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Wind effects on soil erosion by water — A sensitivity analysis using model simulations on catchment scale

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ABSTRACT

Soil erosion by water is affected by raindrops hitting the soil surface. Under windy conditions the droplets are forced to divert from vertical fall which affects their erosional intensity. To consider this effect the paper reports on model simulations with the EROSION 3D model taking into account wind speed and wind direction.
Based on measured data achieved by wind tunnel experiments a set of algorithms was derived, which describes the diversion angle of rain drops as a function of wind speed and the resulting impact angle on inclined slopes as a function of wind direction. Using a small catchment in the ore mountain range of Saxony/East Germany as example several test runs were performed comparing wind impact from different directions (north, east, south, west) with no wind conditions. Model simulations based on these scenarios result in plausible estimations of soil loss under wind impact and improve the understanding of wind impacted soil erosion which cannot be measured yet on catchment scale. As the simulated scenarios show erosion can be increased as well as decreased due to wind impact. The effect of wind impact on soil erosion by water is substantial and thus it should not be neglected in mathematical soil erosion models.

1. Introduction

Soil erosion by water results from rainwater runoff and raindrops hitting the soil surface respectively water layer simultaneously. In terms of physical algorithms the interaction of these impacts is very complex to describe. Physically based soil erosion models usually characterize the erosional effect of running water as stream power (Nearing et al. 1997) which equals the loss of potential energy as the water flows downhill. The impact of droplets is represented commonly by their kinetic energy which is estimated from rainfall intensity. As both parameters are purely scalar variables the interaction of runoff and droplets cannot be described accurately. Actually, raindrops do not fall vertically due to wind speed and wind direction and usually hit an inclined surface (Pedersen and Hasholt, 1994; Sharon and Arazi, 1997). Apparently, the erosive impact of raindrops is substantially affected by the angle in which the droplets hit the soil surface respectively water layer (Erpul et al. 1998, 2002, 2003; De Lima et al. 1992, Gabriels et al. 1997a, 1997b; Iserloh et al., 2013). Additionally, vegetation affects raindrop impact essentially depending on ground cover (Schindewolf and Schmidt, 2012).

A first attempt to consider the effects of wind speed and direction on the falling angle of rain drops was implemented in the EROSION 2D model (Schmidt and Mauersberger, 2009). EROSION 2D is a physically based soil erosion model based on the momentum flux approach introduced by Schmidt (1991). This approach facilitates the consideration of wind effects on drop impact by using vectorial variables (momentum flux) instead of scalar ones (kinetic energy). This paper presents a further extension of the EROSION 2D/3D model, which allows simulating the impact of wind speed and direction on soil loss by water on catchment scale. Since spatially and temporally distributed data on wind speed and direction are not yet available in the context with measured soil loss by water, an attempt is made to validate the model by using hypothetical wind scenarios.

2. Materials and methods

2.1. EROSION 3D model approach

The study refers to the EROSION 3D catchment scale water erosion model, which is predominantly based on physical principles. The model simulates the detachment of soil particles, the transport respectively deposition of detached soil particles by overland flow as well as the sediment delivery into downstream water courses as caused by single events.

The model is based on the momentum flux approach (1) developed by Schmidt (1991, 1992, 1996). The underlying assumption of this approach is that the erosive impact of overland flow and the droplets hitting the soil surface is proportional to the momentum fluxes exerted by

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the flow and the falling droplets respectively, defined in general form by:

$$\phi = \frac{m \cdot v}{t}; \frac{kg \cdot m}{s \cdot s} = \frac{kg \cdot m}{s^2} = N \tag{1}$$

where m/t is the mass rate of surface runoff respectively rainfall and v is the runoff velocity respectively fall velocity of droplets.

As Fig. 1 shows momentum fluxes shall be regarded as vectors.

Assuming a macroscopic perspective erosion occurs if the sum of all mobilizing forces acting on the soil particles (given by the momentum fluxes of surface runoff φ_q and raindrops φ_r) is greater than the sum of those forces that prevent particles from being detached and transported. In all other cases, no particles are eroded from the soil surface. Following this concept the erosional effects of raindrops and overland flow can be related to the soil's resistance to erosion (given by the critical momentum flux φ_{crit}) to give a dimensionless coefficient E (2):

$$E = \frac{\phi_q + \phi_r \cdot \sin\alpha}{\phi_{crit.}} \tag{2}$$

where φ_q is the momentum flux exerted by surface runoff [N], $\varphi_{r,}$ is the momentum flux exerted by raindrops [N] and $\varphi_{crit.}$ is the critical momentum flux (erosional resistance) [N].

Erosion occurs if $E > 1$ whereas $E \le 1$ characterizes the erosion-free state of flow.

The momentum flux exerted by raindrops is defined as (3):

$$\phi_r = r_\alpha \cdot \rho_r \cdot v_r \cdot A \cdot \sin\alpha \cdot (1 - C_L) \tag{3}$$

where φ_r is the momentum flux exerted by raindrops [N], $r_\alpha = r\, cos\alpha$ is the effective rainfall intensity [m/s] related to the slope surface, ρ_r is the fluid density of rainwater [kg/m^3], v_r is the mean fall velocity of raindrops, A is the area of the slope segment [m^2], α is the slope angle and C_L is the ground cover. The effective rainfall intensity r_α is introduced to Eq. (3) because rainfall intensity data as provided by Germany's National Meteorological Service refer to a horizontal plane. To calculate runoff generation and soil detachment these intensity data have to be transferred to inclined surfaces.

In analogy to Eq. (3) the momentum flux exerted by overland flow is determined by:

$$\phi_q = q \cdot \rho_q \cdot \Delta y \cdot v_q \tag{4}$$

where φ_q is the momentum flux exerted by flow [N], q is the volume rate of flow [m^3/(m s)], ρ_q is the fluid density [kg/m^3], Δy is the width of the slope segment [m] and v_q is the mean flow velocity [m/s].

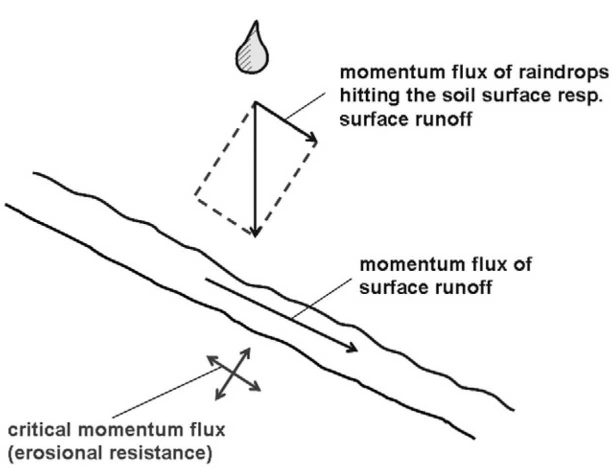

Fig. 1. EROSION 3D momentum flux approach.

In order to transport detached particles the uplift by vertical (turbulent) flow components of surface runoff must counteract the gravitational settling of the suspended particles (Fig. 2). Since surface runoff in this case is usually developed as a thin water film in the range of millimetres up to some centimetres in depth, flow turbulence is predominantly a result of raindrop impact and not due to friction effects within the water film. Raindrop impact results in an irregular motion of surface runoff, which is essential for the lift up of eroded particles and particle transport in suspension. Without raindrop impact and consequently without turbulence only bedload transport occurs which is far less effective than sediment transport in suspension.

To transfer the concept of particle transportation consistently to the momentum flux approach, the vertical momentum flux component of the (turbulent) flow on the one side and the critical momentum flux of particles, which is a function of particle size, fluid density and fluid viscosity, on the other side have to take under consideration.

Hence the prior condition for particle transport is given by Eq. (5):

$$\phi_{q,vert.} \ge \phi_{p,crit.} \tag{5}$$

where $\varphi_{q,vert.}$ is the vertical momentum flux component of surface runoff [N] and $\varphi_{p,crit.}$ is the momentum flux of suspended particles [N].

Transport capacity has been reached, when the vertical momentum flux component of the flow equals the critical momentum flux of the suspended particles.

The concentration of particles at transport capacity can be expressed as:

$$c_{\max} = \frac{1}{\kappa} \; \frac{\phi_q + \phi_r}{\rho_p \; A \; v_p{}^2} \tag{6}$$

where $c_{\max}$ is the concentration of particles at transport capacity [m^3/m^3], κ ($\approx$1000) is an empirical factor, φ_q is the momentum flux exerted by flow [N], φ_r is the momentum flux exerted by raindrops [N], ρ_p is the particle density [kg/m^3], A is the area of slope segment [m^2] and v_p is the settling velocity of soil particles [m/s].

Deposition occurs, when the momentum flux of the particles exceeds the vertical momentum flux component of the flow.

The runoff subroutine of EROSION 2D/3D uses a modified Green and Ampt (1911) infiltration equation in order to calculate rainfall excess:

$$i = k_s \cdot g + k_s \cdot \frac{\Psi_{m0}}{\sqrt{\dfrac{2k_s \cdot \Psi_{m0} \cdot t}{\rho_f \cdot (\Theta_s - \Theta_0)}}} \tag{7}$$

where i is the infiltration rate [kg/(m^2 s)], k_s is the saturated hydraulic conductivity [(kg s)/m^3], g is gravity [m/s^2], Ψ_{mo} is the matric potential related to the initial water content Θ_0 [N m/kg], t is the time [s], ρ_f is the fluid density [kg/m^3], Θ_s is the saturated water content [m^3/m^3] and Θ_0 is the initial water content [m^3/m^3]. The derivation of Eq. (7) is described in more detail by Weigert and Schmidt (2005).

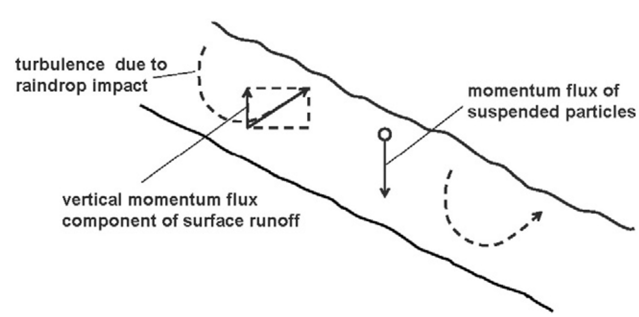

Fig. 2. EROSION 3D transport capacity approach.