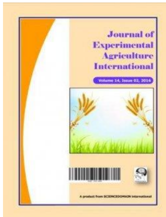

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Evaluating of Sediment Delivery Ratio on Spatial and Temporal Variabilities in Semiarid Watershed Brazil

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Authors' contributions

This work was carried out in collaboration between all authors. All authors read and approved the final manuscript.

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ABSTRACT

Evaluation of sediment delivery ratio is important for determining watershed sediment yield. Rates of both interrill and rill erosion were calculated under shrub and uncovered Inceptisols conditions and were not observed to the presence by ravines and gullies in the watershed of Jacu River, in a semiarid region, Brazil. Direct measurement campaigns of suspended sediment and bedload were also carried out by means of the US DH–48 for collection of suspended sediment samples and US BLH–84used to collect samples bed load. The soil loss due to interril erosion under uncovered conditions was equal to 8.43 t ha-1 and was considered high, and the same was true for the values of rill erosion with erodibility equal to 0.0021142 kg N-1 s-1 and critical shear stress (τc) equal to 2.34 Pa. The mean value of sediment delivery ratio of Jacu watershed was equal to 0.165 and ranged from 0.29 in the year 2008 to 0.026 in 2010. This variation was associated with the natural variability of semiarid environment, indicating the necessity of assessment for a longer period to deepen our knowledge of sediment delivery ratio of the Jacu semiarid watershed.

Keywords: Watershed sediment yield; semiarid region; sediment delivery ratio; erosion.

1. INTRODUCTION

In semiarid climatic zones, hydrological processes are variable both in time and in space. Suspended sediment load is generally high and reaches a maximum value at the beginning of flood season and after dry periods [1]. Therefore, only some of the eroded soil is routed to the basin outlet.

The ratio between the watershed sediment yield at the basin outlet and soil erosion over the basin is called the sediment delivery ratio (SDR) [2]. The values of SDR for an area have been found to be affected by catchment sediment sources, transport system, texture of eroded material, urbanization, and land cover [3] and [4]. However, sediment yield is usually not available as a direct measurement for many watersheds but is estimated by using SDR, defined as the fraction of gross erosion that is transported from a given watershed in a given time interval.

Prediction of SDR is important for sediment control needed for sustainable development of natural resources and environmental protection [5]. Estimating the amount of soil loss from watersheds and sediment yield for watershed is the first step [6] for computing SDR. High sediment yields are produced in semiarid environments because of the interaction between erosive energy and vegetation density, even if climatic seasonality, relief, watershed lithology and the extent of human activity combine to influence the erosion pattern.

Estimation of sediment transport during precipitation events is necessary for the calculation of long-term sediment yields from basins, as one single event may not represent the transport of several ‘normal’ years [7]. The equation due to Lane et al. [8] is used to descreve erosion in interrill. The Duboys channel scour equation [9] has been modified for rill erosion [10]. In the WEPP model [8] one considers the effect of runoff and water infiltration rate of breakdown. Sediment Delivery Ratio (SDR, equations [3]) have been used to estimate catchment-scale sediment yield.

The WEPP, used in the water erosion prediction Project, is one of the most promising models owing to its theoretical basis and mathematical formalization of the physical processes of soil erosion [11]. Sediment mobilized by interrill and rill erosion may be deposited by a variety of mechanisms prior to reaching stream channels [12]. The objectives of this study, therefore, were to predict sediment delivery ratio and estimate sediment transport during the events of hydraulic erosion on the semiarid Jacu watershead located in Northeastern Pernambuco, Brazil.

2. MATERIALS AND METHODS

The study area is located in the Jacu watershed limited between the coordinates latitude -8°07'55" S and -8°09'07" S and longitude -38°23'20" Wand -38°24'14" W, Fig.1 in a semiarid environment between the cities of Serra Talhada and Floresta in the state of Pernambuco, Brazil. The climate is classified as hot and dry, BWh according to the Köppen type climate classification. The most common soil types found in the watershed include the Entisol Udorthent and Fluvent raised by [13] and Inceptisol Ochrept [14].

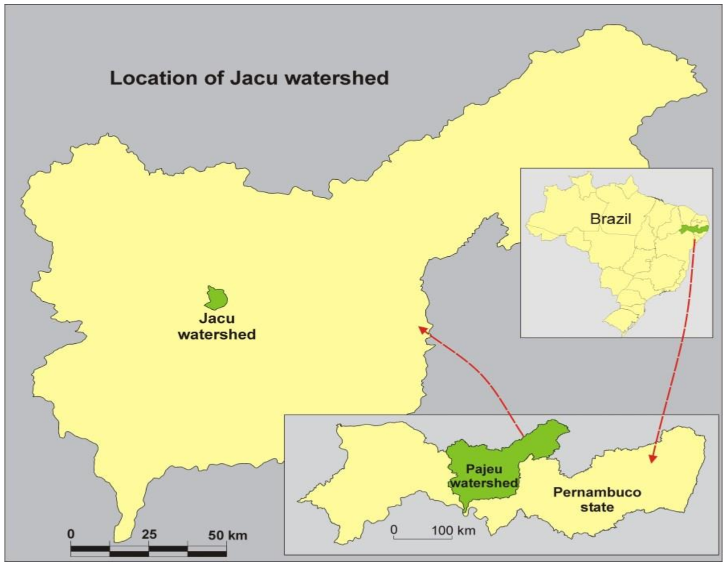

Fig. 1. Location of experimental area Jacu watersehed in Brazil

To measure stream flow rate, was installed in the control section of Jacu River the sensor for measure flow with data logger SL2000MIM for the monitoring station 23 campaigns were performed for direct measurement of hydraulic characteristics of speed and height of runoff in Jacu river. The average runoff velocity (m s^{-1}) was determined by integration of the profile through the use of a type of current meter.

The suspended sediment yield (Y) was calculated by solid discharge measured continuously in accordance with the procedure of the United States Geological Survey [15], with the use of one of sampler's sediments (US BLH-84) with the collections of bottom sediment. The method of Equal Width Increment (EWI) was used for sampling suspended sediment and in the bottom sediment.

Samples were collected by lowering and raising a sampler through the water column at the center of each increment utilizing a US DH-48 for collection of suspended sediment sampler at equal width intervals across the stream. The transit rate used for making possible the collection of representative samples was equal in both directions to seeking smaller probability to error [16].

After collecting the suspended sediment samples were taken to the laboratory where they were dried at 60°C for the determination of the concentration values of sediment, which was obtained by evaporation method indicated by United States Geological Survey [15]. The suspended solid discharge (QSS) was determined by summing the product of suspended sediment concentration (CSS) and respective liquid discharge (Q) of each vertical[17].

$$Q_{SS} \equiv \sum (C_{SS}\ Q\ l_i)\ 0{,}0864 \quad (1)$$

In this research, the solid bedload discharge was determined the following formula is applied [18].

$$Y_{SS} = \frac{Q_{SS}\ X}{A} \quad (2)$$

Gross erosion is the sum of soil loss from rill and interrill erosion, ephemeral gullies and classical gully reported in tons/acre/year. The study used field observation and not found the presence by ravines and gullies in the watershed of Jacu River.

For erosion research was used rainfall simulator with 80 - 150 Veejet nozzles, having an impact energy of 2750 kj (ha cm) [19] in interrill simulators and reproduce a distribution of droplet size and levels of kinetic energy near the natural rainfall. The average rainfall intensity 90mh^{-1} was measured using a set of 10 pluviometers placed at random within and adjacent to the working area of experimental plots.

The plots consisted of an area of 2 m 2 (1 m wide and 2 m long), with the longer dimension in the direction of slope, and were bounded by galvanized sheet metal 30 cm, driven into the ground at 20 cm depth.

Three treatments replicated three times: soil with semi-shrubby caatinga vegetation; soil with herbaceous residue in decomposition and soil uncovered; representing three likely conditions typical of interrill erosion in the watershed were employed. The experimental design was completely randomized in that treatments were assigned to units completely by chance in three replicates of each treatment.

Statistical analysis was performed using SAS version 8.0 [20], using Tukey's difference between the mean efficiencies at a 5 % level of significance and Curve Expert for comparing regression models of the best fit equation.

The pre-formed rill was delimited laterally by placing zinc metal sheets buried in the soil, subjected to erosion tests that were applied with 04 (four) flow levels randomly and for 20 minutes [21]. At the upper end, rill energy dissipaters were buried in the form of round plastic containers, so that the upper edge of the container was at the level of soil surface.

These containers had hoses for conducting water in order to reach the rill by overflowing of containers. The collected volumes of samples of liquid and solid discharges were measured in a test tube and placed in plastic containers 1L for subsequent determination of sediment concentration.

Flow velocity was measured visually with a dye tracing technique (potassium permanganate) using a stopwatch to record the time required for the dye to travel a given distance [22-24] was determined by multiplying the values obtained during the testing of surface velocity by a correction factor $\alpha = 0.6$ [21,25,26].

The slope of plots on rill was determined prior to testing, with the aid of a level, obtaining the height difference between two points of known distance, the result being expressed in mm^{-1}. In order to calculate the hydraulic radius of a preformed rill (A/P), the cross sectional area (A) of the rill and the wetted perimeter (P) was determined using perfilometer.

The perimeter of the rill was measured utilizing a curvimeter analog. The hydraulic radius that was used to calculate the shear stress of flow. From the mass of dry soil and the duration of sampling, the rates of breakdown of soil in the rill [21].

Assuming that the erosion of rill with the addition of flow, sediment load was much greater than the transport capacity, the capacity of breakdown of flow in the rill was used for determining the momentary rate of breakdown of flow [27].

Thus, soil erodibility in sulcus was determined by linear regression analysis between the average values of shear stress and the breakdown of soil obtained for each flow, as in the prediction model WEPP [28]. The soil losses were calculated from the data of instantaneous sediment concentration of runoff and the liquid discharge [29].

Experimental evaluation was done for increasing levels of flow: 1) Flow 14.95 L min^{-1}; 2) Flow 28.70 L min^{-1}; 3) Flow 39.85 L min^{-1}; and 4) Flow 67.405 L min^{-1} in four replications. Statistical analysis was performed using SAS version 8.0 [20], using Tukey's difference between the mean efficiencies at a 5 % level of significance. Curve Expert was used for comparing regression of the best-fit equation.

3. RESULTS AND DISCUSSION

Vegetation reduced flow velocity by providing a rough surface that slowed runoff velocity and promoted infiltration [30], achieved the same effect of retardation of flow through the dossal of caatinga. These results showed the importance of the caatinga vegetation cover to protect the soil of the semiarid watershed. From Table 1 it was observed that the values of hydraulic roughness for the conditions of vegetation were higher than in the uncovered soil, justifying the reduction in speed and flow and showing that the elements of dossel of caatinga vegetation and residues in contact with soil gave rise to physical and hydraulic resistance to runoff.

The flow Reynolds number and Froude number characterised a laminar and subcritical flow regime, as indicated by the values of $Re < 500$ and $Fr < 1$, respectively, typical of interrill erosion flow conditions [31-34].

The caatinga vegetation and litter on soil developed a high degree of contact that increased opportunities for infiltration slowing down, giving more time for infiltration. This was confirmed by the roughness elevation (f) and infiltration rates. Water was stored in the foliage, giving more time for infiltration, so reducing the volume of runoff [35,36,30] obtained similar relationships.

Table 1. Hydraulic characteristics of runoff generated by simulated rainfall under the conditions studied in the watershed of Jacu River

	Treatments		
Variables	**T1**	**T2**	**T3**
$q(m^2 s^{-1})$	1.4×10^{-5} B	1.9×10^{-5} A	2.9×10^{-5} A
h(mm)	0.68 ns	1.115 ns	0.68 ns
$V(m\ s^{-1})$	0.017 A	0.015 A	0.043 B
Re(adm)	17.46 ns	22.36 ns	34.58 ns
Fr(adm)	0.2391 A	0.1466 B	0.5368 A
log f(adm)	1.0643 A	1.3940 A	0.2273 B

Means followed by capital letters in the same row do not differ from each other, 5% level of significance, in Tukey test. q =liquid discharge; h= blade height of runoff; V= runoff velocity; Re= Reynolds number; Fr= Froude number; log f = hydraulic roughness (Darcy Weisbach coefficient);Treatments:T1: caatinga vegetation semi-shrub; T2: litter; T3: undercoverd soil.

Table 2. Infiltration rates, runoff coefficient (C), soil detachment rates in interrill (Di), and soil loss (PS) obtained under diferents treatments studied

	Treatments		
Variables	**T1**	**T2**	**T3**
Infiltration rates($mm\ h^{-1}$)	38.41 A	41.84 A	9.29 B
C(adm)	0.36 B	0.55 A	0.89 A
$D_i(Kg\ m^{-2} s^{-1})$	8×10^{-5} B	4×10^{-5} B	3.2×10^{-4} B
$PS(t\ ha^{-1})$	1.22 B	0.74 B	8.43 A

**Means followed by the same capital letters on the lines do not differ significantly by the Tukey test ($p < 0.05$).Treatments: T1: Caatinga semi- shorubby; T2: Litter; T3: uncovered soil.*

The soil loss for the Inceptisol uncovered area 8.43 t ha^{-1} was much higher than that observed by the caatinga vegetation semi-shrubby conditions and soil covered by litter in Table 2, constituting very high losses for young soils with poorly developed profiles, and caatinga deciduous vegetation included total loss of leaves during the dry season. Results showed that soil losses were considered very low as proposed by U.S. Department of Agriculture, FAO [37] in [38]; established in the 1950s soil-loss tolerance values.

In rill erosion the values of Reynolds numbers (Table 3) above 2500 for the larger values of flows applied between 28.7 and 67.4 L min^{-1}, characterized the regime of runoff as turbulent flow, and the lower flow of 14.95 L min^{-1} generated a regime transitional runoff [39], [40], [21,41,42]. The Froude number for all flows was below1.

The regime observed was tranquil or subcritical flow. The average gradient slope in rill plots and roughness measured by the Darcy-Weisbach

Table 3. Different discharge rates applied to the upper end of rills preformed for determining soil erodibility parameters

	Different discharge rates $(L\ min^{-1})$			
Variables	**14.95**	**28.70**	**39.85**	**67.40**
$Q(L\ min^{-1})$	12.465 B	26.135 B	36.554 A	58.723 A
$Vm(m\ s^{-1})$	0.182 B	0.238 A	0.280 A	0.310 A
$S(mm^{-1})$	0.049	0.051	0,052	0,052
Re(adm)	1,920.21 B	5,252.53 A	5,132.24 A	4,522.30 A
Fr(adm)	0.647	0.590	0,750	0,829
log f(adm)	1.396	1.418	1,166	1,087

**Means followed by the same capital letters on the lines do not differ significantly by the Tukey test ($p < 0.05$). Q= liquid discharge; Vm= mean flow velocity; S= slope in rill plots preformed; Re= Reynolds number; Fr= Froude number; log f = hydraulic roughness (Darcy Weisbach coefficient).*

coefficient (Table 3) showed no statistically significant differences.

The shear stress obtained differed significantly when low flow was compared with higher flows (Table 4) depending on the variation of hydraulic radius causing different breakdown rates of soil due to larger flows applied (39,85 and 67,40 L min^{-1}). Similarly, soil losses (PS) were already higher from the second level of flux (6.601 and 24.889 t ha^{-1}) high values were considered for soils normally very shallow and with extreme variability spatial and temporal characteristic of rainfall in semiarid, soil losses associated with man's intervention in land and water.

The value of rill erodibility (Kr) was obtained by coefficient b or slope of the regression line 0.0021142 kg N^{-1} s^{-1} [43,44], as described in [40] and the intercept with the horizontal axis was the critical shear τc 2.34 Pa (Fig. 2).

The rill erodibility values obtained were higher than those determined by Lafayette et al. [45] for Latosols (Oxisols) 0.0016 kg $N^{-1}s^{-1}$, [41] and [25] for two Argisols of 0,012 $KgN^{-1}s^{-1}$ and 0.0104 kg N^{-1} s^{-1}, respectively. This higher value was justified by the fact that this Inceptisol in semiarid regions is young soil, generally shallow and weakly developed soil, than the Latosols (oxisols) and Ultisols that are commonly found.

The value of critical shear stress (τc) of 2.34 was also lower than that determined by various Argisols [41,46,21].

The sediment yield (Yt) ranged from 0.45 to 1.72 t^{-1} y^{-1} and was considered low for 4 years (Table 5). The respective amounts of suspended sediment concentration (SSC) ranging from 874 to 376 mg L^{-1} were considered high for a small watershed and for low values of liquid discharged.

The Jacu watershed showed the average sediment concentration of 874 mg L^{-1} for a period only 45 days of flow in 2010. The rainfall distribution in simple peak events [47] was unimodal or bimodal with interannual variation characterizing the pattern of low rainfall in arid and semiarid regions concentrated in a few months of the year and poorly distributed in the space and the time. The production of sediments was considered low by the standards adopted by the World Meteorological Organization [48] for the transport of sediment limited by climate in intermittent waterways.

Table 4. Erosion parameters in rills preformed under simulated rainfall

	Different discharge rates $(L\ min^{-1})$			
Erodibility parameters	**14.95**	**28.70**	**39.85**	**67.40**
τ(Pa)	4.376 B	5.128 A	6.285 A	13.079 A
$Dr(Kg\ m^{-2}s^{-1})$	0.0028 B	0.0053 B	0.0096 A	0.0246A
$Ps(t\ ha^{-1})$	3.150 B	6.601 A	13.576 A	24.889 A

**Means followed by the same capital letters on the lines do not differ significantly by the Tukey test (p < 0.05).*

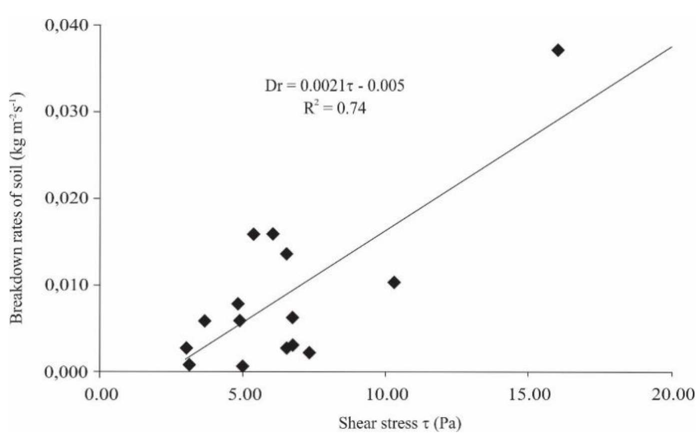

Fig. 2. Rill erodibility (Kr) and critical shear stress (τc) obtained by the linear regression generated by leading to increasing runoff

Table 5. Values of average discharged liquid (Q) discharge suspended solid [Qss] and bottom discharge [QSf]), Sediment yield determined for the period 2008 to 2011

Year	Q	SSC	X	Qss	Qsf	Yss	Ysf	Yt	Yt
	m^3s^{-1}	mg L^{-1}	days	t day^{-1}		t ha^{-1}	$year^{-1}$		t $year^{-1}$
2008	0.12	376.74	76	3.80	0.42	1.38	0.35	1.72	361.66
2009	0.06	428.41	148	2.22	-	1.57	-	1.57	329.27
2010	0.01	874.53	45	0.66	0.05	0.14	0.01	0.15	31.98
2011	0.02	473.00	105	0.87	0.04	0.43	0.02	0.45	94.71

SSC: suspended sediment concentration; Qss: discharge suspended solid; Qsf: bottom discharge solid; Yss: Suspended sediment production; Ysf: Bottom sediment production;Yt: Total sediment production.

The sediment delivery ratio (Table 6) values from 2008 to 2011 were obtained from the total sediment production (Y) in Table 5 and the gross erosion values (E) were obtained across sum the interrill erosion in Table 2 and rill erosion in Table 4. The interrill erosion value used was weighted by the area from the watershed use map and rill erosion was obtained from the flow application of 14.95 $Lmin^{-1}$ that may occur in this watershed for a high return period (100 years) [49].

Table 6. SDR – Sediment delivery ratio measured for period 2008 to 2011

Year	Sediment delivery ratio* (SDR)
2008	0.291
2009	0.265
2010	0.026
2011	0.076
Average	0.165

** Adimensional*

The quantitative fraction of all sediment broken down and transported, but which in reality came to be transported out of the watershead (SDR) varied from 0.29 in the year 2008 to 0.03 in 2010. During this period the 2010 year presented the most irregular rainfall distribution, with a low total annual value of 370.55 mm, occurring the most rainfall on 30/10/2010 with 47 mm.

This unevenness of the rainfall and flow values in semiarid environment as well observed in the values of (SDR) rain results from the convective cells formed from the mass general circulation of the atmosphere, short, small diameter and limited scope, 10 – 14 km [47] giving the rains to arid and semiarid high spatial and temporal variability, and still interannual variability rising with aridity.

That values of the magnitude of the SDR tends to increase with an increase in the area being the maximum 30% or 0.3 to watershed 0.5 to 5.2 km^2 and ranging from 0.1 to 0.38 [3]. In this research were presented estimated values of SDR calculated for an empirical relationship found in the literature equation [9] showed in Table 7.

Table 7. Sediment delivery ratio (SDR) estimated by the equations from [9], [50] and [51]

Equação	Taxa de Entrega de Sedimentos* (SDR)
Vanoni (1975)	0.409
Williams & Berndt (1972)	0.763
NRCS (1979)	0.521

**: Adimensional*

4. CONCLUSION

The sediment yield values obtained for Jacu watershed were low, because it is a small watershed, with average low slope and sediment transport limited by the semiarid climate. The soil losses by interrill erosion in the uncovered soil of 8.43 t ha^{-1}were high, as well as the rill erosion with rill erodibility of 0.0021142 kg N^{-1} s^{-1} and critical shear stress τc of 2.34 Pa. The average value of sediment delivery ratio (SDR) of Jacu watershed was 0.165 with variation of 0.29 for year 2008 to 0.026 in 2010. The large annual variability in the sediment delivery ratio is associated with relief and slope characteristics, drainage pattern, vegetation, land use, texture, and structure of soil needing a longer period of years of assessment to better knowledge of the sediment delivery rate of the Jacu semiarid watershed. The bottom sediments are formed by medium sand particles with diameters ranging from 0.15 to 0.60 mm, uniform and well – graded.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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