

Original Research Article

EVALUATING OF SEDIMENT DELIVERY RATIO ON SPATIAL AND TEMPORAL VARIABILITIES IN SEMIARID WATERSHED BRAZIL

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 was 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 USDH – 48 and USBLH – 84, respectively. The soil loss due to interrill 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 (τ_c) 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 [3]. 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) [27]. 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 [48] and [43]. 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 [37]. Estimating the amount of soil loss from watersheds and sediment yield for watershed is the first step [28] 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 [49]. The equation due to Lane et al. [26] is used to describe erosion in interrill. The Dubois channel scour equation [46] has been modified for rill erosion [32]. In the WEPP model [26] one considers the effect of runoff and water infiltration rate of breakdown. **Was not observed to the presence by ravines and gullies in the watershed of Jacu River.** Sediment Delivery Ratio (SDR, equations [48]) 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 [6]. Sediment mobilized by interrill and rill erosion may be deposited by a variety of mechanisms prior to reaching stream channels [4]. 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 watershed located in Northeastern Pernambuco, Brazil.

2. MATERIAL AND METHODS

The study area is located in the Jacu watershed between the cities of Serra Talhada and Floresta (latitude 8°07'07" S and longitude 38°23'55" W) Fig.1 in a semiarid environment 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 [31] and Inceptisol Ochrept [13].



Figure 1. Location of experimental area Jacu watershed 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 [45], with the use of one of sampler's sediments (DH-48) 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 DH48 sampler at equal width intervals across the stream. The transit rate used was provided Edwards and Glysson [11] to make possible the collection of representative samples to be equal in both directions and less prone to error.

After collecting the suspended sediment, samples were they was dried  0°C for the determination of the concentration values of sediment, which was obtained by the evaporation method indicated by United States Geological Survey [45]. The suspended solid discharge (QSS) was determined by summing the product of suspended sediment concentration (CSS) and respective liquid discharge (Q) of each vertical, following the expression Horowitz [22].

$$Q_{SS} \equiv \sum (C_{SS} Q_i) 0,0864 \dots \dots \dots (1)$$

The solid bedload discharge was determined according Gray [20].

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

86

87 Gross erosion is the sum of soil loss from rill and interrill erosion, ephemeral gullies and classical gully
88 reported in tons/acre/year. Was not observed to the presence by ravines and gullies in the watershed
89 of Jacu River.



90

91 Was used rainfall simulator with 80 - 150 Veejet nozzles, having an impact energy of 2750 kj (ha cm)
92 Meyer and Harmon [29] in interrill simulators and reproduce a distribution of droplet size and levels of
93 kinetic energy near the natural rainfall. The average rainfall intensity 90mh-1 was measured using a
94 set of 10 pluviometers placed at random within and adjacent to the working area of experimental
95 plots.

96

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

100

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

105

106 Statistical analysis was performed using SAS version 8.0 [38], using Tukey's difference between the
107 mean efficiencies at a 5 % level of significance and Curve Expert for comparing regression models of
108 the best fit equation.

109

110 The pre-formed rill was delimited laterally by placing zinc metal sheets buried in the soil, subjected to
111 erosion tests that were applied with 04 (four) flow levels randomly and for 20 minutes [8]. At the upper
112 end, rill energy dissipaters were buried in the form of round plastic containers, so that the upper edge
113 of the container was at the level of soil surface.

114

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

118

119 Flow velocity was measured visually with a dye tracing technique (potassium permanganate) using a
120 stopwatch to record the time required for the dye to travel a given distance [34],[35] and [30] was
121 determined by multiplying the values obtained during the testing of surface velocity by a correction
122 factor $\alpha = 0.6$, which has been used by Cantalice, Braidia & Cassol and Slattery & Bryan, [8], [5] and
123 [42].

124

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

129

130 The perimeter of the rill was measured utilizing a curvimeter analog. The hydraulic radius that was
131 used to calculate the shear stress of flow. From the mass of dry soil and the duration of sampling, the
132 rates of breakdown of soil in the rill were determined as Cantalice et al. [8].

133

134 Assuming that the erosion of rill with the addition of flow, sediment load was much greater than the
135 transport capacity, the capacity of breakdown of flow in the rill was used for determining the
136 momentary rate of breakdown of flow, expressed by Elliot et al. [12].

137

138 Thus, soil erodibility in sulcus was determined by linear regression analysis between the average
139 values of shear stress and the breakdown of soil obtained for each flow, as in the prediction model
140 WEPP [15]. The soil losses were calculated from the data of instantaneous sediment concentration of
141 runoff and the liquid discharge according Cantalice [9].

142

143 Experimental evaluation was done for increasing levels of flow: 1) Flow $14.95 L min^{-1}$; 2) Flow $28.70 L$
144 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 (SAS, 1999) [41], 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 [17], 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 characterized a laminar and subcritical flow regime, as indicated by the values of $Re < 500$ and $Fr < 1$, respectively, typical of interrill erosion flow conditions [21], [10], [2] and [7].

Table 1. Hydraulic characteristics of runoff generated by simulated rainfall under conditions of caatinga vegetation semi-shrub, soil covered by litter and undercoverd soil in the watershed of Jacu River.

Variables	Treatments		
	T1	T2	T3
$q (m^3 s^{-1})$	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); T1: caatinga vegetation semi-shrub; T2: litter; T3: undercoverd soil.

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. Gerits et al. [18], Wainwright [47], and Freitas et al. [17] obtained similar relationships.

Table 2. Infiltration rates, runoff coefficient (C), soil detachment rates in interrill (D_i), and soil loss (PS) obtained under conditions of caatinga vegetation semi-shrub, soil covered by litter and uncovered Inceptisol in Jacu River watershed.

Variables	Treatments		
	T1	T2	T3
Infiltration rates ($m^3 m^{-2} h^{-1}$)	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
$PS (kg m^{-2} s^{-1})$	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 ($p < 0.05$). T1: Caatinga semi-shrubby; 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 [16] in Schertz [40]; 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 [1], [23], [8],[39] and [41]. The Froude number for all flows was below 1.

The regime observed was tranquil or subcritical flow. The average gradient slope in rill plots and roughness measured by the Darcy-Weisbach coefficient (Table 3) showed no statistically significant differences.

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

Variables	Different discharge rates (L min ⁻¹)			
	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 (m m ⁻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).

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 placed extreme environmental variability.

Table 4. Erosion parameters in rills preformed under simulated rainfall.

Erodibility parameters	Different discharge rates (L min ⁻¹)			
	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 ($p < 0.05$).

The value of rill erodibility (Kr) was obtained by coefficient b or slope of the regression line 0.0021142 kg N⁻¹ s⁻¹ [25], [14], as described in Knapen & Poesen [23] and the intercept with the horizontal axis was the critical shear τ_c 2.34 Pa (Fig. 2).

The rill erodibility values obtained were higher than those determined by Lafayette et al. [24] for Latosols (Oxisols) 0.0016 kg N⁻¹ s⁻¹, Schäfer et al. [39] and Braida & Cassol [5] for two Argisols of 0,012 KgN⁻¹s⁻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 (τ_c) of 2.34 was also lower than that determined by various Argisols [39], [19] and [8].

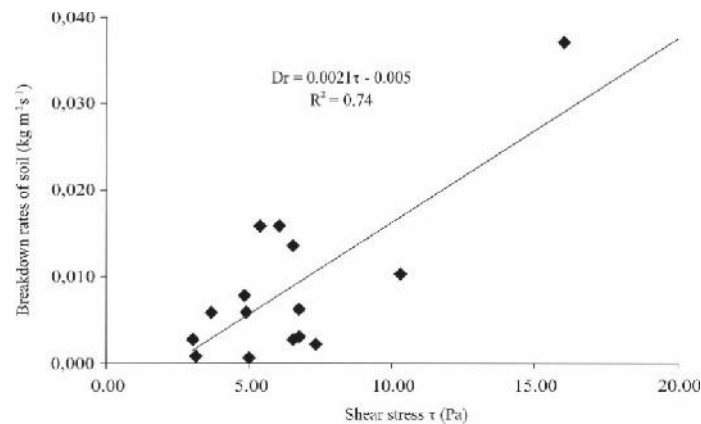


Figure 2. Rill erodibility (K_r) and critical shear stress (τ_c) obtained by the regression line of the soil detachment rates (D_r) with the respective shear stress generated by leading to increasing runoff.

The sediment yield (Y_t) 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 $mg L^{-1}$ was considered high for a small watershed and for low values of liquid discharged.

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 $m^3 s^{-1}$	SSC $mg L^{-1}$	X days	Qss $t day^{-1}$	Qsf	Yss $t ha^{-1}$	Ysf $year^{-1}$	Yt	Yt $t year^{-1}$
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 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 [44] was unimodal or bimodal with interannual variation characterizing the pattern of rainfall in arid and semiarid regions. The production of sediments was considered low by the standards adopted by the World Meteorological Organization [50] for the transport of sediment limited by climate in intermittent waterways.

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) in Tables 2 and 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 $L min^{-1}$ that may occur in this watershed for a high return period (100 years), according to Molinier et al. [33].

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 all sediment broken down and transported, but which in reality came to be transported out of the watershed (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, with the most rainfall occurring on 30/10/2010 with 47 mm. The estimated values of SDR

calculated for an empirical relationship found in the literature (table 5) were nearest to those obtained by the equation in Vanoni [46].

Table 7. Sediment delivery ratio (SDR) estimated by the equations from Vanoni [46], Williams & Berndt [51] and NRCS [36].

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 τ_c 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.

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