to most of the annual precipitation has also been observed in other regions, especially in Australia and North Africa, where arid and semiarid conditions prevail.

Furthermore, 5 min measures at the AW rain gauge indicate a strong intra-event concentration of the rainfall in short intervals (Fig. 4). At the hourly scale—assessed for a shorter period (2004–2011) due to low availability of sub-daily data—it was found that in 75% of the years, 5 to 10% of the total annual precipitation occurs in an interval of 1 h. However, for 13% of the years, the hour with highest precipitation contains 15 to 20% of the annual rainfall.

It is noticed that, even within the hourly time scale, peaks with intense rainfall occur. Figure 4 indicates that for at least half of the years, the most rainy 30 min interval responds to 5 to 15% of the total rainfall for that year.

An overview of the hydrological and sedimentological behavior of the study region is presented in Table 1, which indicates annual values of rainfall, erosivity, runoff, and sediment yield. The temporal pattern of rainfall in the semiarid region of Brazil directly impacts the erosive power of the rain events. In Aiuaba, despite the low annual rainfall (549 mm year⁻¹ on average for the period 1939–2011), the erosivity indices are significant (Table 1). Such a feature relates to the high erosivity of individual rain events compared to other regions, where rainfall tends to be more evenly distributed throughout the event. According to the mapping in Brazil conducted by Silva (2004), the semiarid northeast region has the lowest annual rainfall in the country (400 to 1,000 mm year⁻¹) and has intermediate rates of annual erosivity (2,000 to 8,000 MJ mm ha⁻¹ h⁻¹ year⁻¹).

Erosivity in this region is of the same order of magnitude, for example, of areas in the south/southeast of Brazil where annual rainfall can reach values up to 1,600 mm.

The high magnitude of erosivity in Aiuaba relative to annual rainfall becomes more evident when compared to other locations. Figure 5 indicates that the mean annual erosivity rate in Aiuaba is of the same order of magnitude to the indexes estimated for places in Korea (Lee and Heo 2011), where the rainfall is about 1,500 mm year⁻¹, and Chile (Bonilla and Vidal 2011), with rainfall exceeding 2,000 mm yr⁻¹. When compared to other regions in Brazil, the erosivity index of Aiuaba approaches the values observed in areas with rainfall >1,000 mm yr⁻¹. It is worth noting the same tendency of the erosivity indices of Aiuaba with those estimated by Salako (2010) for Nigeria, which may be explained by climatic similarities of the two regions: position at low latitudes—tropical climate, high temperatures with

Table 2 Rainfall events with highest erosivity in Aiuaba between 2004 and 2009

Date (day/month/year)	E.I ₃₀ (MJ mm ha ⁻¹ h ⁻¹)	Rainfall (mm)		
		Daily total	Máx. 1 h	Máx. 30 min
20/01/05	2,806	82.8	78.2	65.5
09/04/06	1,888	71.9	55.1	50.6
27/02/04	1,311	105.1	44.5	27.7
18/04/07	1,159	53.3	49.3	45.0
29/04/07	1,097	66.5	51.6	36.6

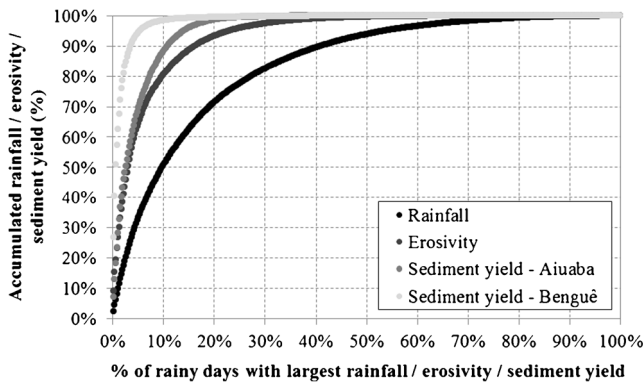


Fig. 6 Relative importance of the days with the highest precipitation, erosivity index, and sediment yield between 2004 and 2009 in Aiuaba

low variations, and rainfall regime mostly driven by the inter-tropical convergence zone.

Table 2 shows the characteristics of the five events with the highest erosivity measured in the period 2004–2009 in Aiuaba. Combined, these events amount to 27% of the erosivity calculated for the entire period of 6 years in which there was a total of 357 days with occurrence of rainfall, of which 102 days had depths >12 mm and were thus capable of generating runoff in the AW according to Figueiredo (2011).

Apart from the days with high magnitude rainfall, the critical events regarding erosivity also include the event on 18th April 2007 with daily rainfall below 60 mm. A strong temporal concentration of rainfall was observed on that event with high percentages of the daily rainfall occurring at intervals of 1 h and 30 min, thus producing high erosivity despite the low rainfall amount. In turn, the day with highest erosivity (20th January 2005 with 2,806 MJ mm ha⁻¹ h⁻¹) was also characterized by a strong temporal concentration of precipitation in addition to the high magnitude (82.8 mm), with 95% of

the rain occurring in an interval of 1 h and 79% of the total daily amount occurring in a 30-min interval. Individually, the erosivity of that specific event was >96% of the monthly indices for the entire study period even though 2005 was a year of regular precipitation, with annual rainfall slightly below the average (see Fig. 2).

The strong concentration of erosivity in a few days in Aiuaba is illustrated in Fig. 6, which shows the relative importance of the days with largest rainfall, erosivity, and sediment yield over the study period (2004–2009). The 10th percentile of the highest magnitude events contains 51% of the precipitation in the period, whereas 80% of all erosivity occurs within that percentile.

Regarding sediment yield, a much higher temporal concentration is observed. Figure 6 indicates that 88 and 98% of the sediment yield over the study period in the Aiuaba and Benguê watersheds, respectively, are within the 10th percentile of the most critical events. This shows a nonlinear relation between rainfall and sediment yield; rather, it indicates that the relation between the variables follows a power function with exponent larger than unity. One should observe that the study watersheds are mainly rural with low population densities (6.5 inhabitants per km²) and encompass large unexploited areas and a preservation site, which covers the entire Aiuaba watershed. In addition, land use has been the same (small scale rain-fed agriculture) for the last few decades in the occupied lands of the Benguê watershed and, therefore, should not introduce temporal variability to the sediment yield.

It is remarkable that the days in which sediment yield is maximal do not coincide with the most critical events in terms of erosivity. Concerning sediment fluxes in the Benguê and Aiuaba watersheds, the period from 20th to 31st January 2004 stands out (Table 3), with sediment yields corresponding to 41 and 31%, respectively, of the total estimated for the 6 years

Table 3 Critical period in terms of sediment yield in the study area between 2004 and 2009

Date (day/month/year)	Rainfall (mm)	E.I ₃₀ (MJ mm ha ⁻¹ h ⁻¹)	Sediment yield (t)	
			Aiuaba	Benguê
20/01/2004	60.9	327.4	0.5	291.5
21/01/2004	22.0	33.2	0.0	461.7
22/01/2004	18.0	103.3	0.7	560.9
23/01/2004	25.1	90.1	0.9	640.8
24/01/2004	23.5	55.2	2.1	1,280.7
25/01/2004	58.1	751.1	8.6	772.8
26/01/2004	0.0	0.0	6.5	33.6
27/01/2004	37.3	239.1	1.5	287.6
28/01/2004	21.8	102.9	4.7	162.1
29/01/2004	4.5	2.2	5.5	21.4
30/01/2004	47.0	671.3	2.6	186.7
31/01/2004	14.9	17.6	3.6	331.1

studied. Ten and six events out of the 15 most critical ones in the Benguê and Aiuaba watersheds, respectively, are contained in those 12 days. In fact, the year 2004 produced unusually high water and sediment discharges in the study area. Lima Neto et al. (2011) estimated that suspended sediment load for the year 2004 in the Upper Jaguaribe Basin (24,000 km²) corresponds to approximately 83% of the total value for a 25-year series (1984–2008). On the other hand, on those same dates (20th to 31st January 2004), rainfall and erosivity index in Aiuaba represent only 8% of the total amount for the study period.

5 Conclusions

Rainfall records in the Aiuaba Experimental Area indicate that the Brazilian semiarid region is characterized by a high temporal concentration of precipitation: 51% of the total rainfall for the period 2004–2009 occurred on 10% of the most rainy days. Furthermore, the variability in the sub-daily time intervals is quite high, causing intense rainfall at short time intervals. As a consequence, events with high erosive power occur despite the low annual rainfall.

The temporal concentration of erosivity is more pronounced than that observed for precipitation: the five most critical events (1% of the total) account for 27% of the cumulative erosivity in 6 years and 80% of all erosivity is concentrated in the 10th percentile of the most critical days. A much higher temporal concentration is observed for sediment yield; the 10% percentile of the most critical events contains 88 and 98%, respectively, of the sediment yield over the study period for the Aiuaba and the Benguê watersheds.

Even though the detachment of significant amount of soil is possible, as indicated by the erosivity data, very low runoff depths (<10 mm year⁻¹ on average) produce a transport-limited environment (Medeiros et al. 2010), restricting sediment propagation along the system. After sequences of rainy days or during extreme events, high transport capacity is achieved and the sediment mobilized on previous events finds suitable conditions to be transported further downstream towards the outlet of the watersheds.

The high temporal concentration of rainfall in short-time intervals, observed in this study, highlights the need for hydrological models to be able to capture sub-daily variations of the driving forces in order to provide accurate simulation of the main hydrologic and sediment transport processes. For instance, the Model of Water Availability in Semiarid Environments (WASA) uses a scale factor to compensate for the attenuation of the rain intensity caused by the daily time step, thus setting an appropriate relationship between rain intensity and soil infiltration capacity and providing a more accurate calculation of Hortonian-type flow (for WASA model application see, for instance, Medeiros et al. 2010).

Acknowledgments The authors acknowledge the Brazilian National Council for Scientific and Technological Development (CNPq) for financing the research projects that generated this manuscript (n. 474323/2011-0 and 200672/2012-6), as well as the German Research Foundation (DFG) for the financial support to the research project “Generation, transport and retention of water and suspended sediments in large dryland catchments”. The authors are also grateful to the Federal Institute of Education Science and Technology of Ceará—IFCE for the grant to support research activities.

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