Comissão 3.2 - Manejo e conservação do solo e da água

RUNOFF AND SEDIMENT TRANSPORT IN A DEGRADED AREA[1]

Edivaldo Lopes Thomaz[2]

ABSTRACT

Gully erosion occurs by the combined action of splash, sheetwash and rill-wash (interrill and rill erosion). These erosion processes have a great capacity for both sediment production and sediment transport. The objectives of this experiment were to evaluate hydrological and sediment transport in a degraded area, severely dissected by gullies; to assess the hydraulic flow characteristics and their aggregate transport capacity; and to measure the initial splash erosion rate. In the study area in Guarapuava, State of Paraná, Brazil (lat 25° 24' S; long 51°24' W; 1034 m asl), the soil was classified as Cambissolo Húmico alumínico, with the following particle-size composition: sand 0.116 kg kg^{-1}; silt 0.180 kg kg^{-1}; and clay 0.704 kg kg^{-1}. The approach of this research was based on microcatchments formed in the ground, to study the hydrological response and sediment transport. A total of eight rill systems were simulated with dry and wet soil. An average rainfall of 33.7 ± 4.0 mm was produced for 35 to 54 min by a rainfall simulator. The equipment was installed, and a trough was placed at the end of the rill to collect sediments and water. During the simulation, the following variables were measured: time to runoff, time to ponding, time of recession, flow velocity, depth, ratio of the initial splash and grain size. The rainsplash of dry topsoil was more than twice as high as under moist conditions (5 g m^{-2} min^{-1} and 2 g m^{-2} min^{-1}, respectively). The characteristics of the flow hydraulics indicate transition from laminar to turbulent flow [Re (Reynolds number) 1000–2000]. In addition, it was observed that a flow velocity of 0.12 m s^{-1} was the threshold for turbulent flow (Re > 2000), especially at the end of the rainfall simulation. The rill flow tended to be subcritical [Fr (Froude Number) < 1.0]. The variation in hydrological attributes (infiltration and runoff) was lower, while the sediment yield was variable. The erosion in the rill systems was characterized as limited transport, although the degraded area generated an average of 394 g m^{-2} of sediment in each simulation.

Index terms: field measurement, water erosion, simulated rain, rainsplash, runoff.

---

(1) Received for publication in January 05, 2011 and approved in November 15, 2011.

(2) Professor, Department of Geography, State University of Center-West – UNICENTRO. St. Simeão Camargo Varela de Sá 2003, Mai-Box 3010. Zip Code 85040-430 Guarapuava (PR) Brazil. Fellow from CNPq. E-mail: edivaldo.thomaz@pq.cnpq.br

RESUMO: *ESCOAMENTO E TRANSPORTE DE SEDIMENTO EM UMA ÁREA DEGRADADA*

O processo erosivo em ravina ocorre pela ação combinada do salpico, fluxo difuso e fluxo concentrado (erosão entre sulcos e em sulcos). Esses processos erosivos possuem grande capacidade de produção e transporte de sedimento. Os objetivos deste estudo foram: avaliar o escoamento e o transporte de sedimento em uma área degradada severamente dissecada por ravinas; avaliar as características hidráulicas do escoamento e a capacidade de transporte de agregado; e mensurar a taxa inicial de salpico. A área de estudo localiza-se no município de Guarapuava, no Estado do Paraná, Brasil (coordenadas: 25°24' S e 51°24' W e altitude de 1.034 m). O solo é classificado como Cambissolo Húmico Alumínico, tendo a seguinte composição granulométrica: areia, 0,116 kg kg^{-1}; silte, 0,180 kg kg^{-1}; e argila, 0,704 kg kg^{-1}. Foram utilizadas ravinas para o estudo da resposta hidrológica e transporte de sedimento (ou seja, parcela não fechada). A simulação de chuva foi feita em oito ravinas, com solo seco e úmido. A chuva aplicada teve duração de 35 a 54 min, com intensidade de 33,7 ± 4,0 mm. Foi instalado o simulador, e posicionou-se uma calha na saída da ravina, para coletar sedimento e água. Durante a simulação, as seguintes variáveis foram medidas: tempo de concentração, tempo de empoçamento, tempo de recessão, velocidade do fluxo e profundidade do fluxo. A taxa de salpico com o solo seco foi mais de duas vezes superior em comparação à do solo úmido: 5 e 2 g m^{-2} min^{-1}, respectivamente. O fluxo apresentou condição hidráulica transicional entre laminar e turbulento (Re 1.000 to 2.000). Observou-se que a velocidade do fluxo de 0,12 m s^{-1} foi o limiar para ele tornar-se turbulento (Re > 2000), sobretudo no final da simulação. O fluxo na ravina tendeu a subcrítico (Fr < 1,0). Os parâmetros hidrológicos (infiltração e escoamento) tiveram menor variação, enquanto a produção de sedimento foi variável. A erosão nas ravinas foi caracterizada como transporte limitado, embora a perda de solo registrada na área degradada tenha sido, em média, de 394 g m^{-2} em cada simulação.

Termos de indexação: mensuração em campo, erosão hídrica, chuva simulada, salpico, escoamento.

INTRODUCTION

Water erosion is one of the major geomorphological processes on hillslopes. Erosion consists of three phases: particle detachment, transport and deposition. The onset of erosion occurs as raindrops hit the soil surface, resulting in the detachment of soil particles (Ellison, 1950). Subsequently, particle transportation occurs through overland flow (selective transport). This stage is recognized as interrill erosion (first phase) (Emmett, 1970). This erosion process (interrill) is one of the most-studied of the Brazilian territory and worldwide, described mainly for hillslopes used for agricultural systems (Silva et al., 1986; Agassi & Bradford, 1999; Montgomery, 2007; Hartemink, 2008; Nunes & Cassol, 2011).

A literature survey on soil erosion research in Brazil indicates that the main focus of erosion studies is the agricultural perspective (Barreto et al., 2008), most commonly comparing agricultural managements with regard to soil loss (Barreto et al., 2009). Erosion studies are important in view of the economic and environmental costs this process entails. In Brazil, the total cost of soil erosion in the state of Paraná is estimated at 242 million dollars a year (Telles et al., 2011).

In Brazil, numerous studies are related to interrill erosion, e.g.: the effects of sugarcane residue cover on soil loss reduction (Bezerra & Cantalice, 2006); methods of native pasture improvement and their influences on runoff and soil loss (Cassol et al., 1999); assessment of soil loss and runoff on forest ecosystems (Martins et al., 2003); determining the interrill erodibility factor (Ki) for use in the soil erosion prediction model (WEPP) (Cassol & Lima, 2003); and nutrient loss due to water erosion (Bertol et al., 2003).

Other studies on a larger scale tried to assess soil erosion in large geomorphological systems (hillslopes and catchments) as land use effects on runoff and erosion from the field/plot to catchment scales (Castro et al., 1999). The Cesium-137 method has been used to estimate erosion processes on the catchment scale (Andrello et al., 2004).

Rill erosion (concentrated flow) is studied far less than interrill erosion. During this second erosion stage, transport occurs as concentrated flow (non-selective transport). Rills are formed and induce profound changes in hydraulic flow conditions, the geometric arrangement of channels and sediment transport (Merz & Bryan, 1993, Cantalice et al., 2005, Govers, et al., 2007).

The first study of rill initiation indicated the role of overland flow velocity and depth (Horton, 1945). Subsequent studies suggested that rill initiation was not clearly defined by any specific hydraulic threshold (Slattery & Bryan, 1992); additionally, the effects of dynamics related to soil properties are of utmost importance (Bryan, 2000).

The transport of sediment carried by runoff into gullies (i.e., degraded areas) is extremely powerful and results in 50–90 % of sediment removal from the hillslope (Knighton, 1998); Govers & Poesen (1988) reported that 54–78 % of the sediments were produced by rill erosion, while Morgan et al. (1986) found that in England, rill erosion accounted for only 20–50 % of the total erosion.

Severely eroded and degraded areas are important sediment sources because they contain completely bare soil (Thomaz & Antoneli, 2008; Thomaz &Luiz, 2012). Additionally, rill structure increases the efficiency of runoff and sediment transport due to the arrangement of the drainage network, which links interrill sectors with main and secondary rills. Even if erosion is limited to small patches in the landscape (restricted areas), the sediment yield is higher than in the adjacent areas. In addition, there has been little quantification of sediment production, hydraulic runoff characteristics and sediment transport in entire rill systems of degraded areas, compared with agricultural land.

The objectives of this study were: to evaluate the hydrological and sediment transport in a degraded area severely dissected by a complex rill system; to assess the hydraulic flow characteristics and its aggregate transport capacity in the rill system; and to measure the initial rate of splash erosion.

MATERIALS AND METHODS

Field characteristics

The study area is located in the municipality Guarapuava in the state of Paraná, Brazil (Figure 1). (25°24' S; 51°24' W; 1034 m). The degraded area is approximately 0.5 ha, and the severely degraded area is approximately 1300 m^2 (nucleus with a complex rill system). The soil in the study area was classified as Cambissolo Húmico alumínico (Embrapa, 2006). The soil originated from basalt rock, is very clayey (sand 0.116 kg kg^{-1}; silt 0.180 kg kg^{-1}; clay 0.704 kg kg^{-1}), with a mean depth of approximately 1 m; the surface bulk density is 1.24 ± 0.05 g cm^{-3}, total porosity 53.1 ± 0.02 % and the C content 1.54 g dm^{-3}. The slope degree is 8 %, and the hillslope form is convex-concave. According to Köppen (1948), the climate was classified as Cfa (mesothermic, subtropical humid),

Figure 1. Study area (ES: Experimental Site).

with average temperatures in the hottest and coldest months of 20.8 °C (January) and 12.7 °C (July), respectively, and an average annual temperature of approximately 17 °C. The average annual precipitation is 1914.9 ± 361.7 mm, distributed throughout the year (long-term 1976-2008) (IAPAR, 2008).

Rainfall simulation characteristics and experimental design

Erosion measurements are fraught with difficulties due to errors and technical problems regarding measurements and the variety of conditions under which erosion occurs. Measurement plots have some limitations with regard to the plot size and the boundary effect; this technique might be considered a closed system. The approach used was based on a study of Bryan (1994), because the author used previously formed microcatchments to study the hydrological response and sediment transport. Rill systems are common in degraded areas and pre-existed in the study area. In this case, it is not necessary to use galvanized sheets to mark off the contribution area (bounded plot) because the boundaries are defined by the rills (drainage system).

The simulation areas ranged from 4 to 9.9 m^2; the average length of the main rill ranged from 4.8 to 7.2 m (average of 5.5 m), while the secondary rills had an average length of 3.5 m (rill density 1.5 ± 0.2 m m^2) (Table 1).

In a natural rainstorm, the raindrops have diameters ranging from approximately 0.5 to 6 mm. Thus, if the objective of field measurements is to simulate natural rainfall, a multi-drop rainulator is an adequate device (Agassi & Bradford, 1999). The multi-drop simulator consisted of a framework of iron pipes (¾”), a 5-m-tall nozzle (SPRACO) and water was supplied by a 2.5-HP gasoline water pump. The simulated rainfall was dripped from a height of 5 m for a period of 35–54 min (Table 1). The drop diameter varied from 0.35 to 6.35 mm, with a mean of 2.40 mm. The device produces rain with 90 % of the kinetic energy of natural rainfall and similar intensity (Bryan, 1994).

The equipment was installed and a trough was placed at the end of the rill outlet to collect sediment and water. The following variables were measured during simulation: time to runoff, time to ponding, time of recession, flow velocity and depth. After runoff initiation, the flow was measured every 2 min; additionally, the water was assessed in the laboratory for sediment concentration (oven evaporation). The rain intensity was measured with six manual rain gauges installed in the simulation area. The water for the rain simulation came from a stream located near the experimental site (turbidity < 7.6 NTU).

The splash rate was measured in a splash cup designed by Morgan (1981). Before the rainfall began, five splash cups were installed in the simulation area, and the rainfall was maintained for 5 to 8 min. After this time, the splash cups were removed to quantify the detachment rate (g m^{-2} min^{-1}) and analyze grain size. The period for splash rate measurement was similar to that used by Wainwright (1996) because after rainfall, an interaction between the raindrops and the water on the surface occurs and causes a reduction in the splash rate (Bryan, 2000).

Metal rings that (volume 95.5 cm^{-3}) were used to collect surface soil (0–5 cm) to assess water-stable aggregates (WSA) > 0.5 mm (Bryan, 1968). The samples (50 g) were shaken in tap water (temperature 20 °C and 39.0 µS) for 20 min at 30 rpm (Kemper & Rosenau, 1986). The weight of the water-stable aggregates (WSA) > 0.5 mm was expressed as percentage of the original soil weight. The dry aggregate stability of the surface soil (0–5 cm) in both the interrill and micro- fan deposits at the rill outlet were determined using

Table 1. Rill system and rainfall simulation characteristics

Rill system	Antecedent moisture	Rainfall		Rill density	Rill area	Water characteristics
		Duration	Intensity			
	%	min	mm h^{-1}	m m^2	m^2	Temp. °C/µS
R1	9.7 ± 1.2	54	33.9	nr	8.6	nr
R2	5.8 ± 0.9	35	39.4	nr	4.0	nr
R3	27.2 ± 2.7	50	33.2	1.5	8.9	17.1/61
R4	27.2 ± 2.7	50	31.1	1.3	9.9	20.5/60.8
R5	27.2 ± 2.7	50	30.2	1.4	8.4	nr
R6	27.2 ± 2.7	50	28.7	1.7	6.8	21.1/58.8
R7	13.6 ± 2.1	39	33.9	nr	8.6	nr
R8	10.0 ± 0.6	44	39.4	nr	4.0	nr

Note: nr (not recorded). µS: electrical conductivity.

a set of sieves (mesh size 2.0, 1.0, 0.5, 0.25, 0.125, and < 0.125 mm). The samples (50 g) were agitated for one minute (Díaz-Zorita et al., 2002). The total material retained in the trough during each rainfall simulation was separated with the same set of sieves. The grain size distribution was analyzed (mean and standard deviation) through descriptive statistics.

The flow width and depth were measured by a thin ruler, and the flow velocity was measured using blue methylene (dye tracing) (Govers, 1992). The average of these parameters was obtained from 3–5 replications, and the flow velocity corrected by multiplying the conversion factor (0.7) by the shallow flow (Dunne & Dietrich, 1980; Slattery & Bryan, 1992). The flow velocity and flow depth were measured at approximately 1.5 m above the trough (rill outlet). Certain hydraulic parameters were measured and are described in the following equation (Reynolds number (Re), Froude Number (Fr), Darcy-Weisbach friction factor (ff), shear stress and stream power. The hydraulic parameters were measured only in the rill systems R3, R4, R5 and R6 because the simulation time and antecedent moisture conditions were similar.

$$Re = VR/\upsilon \quad (1)$$

were, Re = Reynolds number; V = flow velocity (m s^{-1}); R = hydraulic radius (m); υ = fluid viscosity (m^2 s^{-1}).

$$Fr = V/(gR)^{0.5} \quad (2)$$

were, Fr = Froude number; g = acceleration due to gravity (m s^{-2}).

$$ff = 8gRS/V^2 \quad (3)$$

were, ff = Darcy-Weisbach friction factor; S = slope (m m^{-1}).

$$\tau = \rho gRS \quad (4)$$

were, τ = shear stress (Pa); ρ = density of water (kg m^{-3}).

$$\omega = \rho qgS \quad (5)$$

were, ω = stream power (W m^{-2}); q = discharge (m^3 s^{-1}).

RESULTS AND DISCUSSION

Rainsplash

A large amount of particles was removed in two simulations (R1 and R2) from the dry topsoil. The particle detachment rate under these conditions was more than twice as high as on surface with higher moisture content (Table 2). Additionally, the rain intensity was slightly higher in these two simulations.

Particles between 0.063–0.250 mm are the most detachable by raindrop impact (Morgan, 2005). The particle sizes detached by splash were distributed as follows: 42.3 ± 7.8 % of the macroaggregates were > 0.250 mm, while 57.7 ± 4.5 % of the microaggregates were < 0.250 mm. The measurements show that rainsplash mobilized approximately 45.3 % of the total material transported through the rill system. However, of the total amount of particles > 0.250 mm detached by splash, only 70 % reached the rill outlet. An even lower percentage (40 %) of particles < 0.250 mm reached the rill outlet. Material that was previously deposited on the rill bottom and subsequently transported by the concentrated flow should be considered in this evaluation.

Splash rates increased at the beginning of the rain event and then decreased (Mermut et al., 1997). When the soil is dry, soil loss is greater, and much energy is expended in breaking particles; when the soil water increases, the shear strength of the drop decreases because the soil becomes fluid and increasingly vulnerable to water inflow. Finally, during the rainfall event, the water on the surface increased and the drops consequently began to interact with the shallow flow that reduced soil particle detachment by drop impact (Bryan, 2000).

In addition, the surface in the degraded areas is exposed to a constant drying cycle, causing weakness in the aggregate structure (mechanical breakdown) and increasing the splash rate. According to Kuhn & Bryan (2004), this dynamic is important to aggregate breakdown during interstorm periods.

Hydrological response and soil loss

The time to ponding at scattered points within the plot was approximately 10 min. The recession

Table 2. Total amount of particles detached by rainsplash

Measurement(1)	Detached particle	Total detached particle
	g m^{-2} min^{-1}	g m^{-2}
R1	4.5(2)	22.4
R2	5.6	27.8
R3	2.4	11.8
R4	1.1	8.8
R5	1.4	11.3
R6	3.4	27.5

(1) R1 and R2 (dry soil); R3 to R6 (moist soil). (2) Average of 5 splash cups.

time was only 1.1 min because the soil had a high infiltration capacity (27.8 mm h^{-1}) in the end of the simulation. Infiltration was higher at the beginning of simulation, and gradually decreased throughout the experiment. Infiltration increased during the simulation in only one rill system (R4). This increase occurred due to the presence of bioturbation (ant holes), which intercepted the rill flow for approximately 5 min. As a result, at this time, the infiltration increased from 24.0 mm h^{-1} to 28.0 mm h^{-1}.

Even in the simulation with high antecedent moisture (R3, 4, 5 and 6), high soil infiltration capacity was recorded (20.7–27.7 mm h^{-1}) (Table 3); infiltration rates from 15 to 30 mm h^{-1} are considered high (Reichardt, 1990).

During the simulation, ponding began in the sectors of the interrill and then expanded gradually down the rill; subsequently, some ponding occurred in the main rill. The average time for the contribution to the runoff of the whole rill system was 21 min. This delay between the diffuse flow contribution from the interrill and concentrated flow in the rill was due to the flow being completely absorbed by the sediments that had been previously deposited at the rill bottom. The concentrated flow in the rills that had a large amount of sediment at the bottom occurred due to the coalescence of small ponds. Thus, the dynamic flow within the rill consisted of a sequence of rilles and a pool; in addition, scouring deposits were formed within the rill, particularly near the trough.

There was significant runoff and sediment transport from the secondary rills to the main rill. Microchannels were formed in the interrill sectors; however, they were not detectable before the rainfall simulation (tertiary protochannel). It was verified that these channels carried a significant quantity of sediment particles by shallow flow into the main rill. The saturation condition in the interrill area occasionally caused small amounts of "mudflow" transport in some of the microchannels (fluidized flow sediment). Bank collapse and scouring deposition were observed in the main rill.

During the measurements, the sediment concentration ranged from 0.1 to 35.5 g L^{-1}, with an average of 7.8 g L^{-1} (all rill systems were considered); however, the sediment yield pattern was irregular. Rill systems R3 and R4 showed higher concentrations at the beginning of the experiment (15.3 g L^{-1}) and then decreased gradually at the end of the measurement (2.1 g L^{-1}). In contrast, in rill systems R5 and R6, the sediment concentration was lower at the beginning of the experiment (2.9 g L^{-1}) and increased progressively at the end (21.8 g L^{-1}). Finally, in rill systems R7 and R8, the sediment concentration was irregular with pulses of increase and decrease in the sediment concentration throughout the experiment. Despite the variability in the sediment concentration, the soil loss and the sediment yield were less variable in the rill systems (Table 3).

Hydraulic flow characteristics and sediment transport

The hydraulic flow conditions were highly variable in the rill systems. At least three interrill, rill and rill outlet flow patterns were identified. The interrill sectors were dominated by diffuse flow with a depth of approximately 1 mm; thus, there was an important interaction between the raindrop impact and the shallow overland flow because the water layer was not thick enough to protect the laminar flow against the raindrop impact. Past studies have indicated that the increase in the turbulence of overland flow due to the raindrop impact modifies the hydraulic conditions of the overland flow and the transport capacity (Emmett, 1970). In this case, sediment transport from the interrill into the rill occurred through fine particle drag. However, concentrated flow occurred in the main and secondary rills; this will be discussed in detail in a

Table 3. Summary of sediment production and hydrological response in the rill systems

Rill system	Mean sed. conc.	Soil loss	Sediment yield	Infiltration	Runoff Coefficient
	g L^{-1}	g m^{-2}		mm h^{-1}	%
R1	-	-	-	33.9	-
R2	-	-	-	39.4	-
R3	22.7	41.3	43.9	27.7	19.7
R4	81.3	10.3	18.5	25.7	21.0
R5	205.2	15.1	39.5	23.0	31.6
R6	20.7	20.5	23.5	20.7	38.1
R7	9.5	20.5	21.6	26.9	20.7
R8	207.2	39.8	91.6	25.2	36.2

later section. Finally, the flow near the trough was wider (37.2 ± 8.0 cm) and shallower (< 2.0 mm). These hydraulic geometry changes resulted in conditions for material deposition, micro-fans and scouring formation at the rill outlet (near the trough).

The rill flow increased in depth, width and velocity from the headwaters downstream. The flow depth varied from 2.3 to 5.3 mm (average 3.5 ± 0.9 mm), the flow width from 4.9 to 15.6 cm (average 8.5 ± 4.0 cm) and the flow velocity from 0.06 m s^{-1} to 0.21 m s^{-1} (average 0.12 ± 0.04 m s^{-1}). The discharge ranged from 1.5 to 17.0 cm^3 s^{-1} (average 11.5 ± 4.7 cm^3 s^{-1}) and tended to increase at the end of the experiment. The depth, flow velocity and discharge are essential for sediment transport. During the simulations, a change in these parameters was observed, affecting the hydraulic flow characteristics and sediment transport rate. The sediment concentration and hydraulic parameters were measured during the experiment in each rill system (Table 4).

The Reynolds number tended to increase at the end of each experiment, particularly when the flow velocity was higher. It was observed that a flow velocity of 0.12 m s^{-1} was the threshold for turbulent flow (Re > 2000). The Reynolds number (Re) measured during each experiment ranged from 793.7 to 3603.6. The average of the simulations was 1685.9 ± 712.8; thus, this pattern indicates transitional flow characteristics from laminar to turbulent flow (Re 1000 to 2000). However, the flow behavior varied in each rill system. The flow in rill R4 was transitional (Re 1403.8), while rills R3 and R6 registered turbulent flows of 2418 and 2487, respectively, only at the end of the experiment (Re > 2000). Additionally, turbulent and supercritical flow were observed in rill R5 (Fr ≥ 1.0), while in the other rills, the flow was subcritical (Fr < 1.0) (Table 4).

The data from this study are similar to those recorded by Cantalice et al. (2005) under simulated rainfall on preformed rills and without additional flow (run-on). However, the results of this study could not be compared directly to other studies because they were related to interrill (Emmet, 1970; Cassol & Lima, 2003; Nunes & Cassol, 2011) or rill initiation processes (Dunne & Aubry, 1986, Slattery & Bryan, 1992), or the experiment was performed on preformed rills (Cantalice et al., 2005). In contrast, the hydroerosive processes measured in this study were carried out in a well-established rill system. Nevertheless, the flow velocity and discharge recorded in the rill system were similar to the empirical model proposed by Govers (1992) for bare soil.

It was observed during the simulation that the surface of the interrill sector was more homogeneous and smoother than the rill bottom. Also, poorly sorted sediment was deposited at the rill bottom, increasing the surface roughness. Despite this roughness within the rill combined with the shallow flow, the relationship between the Reynolds number and the Darcy-Weisbach friction factor indicates that the roughness was throughout the rainfall simulation. According to Bryan (2000), when the relationship between these two parameters results in a concave line (negative), the flow has covered the surface roughness.

The hydraulic conditions for flow and sediment transport did not occur in a linear manner (shear stress and stream power) (Figure 2). The power function (ax^b) was the best relationship between the hydraulic flow and the sediment transport. However, the two hydraulic properties were not significantly different. There was a wide variation that was not explained by the two properties (approximately 50 %). It is emphasized that adjustments to the equations were made in this experiment.

Table 4. Summary of the hydraulic attributes and sediment concentration

Hydraulic attributes	Rill system			
	R3	R4	R5	R6
Discharge (cm^3 s^{-1})	9.8 ± 4.5	11.0 ± 2.9	14.0 ± 4.6	11.6 ± 5.5
Flow velocity (m s^{-1})	0.11 ± 0.02	0.09 ± 0.02	0.18 ± 0.03	0.10 ± 0.01
Flow depth (mm)	3.36 ± 1.0	4.0 (nr)	3.2 ± 0.7	3.5 ± 1.1
Slope (m m^{-1})	0.044 (nr)	0.075 (nr)	0.09 (nr)	0.06 (nr)
Re (Reynolds Number)	1402 ± 587.7	1404 ± 381.8	2303 ± 810.4	1535 ± 623.5
Fr (Froude Number)	0.61 ± 0.11	0.44 ± 0.11	1.00 ± 0.12	0.58 ± 0.05
ff (Darcy-Weisbach friction factor)	0.99 ± 0.27	3.85 ± 2.3	0.76 ± 0.21	1.49 ± 0.34
Shear stress (Pa)	1.45 ± 0.44	2.94 ± (nr)	2.85 ± 0.64	2.06 ± 0.65
Stream power (W m^{-2})	0.47 ± 0.22	0.82 ± 0.22	1.47 ± 0.47	1.00 ± 0.48
Sediment concentration (g L^{-1})	2.7 ± 1.9	12.9 ± 13.1	16.4 ± 9.5	2.1 ± 3.0

nr: not recorded.

Other authors have commented on the difficulties of predicting sediment transport based on physical equations. Cantalice et al. (2005) were able to explain 57 % of the sediment transport using the stream power property in a field experiment, while Slattery & Bryan (1992) could explain 77 % of the sediment transport for the same property in a laboratory experiment.

Aggregate transportation in a rill system

In degraded areas, the soil is exposed (B horizon) and has a low amount of C; in addition, the absence of vegetation results in difficulties regarding the larger aggregate's stability. In the interrill sector, 72.3 % of the total aggregates were > 0.5 mm (Table 5). The interrill sector (rill divided) displayed a large amount of aggregates > 1.0 mm, which are less prone to transportation in shallow flow (Morgan, 2005). In contrast, the characteristics of the material collected at the rill's outlet (micro-fan deposit) were different. At this point, the amount of aggregates > 2.0 mm was very low, and the total amount of aggregates > 0.5 was only 48.3 %. The amount of aggregates ≤ 0.250 mm was high (51.7 %) in comparison with the interrill sector (27.7 %).

Likewise, as the rill materials were deposited, the material that was retained in the trough after the rain simulation was poor in aggregates > 2.0 mm, while the total amount of aggregates > 0.5 mm was barely 45.1 %. In addition, the material retained in the trough had a similar amount of aggregates < 0.250 mm (54.9 %).

Under pressure during dry sieving, the aggregates (particularly > 1.0 mm) remained structured. However, when subjected to water pressure (wetting process), large aggregates broke down into smaller particles. Thus, aggregates > 2.0 mm contribute on average 28.5 % to the smaller fractions (e.g., deposit and trough). Aggregates of 1.0 mm are relatively

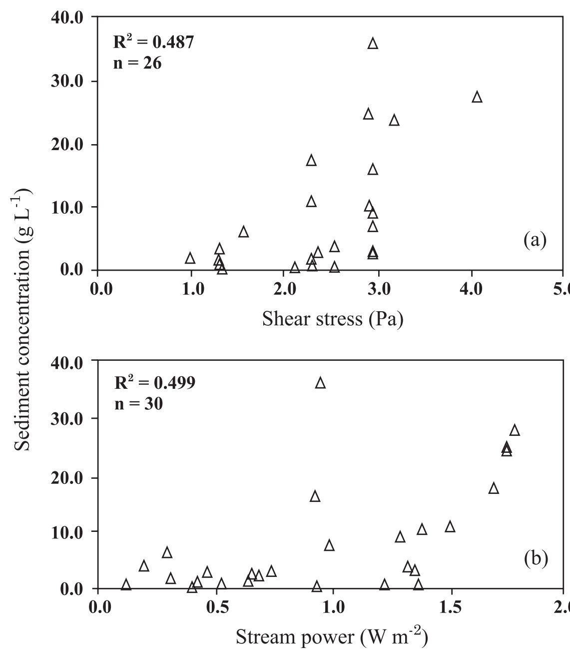

Figure 2. Relationship between the hydraulic parameter and the sediment concentration: (a) shear stress and (b) stream power.

stable in the presence of water and only 5.9 % of the increase in the sizes of the other particles comes from the disruption of these aggregates. The largest increase in the particle fraction due to the disruption of larger aggregates occurs in the following sequence: 0.5 mm (10.4 %), 0.250 mm (9.5 %), < 0.125 mm (7.8 %) and 0.125 mm (6.7 %).

The value registered above indicates that the hydraulic flow conditions during the rainfall simulation reproduced the transport of aggregate similar to that of the rill deposit caused by natural events. The flow probably did not reach the hydraulic conditions to transport aggregates ≥ 1.0 mm, because only 9.4 % of this aggregate class was collected at

Table 5. Distribution of aggregate fraction according to different sieving conditions (dry or moist) and rill system positions (interrill, rill deposit and trough)

Aggregate size	Interrill(1)	Rill deposit outlet(1)	Rainfall Simulator(2) (deposit in trough)	Interrill(3) WSA> 0.5 mm
mm	%			
> 2.0	32.0 ± 1.4	3.5 ± 0.3	0.9 ± 0.4	
1.0	22.2 ± 0.8	16.3 ± 1.4	8.5 ± 2.6	
0.5	18.1 ± 0.4	28.5 ± 1.4	35.7 ± 12.6	51.8 ± 4.1
0.25	13.0 ± 0.9	22.5 ± 0.9	29.7 ± 2.4	
0.125	8.0 ± 0.7	14.7 ± 1.0	13.5 ± 6.6	
< 0,125	6.7 ± 0.6	14.5 ± 2.2	11.7 ± 7.8	
Total	100.0	100.0	100.0	

(1) (n 7). (2) (n 6). (3) (n 11). (1,2) dry aggregate stability and (3) water aggregate stability, average ± S.D.

the trough. On the contrary 19.8% of the aggregates in the rill deposit were ≥ 1.0 mm. Probably, the material accumulated at the rill's exit (deposit) was carried out by several rainfall events with different physical characteristics (e.g., intensity, duration and frequency).

CONCLUSIONS

1. Splash erosion was significant, especially microaggregate detachment < 0.250 mm (57.7%). From a dry soil surface, particle detachment was more than twice as high as from moist surface soil.

2. The stability of aggregates in the degraded area (> 2.0 mm) was low when wetted, which caused slaking into smaller particles.

3. The transport of particles and aggregates in the rill system was non-selective, and particles and aggregates larger than 1.0 mm were carried through the rill system.

4. The hydraulic flow characteristics indicated transitional conditions between laminar and turbulent flow (Re 1000–2000). Additionally, a flow velocity of 0.12 m s^{-1} was observed as the threshold for turbulent flow (Re > 2000), especially at the end of the rainfall simulation. The rill flow tended to be subcritical (Fr < 1.0).

5. The power function (ax^b) was the best relationship between the hydraulic flow and sediment transport, despite the low correlation (< 50%).

ACKNOWLEDGEMENTS

This research was supported by the First Projects Program – Infrastructure for Young Researchers – PPP/2006 (Projects 19/2006 – Fundação Araucária – CNPq). Project: Development and application of rainfall simulator to study erosion processes in degraded area (Protocol 10595).

I would like to thank Hélio Filiposki (*in memoriam*) for his kind permission to carry out the experiments on his property. Also, I would like to thank Adalberto Alves Pereira, Fagner Dallaqua and Felipe Alexandre for their help with the time-consuming field work and laboratory tests.

I am particularly indebted to Prof. Rorke B. Bryan for his advice and for the nozzles to construct the rainfall simulator. Also, the author acknowledges the useful comments from anonymous referees and Associate Editors that helped to improve the paper.

LITERATURE CITED

AGASSI, M. & BRADFORD, J.M. Methodologies for interrill soil erosion studies. Soil Tillage Res., 49:277-287, 1999.

ANDRELLO, A.C.; APPOLONI, C.R. C. & GUIMARÃES, M.F. Soil erosion determination in a watershed from Northern Paraná (Brazil) Using ^{137}Cs. Braz. Arch. Biol. Technol., 47:659:667, 2004.

BARRETTO, A.G.O.P.; BARROS, M.G.E. & SPAROVEK, G. Bibliometria da pesquisa brasileira em erosão acelerada do solo: Instituições, temas, espaço e cronologia. R. Bras. Ci. Solo, 33:1845-1854, 2009.

BARRETTO, A.G.O.P.; BARROS, M.G.E. & SPAROVEK, G. Bibliometria, história e geografia da pesquisa brasileira em erosão acelerada do solo. R. Bras. Ci. Solo, 32:2443-2460, 2008.

BERTOL, I.; MELLO, E.L.; GUADAGNIN, J.C.; ZAPAROLLI, A.L.V. & CARRAFA, M.R. Nutrient losses by water erosion. Sci. Agric., 60:581-586, 2003.

BEZERRA, S.A. & CANTALICE, J.R.B. Erosão entre sulcos em diferentes condições de cobertura do solo, sob cultivo da cana-de-açúcar. R. Bras. Ci. Solo, 30:565-573, 2006.

BRYAN, R.B. Microcatchment hydrological response and sediment transport under simulated rainfall on semi-arid hillslopes. In*:* BRYAN, R.B., ed. Soil erosion, land degradation and social transition: Geoecological analysis of semi-arid tropical region, Kenya. Cremlingen-Destedt, Catena, 1994. p.71-96. (Advances in Geoecology, 27)

BRYAN, R.B. Soil erodibility and processes of water erosion on hillslope. Geomorphology, 32:385-415, 2000.

BRYAN, R.B. The development, use and efficiency of indices of soil erodibility. Geoderma, 2:5-26, 1968.

CANTALICE, J.R.B.; CASSOL, E.A.; REICHERT, J.M., & BORGES, A.L.O. Hidráulica do escoamento e transporte de sedimentos em sulcos em solo franco-argilo-arenoso. R. Bras. Ci. Solo, 29:597-607, 2005.

CASSOL, E.A.; LEVIEN, R.; JONG van LIER, Q. & BADELUCCI, M.P. Infiltração de água e perdas de água e solo por erosão influenciadas por diferentes métodos de melhoramento da pastagem nativa gaúcha. R. Bras. Ci. Solo, 23:923-931, 1999.

CASSOL, E.A. & LIMA, V.S. Erosão em entressulcos sob diferentes tipos de preparo e manejo do solo. Pesq. Agropec. Bras., 38:117-124, 2003.

CASTRO, N.M.R.; AUZET, A.V.; CHEVALLIER, P. & LEPRUN, J.C. Land use change effects on runoff and erosion from plot to catchment's scale on the basaltic plateau of Southern Brazil. Hydrol. Proc., 13:1621-1628, 1999.

DÍAZ-ZORITA, M.; PERFECT, E. & GROVE, J.H. Disruptive methods for assessing soil structure: Review. Soil Tillage Res., 64:3-22, 2002.

DUNNE, T. & DIETRICH, W.E. Experimental study of Horton overland flow: II. Hydraulic characteristics and hillslope hydrographs. Z. Geomorphol. (Supp. Bd.), 35:60–80, 1980.

DUNNE, T. & AUBRY, B.F. Evaluation of Horton´s theory of sheetwash and rill erosion on the basis of field experiments. In: ABRAHAMS, A.D., ed. Hillslope processes. United Kingdom, The Binghamton Symposia in Geomorphology, 1986. p.31-53. (International Series, 16)

ELLISON, W.D. Soil erosion by rainstorms. Science, 111:245-249, 1950.

EMPRESA BRASILEIRA DE PESQUISA AGROPECUÁRIA - EMBRAPA. Centro Nacional de Pesquisa de Solos. Sistema brasileiro de classificação de solos. Rio de Janeiro, 2006. 306p.

EMMETT, W.W. The hydraulics of overland flow on hillslopes. Washington, Geological Survey Professional, 1970. 68p. (Paper 662-A)

GOVERS, G. & POESEN, J. Assessment of the interrill and rill contributions to total soil loss from an upland field plot. Geomorphology, 1:343-354, 1988.

GOVERS, G. Relationship between discharge, velocity and flow area for rills eroding loose, non-layered materials. Earth Surface Proc. Landf., 17:515-528, 1992.

GOVERS, G.; GIMÉNEZ, R. & OOST, K.V. Rill erosion: Exploring the relationship between experiments, modeling and field observations. Earth-Sci. Rev., 84:87-102, 2007.

HARTEMINK, A. E. Soils are back on the global agenda. Soil Use Manag., 24:327-330, 2008.

HORTON, R.E. Erosional development of streams and their drainage basins: Hydrophysical approach to quantitative morphology. B. Geol. Soc. Am., 56:370–375, 1945.

INSTITUTO AGRONÔMICO DO PARANÁ - IAPAR. Histórico da estação agrometeorológica de Guarapuava. Londrina, 2008.

KEMPER, W.D. & ROSENAU, R.C. Aggregate stability and size distribution. In: KLUTE, A., ed. Methods of soil analysis: Physical and mineralogical methods. Madison, SSSA, 1986. Part 1. p.425-442. (Book Series, 5)

KNIGHTON, D. Fluvial forms and processes: a new perspective. London, Arnold, 1998. 383p.

KÖPPEN, W. Climatología: Con un estudio de los climas de la tierra. México, Fondo de Cultura Económica, 1948.

KUHN, N.J. & BRYAN, R.B. Drying, soil surface condition and interrill erosion on two Ontario soils. Catena, 57:113-133, 2004.

MARTINS, S.G.; SILVA, M.L.N.; CURI, N.; FERREIRA, M.M.; FONSECA, S. & MARQUES, J.J.G.S.M. Perdas de solo e água por erosão hídrica em sistemas florestais na região de Aracruz (ES). R. Bras. Ci. Solo, 27:395-403, 2003.

MERMUT, A.R.; LUK, S.H.; RÖMKENS, M.J.M. & POESEN, J.W.A. Soil loss by splash and wash during rainfall from two loess soils. Geoderma, 75:203-214, 1997.

MERZ, W. & BRYAN, R.B. Critical conditions for rill initiation on sandy loam Brunisols: Laboratory and field experiments in southern Ontario, Canada. Geoderma, 57:357-385, 1993.

MORGAN, R.P.C.; MARTIN, L. & NOBLE, C.A. Soil erosion in the United Kingdom: A case study from Mid-Bedfordshire. Silsoe College, 1986. (Occasional Paper,14)

MORGAN, R.P.C. Field measurement of splash erosion. Inter. Assoc. Sci. Hydrol. Publ., 133:373-382, 1981.

MORGAN, R.P.C. Soil erosion and conservation. Oxford, Blackwell, 2005. 304p.

MONTGOMERY, D.R. Soil erosion and agricultural sustainability. Proc. Nat. Acad. Sci. USA, 33:13268-13272, 2007.

NUNES, M.C.M. & CASSOL, E.A. Produção de sedimentos pela erosão em entressulcos em três Latossolos do Rio Grande do Sul. R. Bras. Eng. Agríc. Amb., 15:541-547, 2011.

REICHARDT, K. A água em sistemas agrícolas. São Paulo, Manole, 1990. 188p.

SILVA, I.F.; ANDRADE, A.P.; CAMPOS FILHO, O.R. & OLIVEIRA, F.A.P. Efeito de diferentes coberturas vegetais e de práticas conservacionistas no controle da erosão. R. Bras. Ci. Solo, 10:289-292, 1986.

SLATTERY, M. & BRYAN, R.B. Hydraulic conditions for rill incision under simulated rainfall: a laboratory experiment. Earth Surface Proc. Landf., 17:127-146, 1992.

TELLES, T.S.; GUIMARÃES, M.F. & DECHEN, S.C.F. The costs of soil erosion. R. Bras. Ci. Solo, 35:287-298, 2011.

THOMAZ, E.L. & ANTONELI, V. Erosão e degradação do solo em área cultivada com erva-mate (*Ilex paraguariensis*), Guarapuava-PR. Geociências, 27:21-31, 2008.

THOMAZ, E. L. & LUIZ, J. C. Soil loss, soil degradation and rehabilitation in a degraded land area in Guarapuava (Brazil). Land Degradation & Development, 23:72-81, 2012.

WAINWRIGHT, J. Infiltration, runoff and erosion characteristics of agricultural land in extreme storm events, SE France. Catena, 26:27-47, 1996.