Experimental testing of some basic assumptions used in physically based soil erosion models by means of rill experiments

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Abstract

In spring 2009, four rill experiments were accomplished on a field. Most external factors as well as discharge quantity (9 L min^{-1}) were held constant or at least in a similar range. Following most process based, deterministic soil erosion models, derived hydraulic and erosion parameters should therefore also be also similar. However, the results from the different experiments show clear differences in sediment concentration, transport rates and other measured as well as calculated values. We measured average sediment concentrations oscillating between 1.8 and 44 g L^{-1}, average transport rates between 0.0004 and 0.015 kg s^{-1} and average detachment rates from 0.0006 to 0.015 kg m^{-2} s^{-1}, while the average flow velocity scattered between 0.14 and 0.21 m s^{-1}, the average hydraulic radius from 0.74 up to 1.28 cm and the average slope at the sampling points between 2.1 and 3.2°. These are relative measurement errors (RME) of higher than 60% for the erosion parameters whereas the RMEs

of the parameters used in models to calculate the shear stress values are lower than 20%. In contrast to our experimental results, a model simulation would produce erosion parameters with low RMEs. This reveals the general problems of using process based, deterministic models for erosion in shallow rills. While soil erosion models simulate the processes resulting from the shear forces of flowing water on the soil surface, other processes like side wall failure, headcut retreat and plunge pool dynamics are not taken into account. Our results suggest that these other processes may contribute substantially to rill erosion processes.

1 Introduction

Modelling soil erosion processes is an important task for geomorphologic research and understanding landscape evolution. Soil erosion models are also used to evaluate land use systems, and derive guidelines for land use management. Model concepts can be empirical (e.g. USLE) or based on physical process description (e.g. WEPP, LISEM). There are also stochastic approaches found in the literature for describing and modelling sediment detachment and transport (Einstein, 1937; Mirtskhoulava, 1988; Wilson, 1993; Govindaraju and Kavvas, 1994; Lisle et al., 1998; Hairsine and Rose, 1991; Govers, 1991; Nearing, 1991; Shaw et al., 2008; Sidorchuk, 2002; Sidorchuk et al., 2004; Sidorchuk, 2005 a; Sidorchuk, 2005 b; Sidorchuk et al., 2008; Sidorchuk, 2009). However to date no operational version of these stochastic approaches has been available.

What is the background of physical based soil erosion models?

Most of the models used nowadays are physical based, also called process based. Knapen et al. (2007) distinguish between excess shear stress models and excess stream power models. In the first case, transport and detachment capacities are calculated using shear stress alone, in the other, shear stress is replaced by stream power which is the product of shear stress and flow velocity. In both cases, a critical soil parameter (critical shear stress or critical stream power) is exceeded by a hydraulic factor (shear stress or stream power) which enables an entrainment of soil particles. Shear stress is therefore a basic factor for the physically based soil erosion models, describing the drag force exerted by the flow on the bed (Giménez and Govers, 2002). For inferring shear stress and the derived detachment and transport capacity in soil erosion modelling, a set of input parameters are typically used in slightly varying combinations: slope, liquid density, flow velocity, hydraulic radius, wetted perimeter, flow cross section and water depth (Knapen et al., 2007). Due to the deterministic nature of the physical based models, the same input parameters will always deliver the same results. These models often assume a linear relation between shear stress and soil detachment (Lyle and Smerdon, 1965; Torri et al., 1987; Ghebreiyessus et al., 1994; Nearing et al., 1997), which means that for a given shear stress soil detachment will always be the same

Where have experiments been conducted and what questions have been addressed?

Following Kleinhans et al. (2010) there are several ways for geoscientists to create results or data sets:

- Field observations
- Field experiments
- Laboratory experiments
- Modelling

Measurements on soil erosion have been conducted in both the field and experimentally in the lab. In laboratory experiments, the initial and boundary conditions can be well controlled. Soil parameters are well known, rill forms and slope can be adapted to the specific questions. So, physical laws can be tested in a controlled environment. However Giménez and Govers (2002) showed that parameters determined under laboratory conditions can not be easily transferred to natural environments.

The latter have given detailed insight into partial processes of soil erosion and have been used to derive empirical relationships between descriptors of the forces exerted by flowing water and sediment detachment and transport. For example Brunton and Bryan (2000) and Bryan and Poesen (1989) showed in laboratory experiments that headcut incision and bank collapse are important processes in the development of rills and rill networks. Nevertheless, these processes have not found their way into operative soil erosion modelling. Using the results of their studies, other research groups have often presented different shear stress – based factors like: unit length shear force (Giménez and Govers 2002), stream power (Bagnold, 1977; Hairsine and Rose, 1992; Elliot and Laflen, 1993; Nearing et al., 1997; Zhang et al., 2003), unit stream power (Yang, 1972; Moore and Burch, 1986) and effective stream power (Bagnold, 1980; Govers, 1992a), which show a more or less good fit with soil detachment rates measured in their experiments. These experimentally deduced factors, which are highly depending on the experimental setup, are used often in physically based soil erosion models. As a result, these models show a clear empirical foundation (Stroosnijder, 2005).

The USDA made great efforts in field experimental research for developing the USLE. They used the USDA-Purdue rainfall simulator called “rainulator” developed by Don Meyer and Donald McCune for many erodibility experiments. An extensive 5-year experiment was conducted on 55 Corn Belt soils in the 1960’s by Jerry Mannering (Flanagan et al., 2003).

Most field data about runoff and erosion in rills has been gained from observations during natural rainfall and runoff events or long-term-plot measurements, in only a few cases have controlled experiments been conducted (De Santisteban et al., 2005; Helming et al., 1999; Rejman and Brodowski, 2005). The aim of these studies was to observe rill network formation (Bruno et al., 2008; Mancilla et al., 2005), to define the initial conditions for rilling (Bruno et al., 2008; Bryan et al., 1998; Govers and Poesen, 1988; Slattery and Bryan, 1992; Torri et al., 1987), to study the development of rill head morphology (Bruno et al., 2008; Brunton and Bryan, 2000), to estimate the main hydraulic variables like cross-section area, wetted perimeter, hydraulic radius, mean velocity and shear stress for calculating other hydraulic parameters which could not be measured or estimated (Bruno et al., 2008; Foster et al., 1984; Gilley et al., 1990; Giménez et al., 2004; Govers, 1992 b), to validate existing models (Huang et al. 1996) or to propose mathematical models for estimating soil loss due to rill erosion (Bruno et al., 2008; Foster, 1982; Nearing et al., 1989). Field data are as close to reality as possible. Observations can be collected from a long term plot measurement or by scientists who are in the right place at the right time. This is not always possible, so field experiments are used to trigger the processes to be observed when the measurement team is on site. But both observations and experiments have certain disadvantages:

- Measurement techniques may disturb the processes being observed
- Time scale of human observations is shorter than that of the process under study
- Some processes can not be measured directly or indirectly
- Some processes are chaotic and the spatial and temporal variations are difficult to specify

(Kleinhans et al., 2010)

Nevertheless, simplified experimental setups are ruled by the same natural laws as the processes found in nature. For this, experimental observations can be considered as a simplified but valid representation of the reality (Paola et al., 2009).

Models describe reality in terms of mathematical equations. The physical laws are often simplified to allow numerical solutions, but in many cases it is not clear which laws apply and to what extent simplification is possible. Model parameters are always the result of simplifications. Values of some parameters are not well known, so the model has to be calibrated. Here, the phenomenon of equifinality is a problem: A wide range of parameters can produce the same result. Another problem is that parameters for rill hydraulics are often taken from equations for describing flow behaviour in rivers. Govers (1992 a) and Govers et al. (2007) showed that these equations are not suitable for rill erosion processes. So there is often a mismatch between model results and observed or measured “reality” (Kleinhans et al., 2010).

What is our scientific question?

As shown above, models face large uncertainties often due to a lack of input data. At the same time, field experiments deliver reliable data, as process dimensions operate under natural conditions, and enable direct observation of the processes involved in rill dynamics. So, to bridge the gap between models, parameterisation and observations, field experiments were performed, with specific attention given to the basic hydraulic parameters needed to calculate shear stress. By linking the observations, the determination of hydraulic parameters and the measurement of sediment transport with fundamental formulae used in soil erosion models, we aim to tackle the following questions:

- Do constant shear stress values in different rills on the same field with constant soil parameters (critical shear stress for example) result in the same soil detachment values?

And as a consequence of this question:

- Is the model concept of a linear relation between shear stress and soil detachment suitable for real erosion process combinations in natural rills?

The characteristics of the field site and the experimental set up allow a set of experiments with very similar boundary conditions to be conducted under natural conditions. All required parameters can be measured directly thus avoiding the need for estimates. As a consequence, it was expected that the shear stress exerted by the flowing water would remain within the same order of magnitude for all experiments.

2 Short history of shear stress, critical shear stress and transport capacity

Due to the fact that a great variety of approaches and equations exist to describe the shear stress resulting from flowing water in rills, a soils resistance against this and the transport capacity of flowing water, a review of the development of these relevant parameters is offered in the next chapter. This review shows that the physical definitions of “shear stress”, “critical shear stress” and “transport capacity” are not clearly differentiated , e.g. in some cases the hydraulic parameter “shear stress” and the soil parameter “critical shear stress” are not distinctly separated. This leads to problems concerning the comparability of different studies, and also complicates soil erosion model development.

Over the years the shear stress equation has been changed several times. Different research groups have deleted or added different factors to adapt the equation to their research topic. It is important to differentiate between shear stress τ, a hydraulic parameter, and critical shear stress τ_c or τ_{cr}, a soil parameter. Shear stress must exceed the critical shear stress to cause erosion. In writing this short history, we assumed that shear stress or critical shear stress values are always defined in the unit [Pa = kg m^{-1} s^{-2}], especially if values were missing or not clearly defined by the author. So we calculated the unknown units. We also used the particular label used in the particular literature being referenced so it is possible that different labels and different variables are used for the same physical parameter or that a certain variable has different meanings in different equations.

The first authors using critical shear stress in their studies to describe the resistance of sediments against shear forces were Shields (1936) and Ott and van Uchelen (1936) who translated Shields’ Ph.D. thesis into English. They described the critical shear force for the bed of a rectangular open channel as follows:

$$\tau_b = \gamma * S * D * (1 - \frac{D}{B}) \quad for\ 0 \le \frac{D}{B} \le \frac{1}{2} \text{ and} \qquad \text{Eq. (1)}$$

$$\tau_b = \gamma * S * \frac{B}{4} \quad for\ \frac{D}{B} \ge \frac{1}{2} \qquad \text{Eq. (2)}$$

while for the walls shear stress is defined as

$$\tau_w = \gamma * S * \frac{D}{B} \quad for\ 0 \le \frac{D}{B} \le \frac{1}{2} \text{ and} \qquad \text{Eq. (3)}$$

$$\tau_w = \gamma * S * \frac{B}{2} * (1 - \frac{B}{4 * D}) \quad for\ \frac{D}{B} \ge \frac{1}{2} \qquad \text{Eq. (4)}$$

with γ = unit weight of the fluid [kg m^{-3}], S = slope [m m^{-1}], D = water depth [m] and B = water width [m].

Graf (1971) modified these equations as follows:

$$\tau_c \propto \frac{D * S}{(\frac{\gamma_s - \gamma}{\gamma}) * d} \qquad \text{Eq. (5)}$$

with D = mean depth [m], S = water surface slope [m m^{-1}], γ = specific weight of fluid [kg m^{-3}], γ_S = specific weight of sediment [kg m^{-3}], d = particle diameter [m].

In 1970, Partheniades and Paaswell used critical shear stress to describe the "Erodibility of channels with cohesive boundary". Their critical shear stress equation, derived from empirical studies, was as follows:

$$\tau_c = (\frac{\alpha * n}{1.486})^2 * \gamma_w \qquad \text{Eq. (6)}$$

with τ_c = critical boundary shear stress in pounds per square foot, α as an empirical factor, n = Manning's friction coefficient [$m^{1/3}$ s^{-1}] and γ_w = unit weight of water in pounds per square foot.

Andrews (1984) and Andrews and Erman (1986) described critical shear stress in empirical equations depending on test site:

$$\tau_c = 0.0834 * (\frac{d_i}{d_{50}})^{-0.872} \quad \text{or} \qquad \text{Eq. (7)}$$

$$\tau_c = 0.0384 * (\frac{d_i}{d_{50}})^{-0.887} \qquad \text{Eq. (8)}$$

with $\frac{d_i}{d_{50}}$ = the relationship between a given particle size and the subsurface d_{50} (median particle size).

De Ploey (1990) shows different forms of the critical shear stress equation:

$$\tau_{cr} = \rho * u_{cr}^2 = (\rho * g * R * S)_{cr} = (\rho * g * n^{0.66} * q^{0.66} * S^{0.7})_{cr} \qquad \text{Eq. (9)}$$

with ρ = density of the water [kg m^{-3}], u_{cr} = shear velocity [m s^{-1}], g = gravitation factor [9.81 m s^{-2}], R = hydraulic radius [m], S = sin (slope), n = Manning friction factor [$m^{1/3}$ s^{-1}], q = unit discharge [$m^{7/6}$ s].

In the WEPP model, critical shear stress is calculated as follow:

For cropland with a sand content of more than 30%:

$$\tau_c = 2.67 + 0.65 * CLAY - 0.058 * VFS \qquad \text{Eq. (10)}$$

with CLAY = clay content [%], VFS = very fine sand content [%].

For cropland with a sand content of less than 30%, the critical shear stress is assumed to be constant:

$$\tau_c = 3.5$$

For rangeland the critical shear stress is calculated as follows:

$$\tau_c = 3.23 - 0.056 * SAND - 0.244 * ORGMAT + 0.9 * BD_{dry} \qquad \text{Eq. (11)}$$

with SAND = sand content [%], ORGMAT = organic matter content [%], which is 1.724 times the organic carbon content, and BD_{dry} is the dry soil bulk density [g cm^{-3}] (Flanagan and Livingston, 1995).

The shear stress equation used by Foster (1982) takes this form:

$$\tau = \gamma * y * b^s * (\frac{y_b}{y_p} * a * i_{eff}^2 * C_{it}) \qquad \text{Eq. (12)}$$

with τ = shear stress [Pa], γ = weight density of water (force/volume) [Pa], y = flow depth assuming laminar flow [m], b = time weighting factor in finite difference equation for continuity, s = sine of slope angle, y_b/y_p = ratio of the flow depth on a smooth surface to that in the ponds from depressions and “dams” [m m^{-1}], a = a coefficient to be estimated, i_{eff} = effective rainfall intensity [m s^{-1}], C_{it} which is a subfactor due to soil surface cover, calculated as follow:

$$C_{it} = \exp[-0.21 * (\frac{y_p}{y_b} - 1)]^{1.18} \quad \text{Eq. (13)}$$

Empirical shear stress equations of the form

$$\tau = a * (\rho_s - \rho) * g * D \quad \text{Eq. (14)}$$

with ρ_S = specific weight of the sediment [kg m^{-3}], ρ = specific weight of the water [kg m^{-3}], D = the particle size [m] and a = empirical factor between 0.039 and 0.09 are used by Shields (1936), Miller et al. (1977), Parker et al. (1982), Diplas (1987), Parker (1990), Komar (1987 a,b), Andrews (1983), Ashworth and Ferguson (1989 a,b) and Komar and Carling (1991). Meanwhile, Chisci et al. (1985) used a formula from Landau and Lifchitz (1971) to describe the shear stress as follow:

$$\tau = (\sigma * g)^{\frac{2}{3}} * (3 * \upsilon)^{\frac{1}{3}} * \sin^{\frac{2}{3}} \alpha * q^{\frac{1}{3}} \quad \text{Eq. (15)}$$

with σ = fluid density [kg m^{-3}], g = gravitation [9.81 m s^{-2}], υ = kinematic viscosity [m^2 s^{-1}], α = slope angle and q = runoff discharge rate per unit of width [kg m^{-1} s^{-1}]. The basis of the Landau-Lifchitz shear stress calculation is the Navier-Stokes equation for incompressible fluids (Bell et al. 2007; Fan et al. 2010).

Torri et al. (1987) used the shear stress equation in this form:

$$\tau_r = \sigma * g * R * \tan(\gamma) \quad \text{Eq. (16)}$$

with τ_r = runoff shear stress [Pa], σ = fluid density [kg m^{-3}], g = acceleration of gravity [9.81 m s^{-2}], R =hydraulic radius [m] and γ = slope angle [°].

Ghebreiyessus et al. (1994) used the equation in the following form:

$$\tau = \frac{\gamma * h_L * R}{L} \quad \text{Eq. (17)}$$

with γ = unit density of water [kg m^{-3}], h_L = head loss due to friction [m^2 s^{-2}], R = hydraulic radius [m] and L = channel length [m].

Nearing et al. (1997) described shear stress as follow:

$$\tau_s = \rho_w * g * S * R * \frac{f_s}{f_{tot}} \qquad \text{Eq. (18)}$$

with ρ_w = water density [kg m^{-3}], g = gravitation factor [9.81 m s^{-2}], S = slope, R = hydraulic radius [m] and f_s and f_{tot} = Darcy-Weisbach friction factors for the bare soil and composite surface, respectively.

Giménez and Govers (2002) calculate the hydraulic shear stress using the following equation. This is the form used in the actual physical based soil erosion models.

$$\tau = \rho * g * R * S \qquad \text{Eq. (19)}$$

with ρ = density of the fluid [kg m^{-3}], g = gravitation factor [9.81 m s^{-2}], R = hydraulic radius [m] and S = sin(slope).

Sediment transport is a fundamental part of soil erosion. Parker (1979) developed an empirical function to calculate a transport rate using shear stress as well as critical shear stress. It only calculates a positive transport rate, if the shear stress exceeds the critical shear stress:

$$Q_B = \frac{11.2 * (\tau - \tau_c)^{4.5}}{(\tau_c)^3} \qquad \text{Eq. (20)}$$

with τ_c = threshold value of τ required to initiate particle motion and Q_B = transport rate per unit of width [kg$^{1.5}$ m$^{-1.5}$ s^{-3}]. In this equation it is clear to see that shear stress and critical shear stress are opponents. Critical shear stress is a value for soil stability, shear stress is a value for the erosive impact of the flowing water. In critical shear stress calculations, soil parameters like dry bulk density, grain size distribution and organic content are used, in shear stress calculation hydraulic parameters, roughness, flow velocity and fluid density are variables. Depending on the question, experimental setup or data base, the equations show different forms and have been in most cases simplified overtime.

Most modelling concepts limit the uptake of sediment into the flowing water not only by the processes and forces described above, but also by setting them into equilibrium with the sediment transport capacity (Bagnold, 1963, 1966). Hessel and Jetten (2007) described in their review four different approaches for calculating the transport capacity:

$$TC = \frac{TC_f}{(1 - \frac{TC_f}{\rho_S})}$$ (Govers, 1990) Eq. (21)

$$TC = \frac{q_b * w * \rho_S}{Q}$$ (Abrahams et al., 2001; Low, 1989; Rickenmann, 1990) Eq. (22)

$$TC = \frac{q_S * w}{Q}$$ (Yalin, 1993; Bagnold, 1980) Eq. (23)

$$TC = \frac{\rho_f * \frac{C_P}{1\text{E}6}}{(1 - \frac{C_P}{1\text{E}6})}$$ (Yang, 1973) Eq. (24)

with TC = transport capacity in clear water [g L^{-1}], TC_f = transport capacity in sediment-water [g L^{-1}], ρ_S = density of solid material [kg m^{-3}], q_b = volumetric bedload transport per unit width [m^2 s^{-1}], q_s = sediment transport rate [kg m s^{-1}] w = flow width [m], Q = runoff [m^3 s^{-1}], ρ_f = fluid density [kg m^{-3}] and C_P = concentration [ppm]

In the WEPP-model, transport capacity is calculated as follow:

$$TC = k_t * \tau_f^{1.5}$$ (Foster et al. 1995) Eq. (25)

with k_t = transport coefficient [$m^{0.5}$ s^2 $kg^{-0.5}$] and τ_f = hydraulic shear acting on the soil [Pa]. In this modification of the equation of Yalin (1963) the transport capacity is described in kg s^{-1}.

It is important to note that the empirical basis of the equations presented above is data sets created by controlled laboratory experiments, field observations or field experiments.

A summary of these equations can be found in Reid and Dunne (1996) and on the EPA-homepage (2009).

3 Materials and Methods

3.1 Study Area:

The Natural Park Bardenas Reales, a 425 km² semiarid landscape, is located in northeast Spain (Navarra), in the Ebro-Basin (Fig. 1). It is bounded by the Aragón river on the north and the Ebro on the south (Desir and Marín, 2007; Murelaga et al., 2002; Sancho et al., 2008). The Ebro basin is filled with debris material from surrounding mountain areas, sediments from an inland sea and, as a consequence of drying up, saline, lacustrine, and marsh sediments. The tertiary and quaternary sediments in the Bardenas Reales consist of open playa-lake deposits, red, grey and green clayey marl and pockets of lacustrine, limestone-like, sandy and gypsum-containing sediments as well as massive marly and lacustrine limestones that form cuestas (Desir and Marín, 2007; Murelaga et al., 2002; Sancho et al., 2008).

The climate in the test area is semi-arid and characterised by irregular, heavy rainfall events with an average of 380 mm a^{-1}, the average annual temperature is 19.2°C, and the potential evapotranspiration rate reaches 1084 mm. In summer and winter, only sporadic rainfall events reach the test areas; the convective precipitations occur in spring and autumn (Causapé et al., 2006; Causapé et al., 2004; Desir and Marín, 2007; Sancho et al., 2008).

Most soils in the region are poorly developed and porous. The A-horizon is thin and contains almost no organic material. Existing soil types are Regosols; at some points Cambisols, Luvisols and Fluvisols have developed. Depending on substrate, carbonate, gypsum and salt content are middle to high, pH is high and soils have a tendency toward sealing and crusting (Schwab et al., 1982).

3.2 Rill test site:

The position of our experimental site is 624817 E 4681907 N. With high-definition aerial photography it was possible to estimate area and length values and to describe soil surface characteristics such as vegetation cover or rills. The 0.75 ha field used for testing is separated into two different soil-surface areas. One area is covered with grass, the other consists of bare soil. Furrows are detectable on the whole area. On a part of the field with nearly bare soil, i.e. vegetation cover is only about 1% and rock fragments cover roughly 2%, approximately 20 furrows have developed into rills in different stages of development (Fig. 2). Average rill length is about 10 m, so we calculated a total rill length of about 200 m. The relationship between rill length and area (rill density) is 267 m ha^{-1}. This is lower than on the ripped field but higher than on a ploughed field which were compared in the study of Hagmann (1996). Four of these rills were randomly chosen for the experiments.

Texture class is at the threshold between poor silty sand and poor loamy sand, gravel content is 1%. Main texture class is fine and very fine sand, nearly half of the fine soil material shows a grain size between 0.2 and 0.063 mm. Grain density and dry bulk density have not been measured directly but estimated as 2.65 g cm^{-3} and 1.68 g cm^{-3}, respectively, following the Ad-hoc-Arbeitsgruppe Boden (2005). Soil material contains 2.2 % organic matter, and the starting soil moisture was 7.5%.

The rills tested developed in this homogeneous substrate, they neither show steps nor plungepools but have different morphological parameters. The rill descriptors with different values for each rill are summarized in table 1, the constant setup, soil and climate factors are presented in table 2.

3.3 Rill experiment:

The rill experiment consists of two runs: in the first run the rill is tested under field conditions; in a second run, about 15 min later, the same rill is tested under wet conditions.

For each run, a motor driven pump is used to maintain a constant discharge of 9 L min^{-1} for 8 minutes, resulting in a total water flow of 72 L (Wirtz et al., 2010).

The flow velocity within the rill is characterized by the travel time of the waterfront and of two colour tracers (food colourings (E 124 (red) and E 13 (blue) started at 3 and 6 minutes after the start of the experiment) measured for every meter using a chronograph. By means of this procedure, three velocity curves are recorded and changes in flow dynamics can be detected.

At the end of the rill, the runoff is continuously measured by a pressure transducer (Ecotech DL/n, V2.35). For calibration of the discharge curve, runoff at the outflow is measured volumetrically at regular intervals. This allows constant measurement of the discharge at high temporal resolution and throughout the whole experiment.

The rill's slope is characterized by measurement using a spring bow with a range of 1m and a digital air lever. It is important to note that slope measurement provides only average slope over the 1 meter. A step or a knick-point in the rill is not considered, but its position and height are recorded.

At three measuring points (MP) along the rill four water samples are taken: the first as soon as the waterfront has reached the sampling point, the second 30 seconds later, and the third and fourth after 1:30 and 2:30 total time from arrival of the water. The sediment concentration is determined by filtration of the samples in the laboratory. (Wirtz et al., 2010)

At each measuring point, rill cross section is measured. With thin metal sticks, the distance between ground level and rill bottom is measured in 0.002 m steps. This allows an accurate calculation of the rill' s cross section area and an estimation of the rill's volume.

3.4 Descriptors for soil detachment

The relationship between detachment rate and detachment capacity respectively the relationship between transport rate and transport capacity is an important value for assessing different processes acting in the rill. These variables are calculated as follow:

$$D_C = K_r * (\tau - \tau_{cr}) \quad \text{(Foster et al., 1995)} \quad \text{Eq. (26)}$$

$$T_C = K_t * R * \tau^{1.5} \quad \text{(modified from Wagenbrenner et al., 2010)} \quad \text{Eq. (27)}$$

$$D_R = \frac{S_C * V * A}{L * WP} \quad \text{Eq. (28)}$$

$$T_R = S_C * V * A \quad \text{Eq. (29)}$$

with D_C = detachment capacity [kg m^{-2} s^{-1}], K_r = rill erodibility factor [s m^{-1}], τ = shear stress [Pa], τ_{cr} = critical shear stress [Pa], T_C = transport capacity [kg s^{-1}], K_t = transport coefficient [s^2 $m^{0.5}$ $kg^{-0.5}$], R = hydraulic radius [m], D_R = detachment rate [kg m^{-2} s^{-1}], S_C = sediment concentration [g L^{-1}], V = flow velocity [m s^{-1}], A = flow area [m^2], L = flow length [m], WP = wetted perimeter [m], T_R = transport rate [kg s^{-1}].

The rill erodibility factor K_r can be calculated for cropland or rangeland; parameters are clay content, very fine sand content, organic material content, dry soil bulk density and the total root biomass within the 0.0 and 0.1 m soil zone. In this case, we used the equation for cropland.

Depending on land use, the parameters for the critical shear stress are clay content, very fine sand content, sand content, organic material content and dry soil bulk density.

Shear stress is calculated as follow:

$$\tau = \rho * g * R * S \quad \text{(Giménez and Govers, 2002)} \quad \text{Eq. (30)}$$

with ρ = fluid density [kg m^{-3}], g = gravitational acceleration (9.81 m s^{-2}), R = hydraulic radius [m] and S = effective slope (sin(slope angle)).

The transport coefficient value is taken from the WEPP-database (Elliot et al., 1989). We used the value of the soil that is most similar to the soil in the test area. In this case, the location is Amarillo, the K_t value is 0.0107 s^2 $m^{0.5}$ $kg^{-0.5}$.

The total runoff at the outlet V_R is calculated. When set in relation to the inflow V_I the runoff coefficient (RC) is obtained. For enabling the comparison of rills with different experimental lengths, we calculate the runoff length factor (RC_L) by multiplying the runoff coefficient with the tested length L. It is an expression of runoff effectiveness and an inverse measure for infiltration capacity within the rill:

$$RC_L = \frac{V_R * L}{V_I} \qquad \text{Eq. (31)}$$

For comparing the variability of the different parameters, we calculated the average of the relative measurement errors (RME) following the DIN 1319-1 (1995). This error is defined as

$$f = \frac{|x_a - x_r|}{x_r} * 100 \qquad \text{Eq. (32)}$$

with x_a as measured value and x_r as “correct” value, we used the mean of the measured values as x_r.

The average values in table 3 are calculated from 12 samples (3 measuring points à 4 samples in each run).

Table 2 shows the constant external parameters. In a model simulation, in most cases average values are used. And because the external parameters are constant (table 2), the 4 different rills would be described by one average value of all rills. So we calculated average values of all samples (4 experiments x 2 runs x 3 measuring points x 4 samples = 96 samples) which are presented in table 4.

The RME describes the difference between the average value of all experiments and the average values of one run. The given RME value in table 4 is the average of the RMEs of the 8 runs. The RME would be much higher if we would calculate the RME between average values of all 96 samples and the single, directly measured sample.

Number of classes was calculated following the Sturges’ rule (Sturges, 1926):

$$k = 1 + 3.32 \lg(n) \qquad \text{Eq. (33)}$$

with k = number of classes and n = number of valid cases. In our calculations, n was 16 and so the calculated number of classes was 5. The class limits were in this case 0-20, 20-40, 40-60, 60-80 and 80-100. There was only one element in the last class, so we defined only 4 classes, with the last class as 60-100.

4 Results

All factors for each run of the four research experiments (RE) are presented in Table 3. Whether values were measured or calculated is also noted.

The highest transport capacity values were seen in RE1a, 1b and 2b; and the highest detachment capacity was also in RE1a and 2b. Shear stress values were highest in RE1, 7.17 Pa in run 1a for shear stress 1 (when sediment concentration and grain density is used to calculate liquid density) and 7.09 in run 1a and 1b for shear stress 2 (when a constant density is assumed). Hydraulic radius and slope show the highest values in RE1a and 1b (1.28 cm and 3.2°). Lowest values measured in RE1 were for the r-l-factor (1.27 m in 1a) and the runoff coefficient (12.6 % also in 1a).

Experiment 2 shows the highest transport rate value (0.0152 kg s^{-1} in 2b), the highest sediment concentration (44.02 g L^{-1} in 2a) and the highest detachment rate (0.0146 kg s^{-1} m^{-2} run 2b). Together with both runs of RE1, run RE2b also shows the highest transport capacity (0.0028 kg s^{-1}). The tested rill part in RE2 contains a rill volume of 0.53 m^3; this is the highest value of the tested rills. Additionally, RE2b also had the highest r-l-factor (7.95 m), the highest runoff intensity (0.5 l s^{-1}) and the highest flow velocity (0.21 m s^{-1}). The highest liquid density was calculated for RE2a (1.027 g cm^{-3}).

In RE3 the highest average cross section area was measured (738.87 cm^2). At 71.54 % RE3b had the highest runoff coefficient. Lowest values measured in RE3b were for transport rate, sediment concentration, detachment rate and liquid density, and in RE3a the lowest flow velocity was measured (0.14 m s^{-1}).

The rill tested in experiment 4 shows the lowest cross section area, the lowest rill volume and the lowest slope. Additionally, in experiment RE4a the lowest values for transport capacity (0.0005 kg s^{-1}), detachment capacity (0.016 kg s^{-1} m^{-2}), runoff intensity (0.15 l s^{-1}), both shear stress values (2.77 and 2.76 Pa, respectively) and hydraulic radius (0.74 cm) were measured.

To compare the variability of the different parameters, we calculated the relative measurement error (RME) for each of them. The RME values for the tested parameters are presented in Figure 3, and they are summarized in Table 4.

The highest RME, 81.7 %, was calculated for the transport rate. RME values of more than 60 % were also calculated for sediment concentration (70.5 %) and detachment rate (67.5 %). Transport capacity (45.5 %), cross section area (41.3 %) and volume (40.9 %) show RME values between 40 and 60 %. RME values between 20 and 40% were calculated for detachment capacity (38.3 %), r-l-factor (36.6 %), runoff intensity (31.6 %), shear stress (28.6 and 28 % respectively for shear stress 1 and shear stress 2) and runoff coefficient (25 %). RME values below 20 % have been measured for flow velocity (10.2 %) and for the input parameters of the shear stress equation hydraulic radius (16.4 %), slope (14.7 %) and liquid density (0.7 %).

5 Discussion

Despite different volume and cross section areas (RME 40.9 and 41.3 %) the hydraulic radius shows a low RME of 16.4 %. This is caused by different runoff values, represented by runoff coefficient and r-l-factor. Because runoff coefficient has a lower RME than r-l-factor (25 and 36.6%, respectively), it is not sufficient for description of runoff, since under different rill-parameters (volume and cross section area) only different runoff values can result in similar hydraulic radius values.

Theoretically, the relationship between a rate and a capacity should not exceed 1 because sedimentation processes reduce this value when the rate is higher than the capacity (Scherer, 2008). But in our experiments, 67 of 96 samples (75%) show higher transport rates than transport capacities, especially in higher sediment concentration ranges (see figure 4).

The transport rate exceeds the transport capacity in 77% of the samples (dry runs) respectively in 63 % (wet runs) of the samples. But regarding the average values of the relationships between Transport rate and transport capacity (only the values higher than 1) the b-runs show a higher value than the a-runs (7 vs. 5.7). In the a-runs, the transport of loose material is the main process, in the b-runs the bank failure and the headcut retreat.

The input parameters for calculating shear stress show RME values below 20%: hydraulic radius with 16.4 %, slope with 14.7 % and liquid density with 0.7 %. The calculated shear stress values are also similar; the variability is 28.6 % when liquid density with sediment concentration considered is used and 28 % if the liquid density of clear water is assumed. The model idea is that there is a linear relation between shear stress and soil detachment volumes, this means that soil loss parameters should also be in the same order of magnitude. For transport and detachment rate, input parameters are still flow velocity and sediment concentration. Flow velocity shows a low variability of 10.2 %. But sediment concentration (70.5 %), transport rate (81.7 %) and detachment rate (67.5 %) show very high variability, all values being over 60 %. This means that in this case, there is no linear relation between shear stress and soil detachment.

The results of the research accomplished by Govers (1991), Liu et al. (1996), Nearing (1998, 1999 a), Risse et al. (1993), Ruttiman et al. (1995), Wendt et al. (1986) and Zhang et al. (1996) underscore the problems. Nearing (1998) tested the variability between replicated soil erosion field plots under natural rainfall to determine the principal factor or factors which correlate with the magnitude of variability. The coefficient of variation ranged in the order of 14% for a measured soil loss of 20 kg m^{-2} to greater than 150% for a measured soil loss of less than 0.01 kg m^{-2}. Ruttiman et al. (1995) statistically analysed the data of four sites, each with five to six reported treatments; each of them with three replicates. The coefficients of variation in soil loss ranged from 3.4% to 173.2%, with an average value of 71%. Wendt et al. (1986) measured soil erosion rates on 40 experimental plots. All plots were cultivated and treated identically. The coefficients of variation for 25 storms ranged from 18% to 91%, with a clearly decreasing variability of soil loss with increasing erosivity of the storms: 15 storms with erosion rates higher than 0.1 kg m^{-2} were noted and 13 showed coefficients of variation less than 30%. Risse et al. (1993) applied the USLE to a large data-set of plot-years and natural runoff plots. Annual values of measured soil loss averaged 3.51 kg m^{-2}, the average magnitude of prediction error was 2.13 kg m^{-2}, that means 60%. Zhang et al. (1996) tested the WEPP-model in a similar way. The average soil loss was 2.18 kg m^{-2} with an average prediction error of 1.34 kg m^{-2} which is 61% of the mean. Liu et al. (1996) compared measured values with WEPP-calculated values. For one of the tested catchments, the sediment yield was under-predicted by approximately 50%. Govers (1991) tested the rill erosion rates on arable land in Central Belgium. The relevant characteristics of the selected fields were similar; the highest standard deviation was 65 m in length and 25.5% in sand content. Mean rill erosion rate from 156 measurements reached 0.36 kg m^{-2}, with a maximum of 3.5 kg m^{-2}, but also no erosion was observed. The RME (relative measurement error calculated using eq. 32) accounts for 131%. The results reflected here show the high variability of soil erosion measurements, even under controlled (this means experimental) conditions.

The very large variability is partially the result of non-homogeneous parameters used for soil characteristics and rainfall. On experimental plots, infiltration rates and soil aggregate stability can be highly variable (Ajayi and Horta, 2007), and natural rainfall shows a high spatial and temporal variability (Dunkerley, 2008). Therefore, the input parameters for the different measurements reflected in the studies mentioned above were not really comparable. Nevertheless, the results also make clear that modelling soil erosion involves uncertainty in model input as well as in the data that can be used for model calibration and validation. In the field, the spatial and temporal variability of soil conditions cannot be avoided, and is, furthermore, part of the investigations. Therefore, additional input parameters such as rainfall or flow should be kept constant to generate comparable data. There is a high variability in soil erosion processes that can not be represented by a single factor like shear stress. The shear stress equation implies that drag forces are the dominant forces controlling erosion. But rill erosion is the result of the combination of different processes including headcut erosion, sidewall sloughing, tunnelling, micro-piping, slaking piping and sapping (Bryan et al., 1989; Bryan, 1990; Knapen et al., 2007; Owoputi and Stolte, 1995; Rapp, 1998; Zhu et al., 1995). These processes are not accounted for in shear stress equations, although there is ample evidence to support their importance. Zhu et al. (1995) concluded in laboratory experiments that the contribution of headcutting in detachment processes was four times as high as the contribution of bed scours. Kohl (1988) found that headcutting accounted for up to 60% of total rill erosion for the soil erodibility data of WEPP. Stefanovic and Bryan (2009) tested, in laboratory experiments, the development of rills on a loamy sand and on a sandy loam and showed that concentrated flow causes sediment production primarily from knickpoints, chutes, meanders and bank failure. Govers (1987) distinguished between hydraulic erosion, mass wasting processes on rill sidewalls, gullying and piping. During his study in Huldenberg, the loamy hilly region of Flandres, the field was conventionally tilled and a seedbed was prepared. Hydraulic rill erosion mostly occurred during three observed runoff events with peak discharges between 70 and 90 L s^{-1} (4200 – 5400 L min^{-1}). Runoff rates during other events were always below 25 L s^{-1} (1500 L min^{-1}). We used runoff rates of 9 L min^{-1} which turned out to be too low to produce hydraulic rill erosion. However, it was sufficient to cause mass wasting processes on rill sidewalls. In the observed runoff events (Govers, 1987), mass wasting processes caused 37% of total erosion in rills. But in erosion modelling, rill erosion is considered to be only dependent on the erosive power of the flowing water, represented by shear stress, unit length shear force or stream power. The process of gullying, the retreat erosion at knickpoints and headcuts, is not considered in rill erosion formulas. This process caused about 12% of rill erosion rates in the study of Govers (1987). In our experiments, we only cause mass wasting and gullying processes, so the relations between hydraulic parameters and sediment concentration are mostly low. However hydraulic rill erosion only occurs in extreme runoff events suggesting that, in most cases, runoff values are too low to cause this process (Govers, 1987). All these observations agree with our own observations and measurements. In addition, there are several studies and models looking at headcut retreat (Bennettt, 1999; Robinson et al., 2000; Alonso and Bennett, 2002; Bennett and Alonso, 2005; Bennett and Alonso, 2000; Flores-Cervantes et al., 2006; Gordon et al., 2007) and bank failure (Parker, 1983; Kovacs and Parker, 1994). These results have not (yet) been applied in soil erosion models.

Knapen et al. (2007) calculated the correlation of shear stress, unit length shear force, stream power and Reynolds number with the detachment capacity using several WEPP datasets. The best average correlation was determined for stream power with $R^2 = 0.59$. The R^2 values for the shear stress variable used in the WEPP datasets were never strong. Knapen et al. (2007, p. 80f.) describes the shear stress as follows: „Although the use of flow shear stress as a soil detachment predictor can be contested, critical shear stress (τ_{cr}) and concentrated flow erodibility KC (...) have been selected as the most universal parameters to describe soil erosion resistance to concentrated flow.“ The correlations between these factors and the soil detachment capacities show very different results. There is not a single parameter that always shows the best correlation.

Other groups found linear correlations between an hydraulic parameter and an erosion parameter as well as in laboratory flume experiments (Partheniades and Paaswell, 1970, Nearing et al., 1997, Ghebreiyessus et al., 1994, Torri et al., 1987, Giménez and Govers, 2002) and in field research (Elliot et al., 1989, Nearing et al., 1997, Nearing et al., 1999 b). We can not confirm these observations, in our field experiments there is not only no linear relationship between hydraulic parameter and erosion parameter but there is no clear relationship at all.

In a laboratory study, Nearing et al. (1991) measured flow shear stresses ranging from 0.5 to 2 Pa, while tensile strengths ranged from 1 to 2 kPa, a difference in magnitude of 1000. Despite this, detachment rates of nearly 300 g m^{-2} s^{-1} were measured. Nearing explained this as being the result of turbulent burst events which are much greater than the average flow shear stresses. Nearing and Parker (1994) further investigated the influence of turbulence on shear stress. They showed that under turbulent flow conditions the same shear stress value results in a clearly higher detachment rate. Differences between detachment rates caused by turbulent and laminar flow increased with increasing shear stress value. This means that the influence of turbulence on soil erosion will be higher when hydraulic conditions lead to a high shear stress value than when shear stress values are in the lower range. This can be the reason that soil erosion models often over-predict small soil losses and under-predict large soil losses. Nearing (1998) explained this by the presence of natural variations in model data, meaning variations that the model is not capable of capturing. These variations will effect a bias in the erosion predictions relative to values on the higher end versus those on the lower end of the range of measured values (Nearing, 1998).

Another reason why the use of the shear stress equation does not deliver satisfactory results is the origin of this equation. The shear stress equation is deduced from Navier Stokes equations which describe the motion of fluids. The equations arise from applying Newton’s second law to fluid motion (net force on a particle is equal to the time rate of change of its linear momentum in an inertial reference frame), combined with the assumption that the fluid stress is the sum of a diffusing viscous term plus a pressure term. Using one of the Navier-Stokes equations, an incompressible fluid can be completely described; thus reducing hydrodynamic questions to a mathematical problem. But this problem consists of a system of second order nonlinear partial differential equations which require the most powerful computers to numerically solve even the easiest cases. For the general, 3-dimensional case, existence- uniqueness- and regularity statements are not yet proven. Indeed, the Clay Mathematics Institute (CMI) included this in their “Millennium Prize Problems” which represent the most important open problems in mathematics, and has offered a prize of US$ 1,000,000 for a solution or a counter example. (Seiler, 2002; Constantin, 2001; Fefferman, 2006; Temam, 2000; Wiegner, 1999; Schneider, 2008)

The inconsistencies between the experimental results and the physically based model assumptions can be the consequence of several things such as uncertainties in measurements on the one hand or, on the other hand, inconsistent and incomplete process representations within the models. Uncertainty in the measurement of soil erosion has been a strong point of discussion (Stroosnijder, 2005), which is certainly also still not solved. The experimental setup applied in this study aimed to hinder systematic errors and their propagation. The design of the inlet, the flume for runoff measurement and the monitoring of flow and sediment transport reduced disturbance to a minimum. The results of measurements are also within the range measured in other experiments (e.g. Knapen et al., 2007). This, in combination with qualitative process observations made during the experiments, allows us to draw the conclusion that the source of errors is found in the model concepts. It has been shown that the physical definition of the parameters is not clear (see chapter 2: Short history of shear stress, critical shear stress and transport capacity), and their mostly empirical foundation does not fit the high temporal and spatial variability of processes within a rill. Different processes take part in different intensities and this fact causes high variability in sediment concentration, transport and detachment rates. But the spatial and temporal distribution of the different processes is highly randomly controlled.

Another important fact which can not be handled by the physically based models is the heterogeneity in critical shear stress. In this study, we performed our experiments on one field with uniform treatment, so the soil parameters are as constant as possible. And as a consequence, we assumed the critical shear stress to be constant in our experiments. In the used typical model, the critical shear stress for cropland with a sand content > 30% (at our test side: about 80%, mainly middle, fine and very fine sand) is calculated using the clay and the very fine sand content and these values are constant. This assumes a constant critical shear stress but in reality, this homogeneity is not given. The critical shear stress can also change between experiments or within one experiment caused by wetting and drying, sealing and crusting. These changes can not be reflected by the models.

The results make it clear that there is not a simple linear relation between a single hydraulic parameter and soil detachment rate. Depending on the model purpose and scale, these factors can be used to predict the magnitude of rill detachment but they are not applicable for the simulation of rill erosion with high-resolution spatial and temporal change in processes. A newer approach is the use of probability density functions to predict soil detachment. The best, although not yet operational, version of this approach has been developed by Sidorchuk (Sidorchuk, 2002; Sidorchuk et al., 2004; Sidorchuk, 2005 a; Sidorchuk, 2005 b; Sidorchuk et al., 2008; Sidorchuk, 2009).

5 Conclusion

The results of this study clearly show that the model concept of most physical based soil erosion models is not suitable for modelling rill erosion processes. These models assume a linear relation between shear stress and soil detachment. That means, when input parameters for calculating shear stress are constant, or at least in a similar range, the erosion parameters should also be in the same range. In our experiments, hydraulic radius, flow velocity, slope and liquid density showed similar values but the resulting erosion parameters of sediment concentration, and detachment and transport rates show variability values of more than 60 %. Measured total rill erosion rates are the sum of erosion rates caused by a combination of different soil erosion processes with different spatial and temporal distribution. This combination can not be described by one single equation. There are two different ways to address this conundrum. The first is to modify existing physical based model concepts so that different processes can be taken into account; the second is to head in a new direction, using the concept of stochastic soil erosion modelling. In both cases, much more field experimentation will be needed to provide the required data. A big question is whether or not the experimental setups currently employed can deliver the required data, or if totally new experimental setups will need to be developed.

Acknowledgement

This research was supported by the Internationale Graduiertenzentrum of Trier University. We thank all participants of the field trip to the Bardenas Reales in spring 2009 which supported the accomplishment of the experiments. A special thank goes to our native speaker Demie Moore, which revised the complete paper.

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Table 1: Rill descriptors and values by test rill. MP = Measuring Point

Factor	**Rill 1**	**Rill 2**	**Rill 3**	**Rill 4**
Ø Slope [°]	4.3	3.1	2	2.9
Max. Slope [°]	9.4	5.8	3.1	7.1
Tested flow length [m]	10	14	6	6.5
Maximum width [m]	~ 0.60	~ 0.60	~ 0.25	~ 0.25
Maximum depth [m]	0.182	0.189	0.246	0.086
MP 1 position [m]	3	4	1.5	2
MP 1 slope [°]	1.8	3.5	2.8	3.7
MP 2 position [m]	6	7	3	3.5
MP 2 slope [°]	4.6	3	3.1	1.6
MP 3 position [m]	9	12	4.5	5
MP 3 slope [°]	3.3	2.1	1.5	1

Table 2: Constant parameters

Parameter	**Factor**	**Value**
Setup	Discharge intensity [L min^{-1}]	9
	Discharge quantity [L]	72
	Discharge time [min]	8
Soil	Soil texture	Loamy sand
	Organic matter [%]	~ 2.2
	Land use	Arable land
	Transport Coefficient K_t [s^2 $m^{0.5}$ $kg^{-0.5}$]	0.0107
	Vegetation cover [%]	~ 1
	Rock fragment cover [%]	~ 2
	Starting soil moisture [%]	~ 7.5
	Grain density [g cm^{-3}]	2.65
	Dry bulk density [g cm^{-3}]	1.68
Climate	Average precipitation [mm a^{-1}]	380
	Average annual temperature [°C]	19.2
	Evapotranspiration rate [mm a^{-1}]	1084
	Characterisation	Semi arid

Table 3: Average values of all factors for all experiments. Shear stress 1 includes the sediment concentration and grain density in the liquid density calculation, shear stress 2 is calculated using a constant liquid density of 1 g cm^{-3}. c = value is calculated, m = value is measured. SC = Sediment concentration, cap. = capacity, ND = No Data

Factor	**Unit**	**m/c**	**1a**	**1b**	**2a**	**2b**	**3a**	**3b**	**4a**	**4b**
Transport rate	[kg s^{-1}]	c	0.0055	0.0057	0.0112	0.0152	0.0006	0.0004	0.0015	0.0013
SC	[g L^{-1}]	m	16.32	13.53	44.02	37.51	2.56	1.78	10.19	9.41
Detachment rate	[kg s^{-1} m^{-2}]	c	0.0051	0.0054	0.0123	0.0146	0.0007	0.0006	0.0033	0.0037
Transport cap.	[kg s^{-1}]	c	0.0028	0.0028	0.0022	0.0028	0.0008	0.0018	0.0005	0.0009
Cross section area	[cm^{2}]	m	377.07	377.07	461.07	461.07	738.87	738.87	121.47	121.47
Volume	[m^{3}]	m	0.34	0.34	0.53	0.53	0.33	0.33	0.06	0.06
Detachment cap.	[kg s^{-1} m^{-2}]	c	0.066	0.066	0.052	0.056	0.026	0.039	0.017	0.025
r-l-factor	[m]	m	1.27	4.25	6.39	7.95	3.09	4.29	ND	3.34
Runoff intensity	[L s^{-1}]	m	0.35	0.41	0.28	0.50	0.21	0.34	0.15	0.19
Shear stress 1	[Pa]	c	7.17	7.15	5.88	6.24	3.64	4.75	2.77	3.5
Shear stress 2	[Pa]	c	7.09	7.09	5.73	6.12	3.64	4.75	2.76	3.49
Runoff coefficient	[%]	m	12.68	42.47	45.61	56.78	51.56	71.54	ND	51.33
Hydraulic Radius	[cm]	m	1.28	1.28	1.16	1.19	0.90	1.13	0.74	0.87
Slope	[°]	m	3.2	3.2	2.9	2.9	2.4	2.4	2.1	2.1
Flow velocity	[m s^{-1}]	m	0.15	0.18	0.16	0.21	0.14	0.17	0.16	0.19
Liquid density	[g cm^{-3}]	m	1.010	1.008	1.027	1.023	1.002	1.001	1.006	1.006

Table 4: Variability of different runoff and erosion factors, hydraulic and rill parameters. RME is the relative measurement error. Shear stress 1 includes the sediment concentration and grain density in the liquid density calculation, shear stress 2 is calculated using a constant liquid density of 1 g cm^{-3}.

Factor	**Average**	**RME [%]**
Transport rate [kg s^{-1}]	0.0052	81.7
Sediment Concentration [g L^{-1}]	16.9	70.5
Detachment rate [kg s^{-1} m^{-2}]	0.0057	67.5
Transport capacity [kg s^{-1}]	0.0018	45.5
Cross section area [cm^2]	424.6	41.3
Volume [m^3]	0.4	40.9
Detachment capacity [kg s^{-1} m^{-2}]	0.043	38.3
r-l-factor [m]	4.4	36.6
Runoff intensity [L s^{-1}]	0.3	31.6
Shear stress 1 [Pa]	5.1	28.6
Shear stress 2 [Pa]	5.1	28
Runoff Coefficient [%]	47.4	25
Hydraulic radius [cm]	1.1	16.4
Slope [°]	2.7	14.7
Flow velocity [m s^{-1}]	0.2	10.2
Liquid density [g cm^{-3}]	1.01	0.7

Figure 1: Location of the Bardenas Reales

Figure 2: Field with the tested rills. The crawler as scale in the photo on the right has a length of about 1.5m. RE = rill experiment

Figure 3: The relative measurement errors of the tested parameters. Shear stress 1 includes the sediment concentration and grain density in the liquid density calculation, shear stress 2 is calculated using a constant liquid density of 1 g cm^{-3}.

Figure 4: Relationship between transport rate and transport capacity vs. sediment concentration. The equilibrium line is shown.