Effects of soil slaking and sealing on infiltration – experiments and model approach

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Abstract

The use of soils for agriculture replaces natural vegetation cover with an intermittent coverage by crops. Thus, the protection of soils from direct raindrop impact is temporarily suspended. Soil slaking and sealing are the inevitable consequences. Although these processes affect only the uppermost soil layer of some millimetres in depth, soil slaking and sealing impede substantially the infiltration of rainwater into the soil. The paper presents a theoretical approach which allows one to estimate the change of hydraulic permeability at the soil surface as a function of time after tillage and tillage practice. Based on laboratory and field experiments the method is tested exemplarily.

Key Words

Soil structure, rain water infiltration, soil erosion.

Introduction

Soil slaking and sealing are frequent features of many cultivated soils. The terms ‘slaking’ and ‘sealing’ refer to the breakdown of soil aggregates and the formation of a sealing skin that makes the soil surface less permeable (Mualem *et al* 1990; Assouline 2004). The physical processes of soil slaking and sealing are the result of the kinetic impact of raindrops on the soil surface and the translocation of soil particles by flowing water. When the drop impact forces exceed the internal cohesion of the impacted soil aggregates they break down into primary mineral particles. These particles are transported by surface runoff or washed into the soil surface layer (Figure 1). When deposited the translocated particles could clog soil pores and form superficial layers characterised by higher bulk density and lower saturated hydraulic conductivity than the soil beneath (Betzalel *et al* 1995). Due to the loss of soil water storage and infiltration capacities soil erosion and the risk of flooding are substantially increased. Based on laboratory and field experiments this study aims to estimate the change of hydraulic permeability at the soil surface as a function of time after tillage and tillage practice.

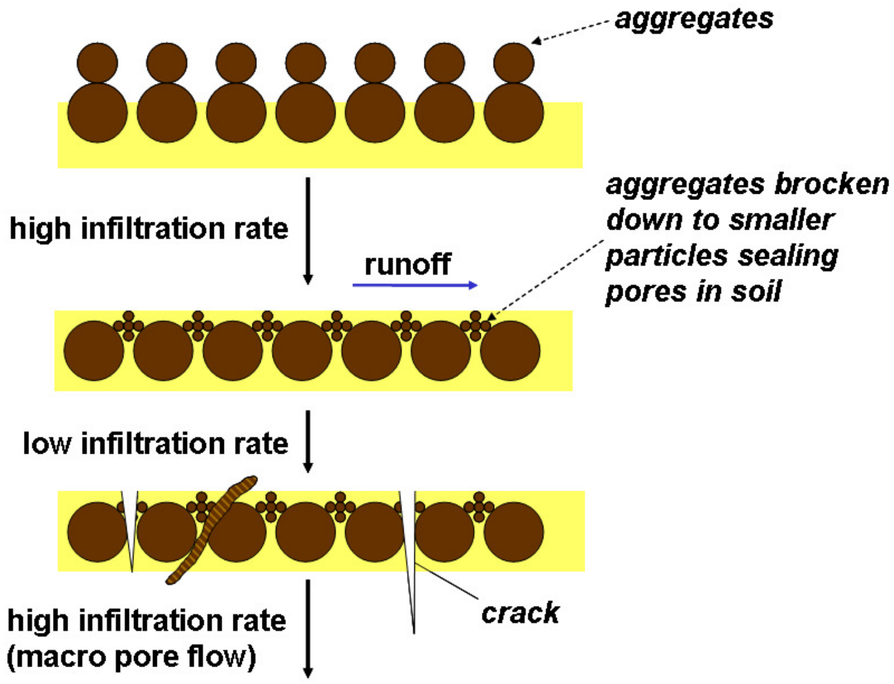

Figure 1. Scheme of soil slaking and sealing processes (adapted from Greener (2001)).

Methods

This paper refers to the EROSION 2D/3D computer model which simulates soil erosion by water on single slopes and small catchments (Schmidt 1996). The runoff subroutine of EROSION 2D/3D uses a modified Green and Ampt infiltration equation in order to calculate rainfall excess:

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

where i ... infiltration rate [kg/(m^2 s)], k_s ... saturated hydraulic conductivity [(kg s)/m^3], g ... gravity [m/s^2], Ψ_{mo} ... matric potential related to the initial water content Θ_0 [N m/kg], t ... time [s], ρ_f ... fluid density [kg/m^3], Θ_s ... saturated water content [m^3/m^3], Θ_0 ... initial water content [m^3/m^3].

According to Campbell 1985 the saturated hydraulic conductivity can be estimated by applying the following empirical function:

$$k_s = 4\cdot 10^{-3} \cdot \left(1{,}3 \cdot 10^{-3} / \rho_b\right)^{1{,}3\cdot b} \cdot \exp\left(-0{,}069 \cdot T - 0{,}037 \cdot U\right)$$

with $$b = \left(10^{-3} \cdot D\right)^{-0{,}5} + 0{,}2 \cdot \delta_p$$

where k_s ... saturated hydraulic conductivity [(kg s)/m^3], ρ_b ... bulk density [kg/m^3], T ... clay content [kg/kg], U ... silt content [kg/kg], b ... parameter [-], D ... mean diameter of soil particles [m], σ_P ... standard derivation of the mean diameter of soil particles [-].

Because Campbell's equation presupposes a rigid soil matrix the temporal variability of soil structure due to tillage, slaking and sealing, shrinking and swelling, biological activities etc. have to be considered by an additional empirical parameter which allows one to calibrate the saturated hydraulic conductivity k_s on the basis of measured data. In the EROSION 2D/3D model this parameter is called skin-factor Sk_f. Values of Sk_f <1 reduce the infiltration rate, in order to take the effects of soil slaking and sealing as well as anthropogenic compaction into account. Values of Sk_f >1 causes a positive correction of infiltration rate, e.g. for the consideration of an increased infiltration in macropores due to soil shrinking, biological activity or tillage impact. If Skf =1 infiltration rate is obviously not affected by either slaking and sealing or macropores. Figure 2 shows the effect of altering the skin-factor in order to fit simulated infiltration rates to measured data from plot experiments.

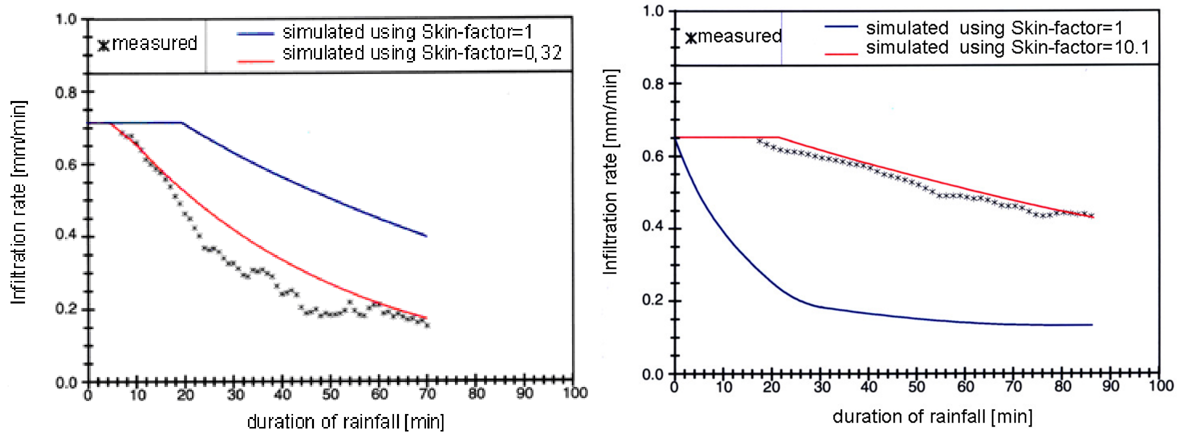

Figure 2. Measured and simulated infiltration rates as a function of time with skin-factor used as fitting parameter.

Results

Using experimental data from two soil erosion plots the temporal variability of skin-factors was estimated as a function of time after tillage. Experiments were conducted on silty soils because these are susceptible to soil slaking and sealing in particular. Data refer to 6 natural rainfall events over a period of approx. 100 days. Generally the results show that just after ploughing the hydraulic conductivity of the top soil is artificially increased and Skin-factors are characterized by values >1. However, because of the weak stability of the loosened top soils they change back to their original bulk density after a certain period of time. Linked to this process generally a compacted and less permeable skin is formed at the soil surface. Accordingly Skinfactors decrease to values <1.

Figure 4 refers to results of laboratory experiments using three different rainfall intensities produced by a capillary rainfall simulator. The skin-factor is plotted as a function of cumulative rainfall instead of time as depicted in Figure 3. The loosened soil at the beginning of the experiment results in rather high skin-factors. As expected, skin-factors decrease with cumulative rainfall and approach a constant value of approximately 1 indicating a stable soil structure. Surprisingly, rainfall intensity does not affect the skin-factor reaction. Consequently kinetic energy of raindrop impact can not be the main trigger for seal formation in contrary to the results of Betzalel *et al* (1995).

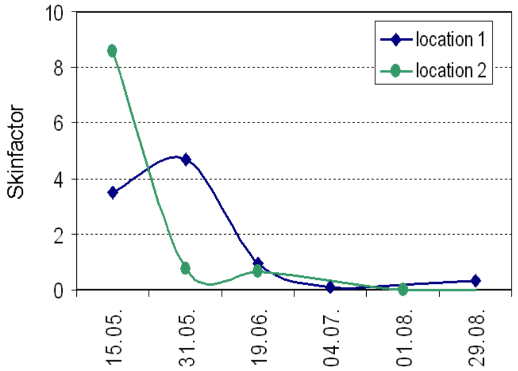

Figure 3. Change of skin-factors over time after tillage (based on experimental results of Botschek 1998).

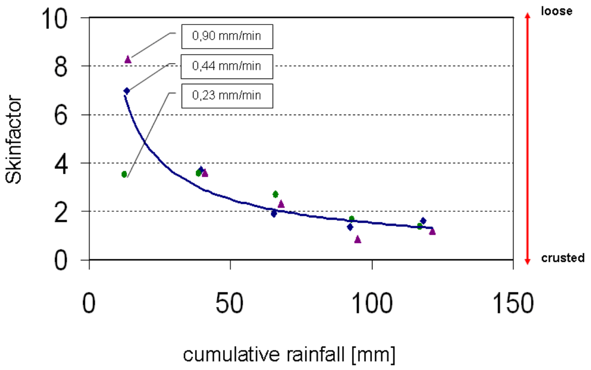

Figure 4. Skin-factor as a function cumulative rainfall

Figure 5 shows skin-factors of 32 fields in the loess region of southeast Germany classified according to different tillage practices. Data are results from plot experiments using a nozzle-type rainfall simulator.

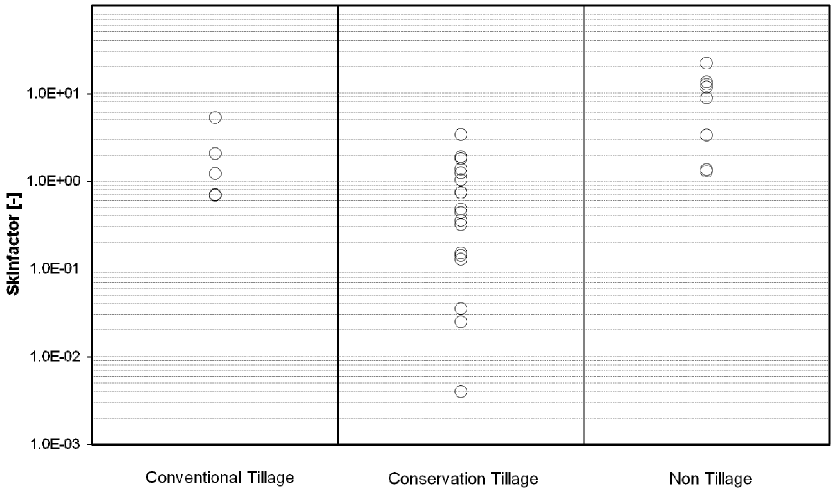

Figure 5. Variation of skin-factors depending on tillage practice (Schindewolf and Schmidt 2009).

Conservation tillage aims to reduce the impact of tillage operation on soil structure by using shallow working cultivators instead of more invasive plows. However, conservation tillage techniques are not defined very well, which might be the reason for the great variation of the resulting skin-factors compared to conventional tillage. Non-tillage practices result in significantly higher skin-factors indicating a higher amount of macropores open to the soil surface compared to conventional and conservation tillage.

Conclusion

The hydrologic effects of soil slaking and sealing can be estimated adequately by using the skin-factor approach. Skin-factors decrease with time after tillage respectively cumulative rainfall due to gradual structural disintegration of the soil surface. The decrease is not affected by rainfall intensity. Non-tillage practices tend to increase skin-factors suggesting a higher share of macropore-flow to infiltration compared to conventional and conservation tillage.

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