This paper was peer-reviewed for scientific content.
Pages 771-776. In: D.E. Stott, R.H. Mohtar and G.C. Steinhardt (eds). 2001. Sustaining the Global Farm. Selected papers from the 10th International Soil Conservation Organization Meeting held May 24-29, 1999 at Purdue University and the USDA-ARS National Soil Erosion Research Laboratory.

Wind Speed Effects on Rain Erosivity

*Katharina Helming**

ABSTRACT

The kinetic energy of rainstorms plays a paramount role in surface sealing, runoff, and erosion processes. Typically, the kinetic energy rate is calculated based on terminal velocity of vertically falling raindrops. Few studies have investigated the effect of wind speed on raindrop velocity, rainfall energy and on inclination angles of raindrops. This paper reports an attempt to determine (i) the effect of wind speed on the kinetic energy of rainstorms, (ii) the relationships between rainstorm intensity and wind speed, and (iii) raindrop impact angle distributions with respect to wind speed, inclination angle, and soil surface geometries. Rainfall amount and wind speed were measured over 24 months. The kinetic energy and the inclination angle of the wind-driven rain were determined with trigonometric functions combining the horizontal wind speed with the vertical drop velocity. The distribution of raindrop impact angles was determined for various soil surfaces represented by digital elevation maps. The results showed: 1) The rainstorm kinetic energy, determined with respect to the wind speed, reached a maximum of 3.5 times the value of the kinetic energy without the wind speed factor. On average, the portion of the raindrop energy derived from wind speed accounted to about one fourth of the total rain energy. 2) There was no association between rainstorm intensity and wind speed. 3) Soil surface roughness was more important for raindrop impact angle distribution than wind speed. The results suggest that wind speed has considerable effects on rainstorm energy, and thus impacts surface sealing and soil erosion processes.

INTRODUCTION

Rainstorm kinetic energy and rainstorm intensity are predominant factors contributing to surface sealing, runoff, and soil erosion processes (Renard et al., 1997). The determination of values for both parameters is therefore of paramount importance for runoff and erosion prediction purposes. Rainstorm intensity can be measured directly with a rain gauge connected to a data logger. Rainstorm kinetic energy, as a *function of the mass and terminal velocity of* raindrops, is more difficult to determine. Typically, rainstorm energy is calculated based on measurements of the relation between rainstorm intensity, raindrop size distribution, and raindrop velocity (Renard et al., 1997). Although Laws and Parsons (1943), as well as Wishmeyer and Smith (1958), emphasized the importance of wind speed on drop velocity and rainstorm kinetic energy, most studies have based rainstorm kinetic energy values on the terminal velocity of vertically-falling drops without incorporating the effect of wind speed on the drop velocity. Only a few studies have dealt with the relationships between rainstorm intensity, wind velocity, and rainstorm energy (Disrud, 1970; De Lima, 1990, Pedersen and Hasholt, 1995).

Wind speed affects not only the rainstorm kinetic energy, but also the directional tilt of the raindrops, which in turn determines the angle of raindrop impact on the soil surface. The degree at which the raindrop makes contact with the soil surface is of importance for the compaction and surface sealing processes, which are predominantly affected by the normal component of the raindrop impact force (Linden et al. 1988; Helming et al. 1993). In the case of vertically-falling rain, soil surface roughness and the surface gradient determine the distribution of the angles of raindrop impact and influence the relation between the normal and tangential impact forces (Helming et al., 1993). In the case of wind-driven oblique rain, the directional and inclination angle of raindrops, as well as the soil surface aspect, are additional factors, which influence the angle of raindrop impact (Sharon et al., 1988; De Lima, 1989). As a result, detailed analyses combining temporally high resolution rainstorm and wind speed measurements with spatially high resolution surface roughness measurements are required to determine the effect of wind speed on the normal component of the raindrop impact forces relative to the soil surface conditions.

The objective of this study was to analyze the relation between rainstorm intensity, wind speed, and rainstorm kinetic energy based on high resolution rainstorm and wind speed measurements through a very simple approach, as well as to determine the normal component of the raindrop impact forces for different degrees of wind speed, soil surface roughness, gradient, and aspect.

MATERIALS AND METHODS

Determination of the kinetic energy of wind-driven rain

Rainstorm and wind speed measurements were carried out during a two-year period (1997 –1998) on an experimental field station at the Center for Agricultural Landscape and Land Use Research (ZALF) in Müncheberg, Germany. The mean annual precipitation is about 540 mm in this area with a maximum in July and August (Krumbiegel and Schwinge 1991). Rainstorm measurements were carried out at 10-minute intervals at 1 m above surface height using a standard rain gauge (WMO-norm), which covers a 0.02 m² surface area, and a 0.1 mm resolution-tipping bucket as a rainfall registration device. The wind speed was measured at

*Katharina Helming, Center for Agricultural Landscape and Land Use Research (ZALF), Eberswalder Str. 84, D-15374 Muencheberg, Germany. *Corresponding author: khelming@zalf.de

2 m above the soil surface in 10-minute intervals.

The analysis of rainfall and wind speed data was based on the 10-minute interval measurements, which were summarized to rainstorm events according to the procedure described in RUSLE (Renard et al., 1997). The rainstorm kinetic energy of vertically falling rain was determined by:

$$E = 0.5 * R * TV^2 \qquad (1)$$

With: E = kinetic rainstorm energy for vertical rain (J m^{-2} mm R^{-1}), R = Rainfall amount (mm), TV = vertical raindrop velocity (m s^{-1}). Since the drop velocities could not be measured in this study, TV was held constant at 6.5 m s^{-1}, or the terminal velocity of an approximately 2 mm diameter raindrop in motionless air (Gunn and Kinzer, 1949; Dingle and Lee, 1972). According to Laws and Parsons (1943) and Joss and Gori (1976), a 2 mm drop size is the median size in rainstorms of around 10 to 30 mm h^{-1} intensity.

For wind-driven rain, raindrop velocity was calculated based on the hypotenuse of the vertical drop velocity vector and the horizontal wind speed vector. The kinetic energy of wind-driven rain was then:

$$EW = 0.5 * R * (TV^2 + WV^2) \qquad (2)$$

With: EW = kinetic energy of wind driven rain (J m^{-2} mm R^{-1}), WV = wind velocity (m s^{-1}). The inclination angle (α) of the raindrop relative to the vertical direction was defined as:

$$\alpha = \arctan\left(\frac{WV}{TV}\right) \qquad (3)$$

Frequency distributions of and regression equations between E and EW were determined for the 10-minute interval measurements as well as for the rainstorm events.

Determination of raindrop impact angle distributions

The distribution of raindrop impact angles and the normal component of raindrop impact forces was determined with respect to the gradient, aspect, and roughness of the soil surface based on high resolution digital elevation models (DEMs). The DEMs were obtained for 0.2 m² areas using a laser scanner (Helming, 1992) with 2 mm grid spacing and 0.2 mm vertical resolution. A grid spacing of 2 mm was chosen because of its correspondence with the assumed 2 mm drop size. The laser measurements were carried out after seedbed preparation at two locations along a cultivated field near the weather station. The random roughness (RR) (Zobeck and Onstad, 1987) and specific surface area (SSA) (Helming et al., 1998) were determined from laser measurements to characterize soil surface roughness.

For each of the 50,000 grid cells in the DEM, the gradient and aspect was determined by applying the so-called D8-method (O'Callaghan and Mark, 1984). As a result, two angles, one relative to the horizontal aspect, and one relative to the vertical gradient defined each grid cell. In combination with the horizontal (wind direction) and vertical (wind speed) angle of the raindrop, the impact angle for each grid cell and the normal component of the raindrop impact force at this cell position could be determined using trigonometric functions. The normal component of the raindrop impact force at each grid cell was then summarized for all grid cells to an area-weighted average.

RESULTS AND DISCUSSION

Wind effect on kinetic rainstorm energy

The rainfall and wind speed data of the two-year measurement period are summarized in Table 1. Rainstorms were recorded in 4,106 of the 105,120 10-minute measurement intervals. The 10-minute events could be summarized to 180 rainstorm events with a total rainfall of 1136 mm. The maximum values of rainstorm intensity, wind speed, and rainstorm energy were greater for the 10-minute events than for the rainstorm events representing higher amplitude of shorter-term measurements. In total as well as on average, the rainstorm kinetic energy (EW), determined with respect to the wind speed, was as high as 1.3 times the value of the rainstorm kinetic energy without the wind speed factor (E). The maximum value of the relation between EW and E was 3.5 for the rainstorm events and 4.7 for the 10-minute events, respectively. According to the cumulative frequency distribution of the relation between EW and E for the 10-minute events, 20 % of the data was greater than 1.5 and 2.3 % was greater than 2.0 (Fig. 1).

Rainstorm intensity and related rainstorm energy per unit time and area are the driving forces for surface sealing,

Table 1: Rainstorm characteristics of 10-minute measurement intervals and rainstorm events measured in 1997 - 1998 in Northeast Germany.

	10-min events	Rain events
number of events	4106	180
mean rainfall amount (mm)	0.3	6.3
max. rainfall amount (mm)	13.9	61.6
max. rainfall intensity (mm h^{-1})	83.4	45.6
total rainfall amount (mm)	1136	1136
mean wind velocity (m s^{-1})	3.2	3.0
max. wind velocity (m s^{-1})	12.5	10.5
max. kin. rain energy E (J m^{-2})	294	1301
max. kin. rain+wind energy EW (J m^{-2})	365	1509
total kin. rain energy E (J m^{-2})	23981	23981
total kin. rain+wind energy EW (J m^{-2})	31778	31778
EW / E (mean)	1.3	1.3
EW / E (max.)	4.7	3.5

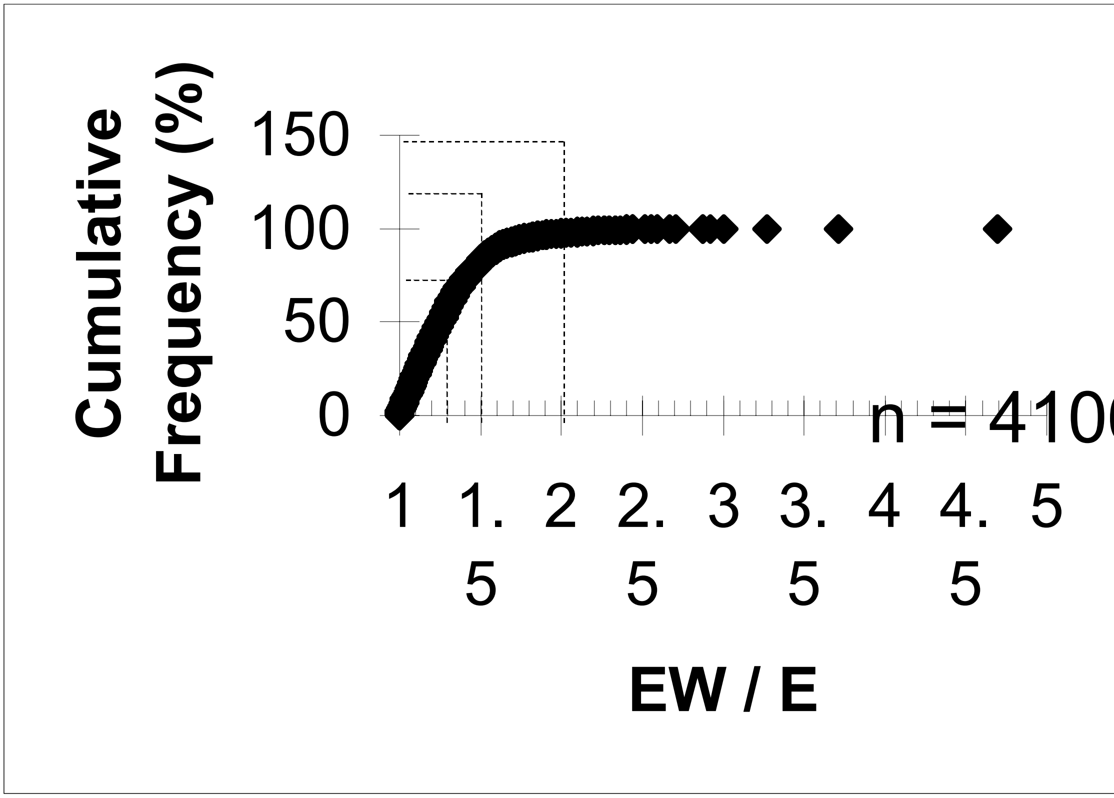

Figure 1: Cumulative frequency distribution of the relation between the kinetic rain+wind energy (EW) and the kinetic rain energy (E) for 10-minute measurement intervals measured in 1997 - 1998.

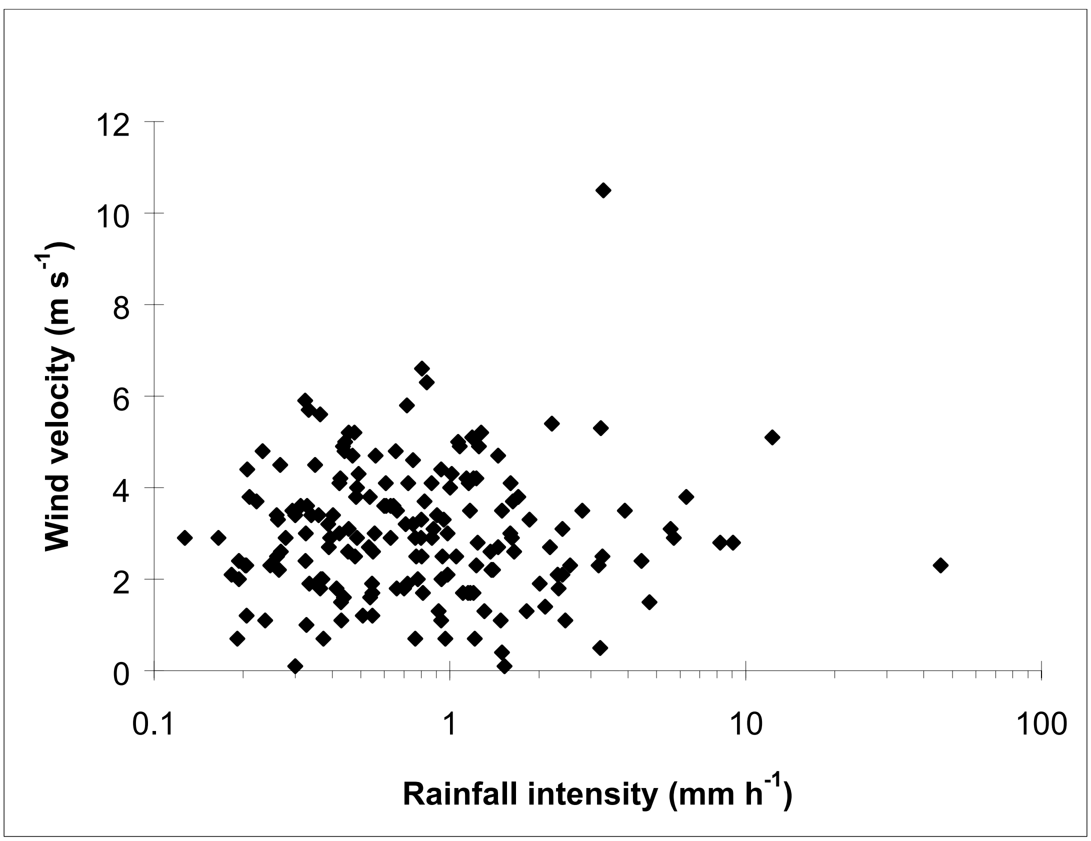

Figure 2: Relation between wind velocity and rainstorm intensity for all rainstorm events measured in 1997 - 1998.

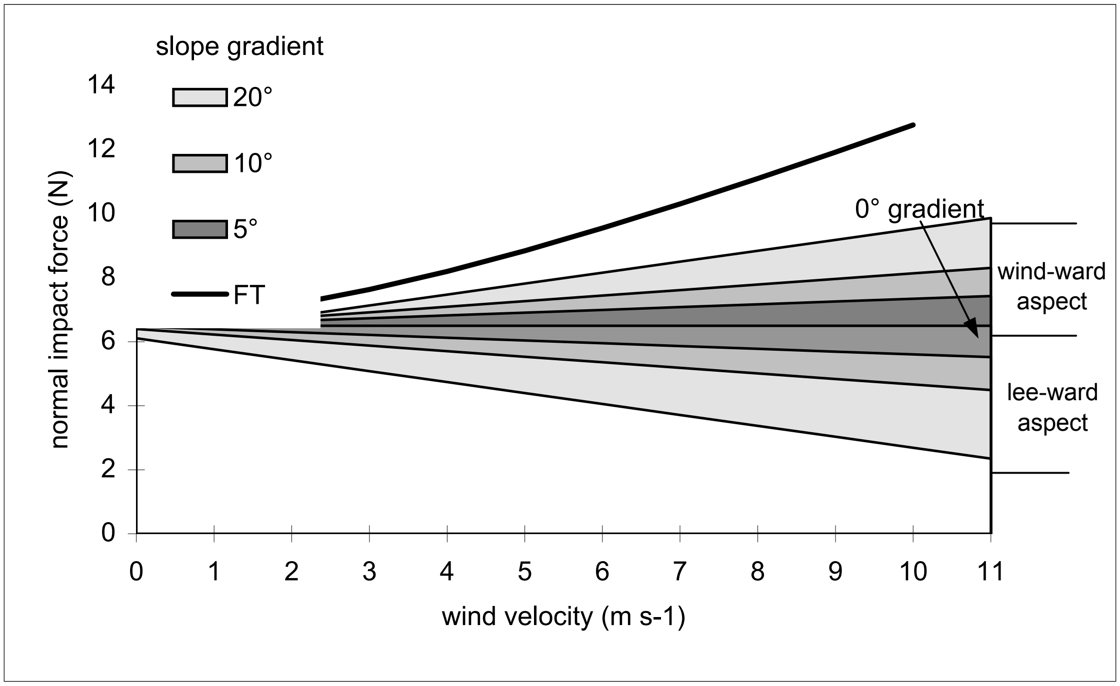

Figure 3: Relation between EW, E, and rainstorm amount for all rainstorm events measured in 1997 - 1998 (closed triangles), and for rainstorm events with more than 30 mm total amount measured in 1994 – 1996 (open cycles).

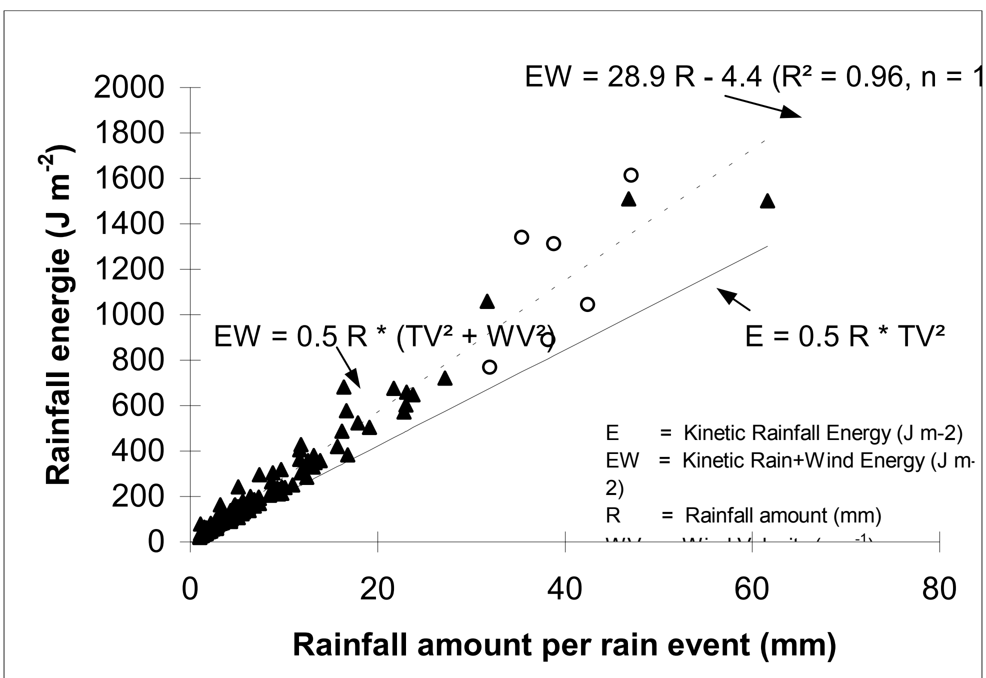

Figure 4: Relation between wind velocity, total impact force (F_T), and normal impact force of raindrops for different slope gradients and aspects on a smooth surface.

runoff generation, and soil erosion. An interesting question is, therefore, whether or not rainstorm intensity is directly related to wind speed, which would result in an exponential increase of rainstorm kinetic energy with increasing rainstorm intensity. This, however, did not seem to be the case. The average values of wind speed per rainstorm event were measured between 0 and 10.5 m s^{-1} without any detectable relation to the rainstorm intensity (Fig. 2). Instead, a linear regression between rainfall amount and rainstorm kinetic energy (EW) was determined (R^2 = 0.96) (Fig. 3). Due to the limited number of 30 mm or more rainfall events, data from 1997 and 1998 were supplemented with rainfall measurements from three additional rainfall-monitoring years (1994–1996) for determination of the regression equation.

In brief, two major results can be concluded from this section: (i) rainfall kinetic energy determined with respect to the wind speed (EW) in relation to the rainfall kinetic energy without the wind speed factor (E) was, on average, greater by a factor of one-third; and (ii) the relationship between rainfall amount and EW was linear. However, these results used a very basic approach to determine EW based on a constant drop size and velocity. Non-linear relationships between amount of rainfall and EW may result when a different distribution of drop size, as a function of rainstorm intensity and/or wind speed, is used in the determination of EW.

Wind effect on raindrop impact angle distribution

The processes of splash and surface sealing are predominantly affected by the normal component of the raindrop impact force (Helming et al., 1993, Linden et al. 1988). In the case of vertically falling rain, the distribution of the impact angles and the resultant normal and tangential forces are determined by the roughness of the soil surface and the slope gradient. In the case of wind-driven oblique rain, the raindrop direction and inclination angle, as well as the surface aspect, are additional factors that determine the impact angle. In the case of a smooth surface, the normal impact force as a function of wind velocity, surface aspect, and gradient is shown in Figure 4. With a zero degree gradient, the normal impact force is provided by the cosine of the inclination angle of the raindrop that is constant with increasing wind velocity. On inclined surfaces, the normal impact force increases with increasing wind velocity in the case of a windward aspect, and decreases with increasing wind velocity in the case of a leeward aspect (Fig. 4).

On natural soil surfaces, surface roughness determines the distribution of the surface gradients at the drop impact location. With increasing surface roughness, the proportional area with steep gradients increases, which in turn decreases the normal impact force, if the rain falls vertically (Helming et al., 1993). Raindrop impact force values for two surface roughness cases are listed in Table 2 for various wind direction and wind velocity conditions. In the case of vertically falling rain, the normal impact force was calculated at 4.9 N for the rough surface (surface B) and 5.4 N for the medium rough surface (surface A), which was 75 % and 83 % of the total impact force, respectively. Again, the proportion of normal force relative to the total force decreased with increasing wind velocity and was the greatest for the case of wind direction perpendicular to the slope aspect. The resultant values of normal impact force were 68 % to 78 % of the total force for 3 m s^{-1} wind velocity (measured average of wind velocity of all rainstorm events) and 42 % to 50 % of total force for 10.5 m s^{-1} (measured maximum of wind velocity of all rainstorm events), respectively. For the case of a smooth surface with the same slope gradient, these values would have been 85 % to 95 % and 43 % to 62 % of the total raindrop force at 3 m s^{-1} and 10.5 m s^{-1} wind velocities. Therefore, soil surface roughness appeared to mitigate the effect of wind speed on the sealing effective portion of rainstorm energy. Despite this mitigation effect, wind speed appears to lead to a spatial heterogeneisation of drop impact angles representing the spatial heterogeneity of surface aspect.

CONCLUSIONS

In this study, a simple approach was conducted to derive an initial evaluation of the importance of wind speed for rainstorm energy. The results suggest that wind speed has considerable effect on rainstorm kinetic energy, specifically during short periods within rainstorm events. On average, the portion of the raindrop energy derived from wind speed accounted to about one fourth of the total kinetic rain energy. Rain energy related soil processes such as surface sealing, runoff and erosion are thus automatically affected by wind speed. The results of this study suggest further, that the distribution of raindrop impact angles on the soil surface, which is an important factor for soil sealing and compaction processes, is also affected by wind speed and wind direction, but surface roughness seems to be the predominant factor for impact angle distribution. The methods applied in this study implied a number of simplifications of the otherwise complex subject. However, the derived results justify the performance of more sophisticated studies of the interrelating effects between rainstorm intensity, wind speed, drop size distribution, and rainstorm kinetic energy.

ACKNOWLEDGEMENTS

Michael Baehr, Dept. of Landscape Modeling, ZALF provided the weather data analyzed in this study. His help is gratefully acknowledged.

REFERENCES

De Lima, J.L.M.P. 1989. The influence of the angle of incidence of the rainfall on the overland flow processes. New directions of surface water modeling 181: 73-82.

De Lima, J.L.M.P. 1990. The effect of oblique rain on inclined surfaces: a nomograph for the rain-gauge correction factor. J. of Hydrology 155: 407-412.

Dingle, A.N. and Y. Lee. 1972. Terminal falls peeds of raindrops. J. of Applied Meteorology 11: 877-879.

Disrud, L.A. 1970. Magnitude, probability and effect of kinetic energy of winds associated with rains in Kansas. Trans. Kansas Academy of Science 73: 237-246.

Gunn, R. and G.D. Kinzer. 1949. Ther terminal velocity of fall for water droplets in stagnant air. Journal of Meteorology 6: 243-248.

Table 2: Normal component of raindrop impact force (area weighted average) as function of wind speed, wind direction, and soil surface roughness.

	WV	**0**	**3.0**	**6.5**	**10.5**
	F_T	**6.5**	**7.2**	**9.2**	**12.3**
	Wind direction		**F_{norm}**		
Surface A:	S	5.4	5.4	5.5	5.6
SSA 1.36; RR 6.35	N	5.4	5.5	5.7	5.9
Gradient: 3.4°	W	5.4	**5.6**	**5.8**	**6.2**
Aspect: west-north	E	5.4	5.4	5.4	5.5
Surface B:	S	4.9	4.9	5.0	5.2
SSA 1.72; RR 12.5	N	4.9	**5.1**	**5.4**	**5.8**
Gradient: 6.4°	W	4.9	5.0	5.2	5.5
Aspect: north	E	4.9	5.0	5.3	5.7

WV = Wind velocity (m s^{-1}); F_T = total raindrop impact force (N); F_{norm} = normal component of drop impact force.

Helming, K. 1992. Die Bedeutung des Mikroreliefs für die Regentropfenerosion. Bodenökologie und Bodengenese, Heft 7, Berlin, 155 pp. (in german).

Helming, K., Ch.H. Roth, R. Wolf und H. Diestel. 1993. Characterization of rainfall - microrelief interactions with runoff using parameters derived from digital elevation models (DEMs). Soil Technology 6, S. 273-286.

Helming, K., M.J.M. Römkens and S.N. Prasad. 1998. Surface roughness related processes of runoff and soil loss: a flume study. Soil Sci. Soc. Am. J. 62, S. 243-250.

Joss, J. and E.G. Gori. 1976. The parametrization of raindrop size distributions. Rivista Italiana di Geofisica 2: 275-283.

Krumbiegel, D. and W. Schwinge. 1991. Witterung – Klima Mecklenburg-Vorpommern, Brandenburg und Berlin. Deutscher Wetterdienst, Wetteramt Potsdam. 80 pp. (in german).

Laws, J.O. and D.A. Parsons. 1943. The relation of raindrop size with intensity. Transactions of the American Geophysical Union 24: 452-459.

Linden, D.R., D.M. Van Doren and R.R. Allmaras. 1988. A model of the effect of tillage induced soil surface roughness on erosion. ISTRO 11th International Conference: Tillage and Traffic in Crop Production 1: 373-378.

O'Callaghan, J.F. and D.M. Mark. 1984. The extraction of drainage networks from digital elevation data. Comput. Vision Graphics Image Process., 28, 328-344.

Pedersen, H.S. and B. Hasholt. 1995. Influence of wind speed on rainsplash erosion. Catena 24, 39-54.

Renard, K.G., G.R. Foster, G.A. Weesies, D.K. McCool and D.C. Yoder. 1997. Predicting soil erosion by water: a guide to conservation planning with the revised universal soil loss equation (RUSLE). USDA-ARS Agric. Handb. 703. U.S. Gov. Print. Office, Washington, DC.

Sharon, D., J. Morin and Y. Moshe. 1988. Micro-topographical variations of rainfall incident on ridges of a cultivated field. Trans ASAE 31: 1715-1722.

Wishmeier, W.H. and D. D. Smith. 1958. Rainfall energy and it's relationship to soil loss. Transactions of the American Geophysical Union 39: 285-291

Zobeck, T.M. and C.A. Onstad. 1987. Tillage and rainfall effects on random roughness – a review. Soil and Tillage Research 9: 1-20.