RAINFALL INFILTRATION UNDER URBAN SOIL SURFACE CONDITIONS – EXPERIMENT AND MODEL RESULTS

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Abstract

The hydrologic behavior of urban soils has been profoundly changed in densely populated areas due to sealing and compaction. As a consequence, the risk of flooding is increased and the groundwater recharge is decreased. Thus, rehabilitating existing areas affected by sealing and compaction and reducing additional soil sealing and/or compaction is a relevant goal for the future development of urban areas. This goal can be achieved by the use of permeable materials for surface covers, local infiltration ponds and ditches and the minimization of covered/sealed surfaces. The evaluation of the hydrologic effects of sealed surfaces and compaction are of importance in both planning and designing appropriate control measures. This paper presents an evaluation model which considers both the characteristics of typical urban surfaces and those of the underlying soils. In the first step, the model calculates the runoff coefficient of the existing unsealed/uncompressed underlying soil based on the approach of Green & Ampt (1911). In the second step, the runoff coefficient of the existing or planned surface cover is identified using a database which contains experimental runoff data for a set of different cover types. These two coefficients serve as a base factor for the evaluation of the specific combination of underlying soil and surface cover.

Additional Keywords: soil conservation, infiltration, aggregation

Introduction

Among soil scientists the term ´soil sealing´ is used in different ways. Sometimes it refers to the changing of soil structure due to raindrop impact or agricultural machinery which makes the top layer of the soil surface less permeable. In this paper ´soil sealing´ is used to describe the loss of soil permeability by impervious materials such as concrete or bitumen or by infrastructure construction covering the soil surface. In many parts of the world the increase of population as well as changes in the standard of living have led to accelerated urbanization and land consumption. This has resulted in an increase in soil sealing, eg. in Germany each second 15 m^2 are covered by new urban fabric (EEA 2001, p. 18). At present, a total of 22000 km^2 (6%) of Germany are sealed. Soil sealing has direct impacts on soil functions as well as indirect impacts on other media. Due to the loss of soil water storage capability and limited runoff retention risk of flooding is increased on the one hand and groundwater recharge is decreased on the other. Apart from these effects distributed drainage networks are necessary to drain the surface water from sealed surfaces. Construction and maintenance of these systems cause high costs. Thus the unsealing of soils respectively the limitation of additional soil sealing is a relevant goal for the future development of urban areas. This goal can be achieved by the use of permeable materials for surface covers, the reduced use of sealed surfaces, local infiltration ponds and ditches. However, at present there is still a lot of ignorance associated with implementing such measures within planning processes. Therefore, this study aimed to present an instrument for assessing and optimizing the implementation of measures for reducing soil sealing in urban areas.

Materials and Methods

The evaluation model presented in this study is based on infiltration physics according to the approach of Green and Ampt (1911). The model is called ROSS: ´RunOff from Sealed Soils´. In the first step ROSS calculates the runoff coefficient of the existing unsealed soil based on the specific physical parameters of the successive soil layers: particle size distribution, bulk density, organic matter content and initial soil moisture. A crusted soil surface texture (a common feature of many cultivated soils) can be considered by means of a so-called skin factor.

In the second step ROSS calculates the runoff coefficient of the existing or planned surface cover using a database which contains experimental permeability data for a set different cover types like brick, bitumen or concrete pavements, gravel and combined brick and grass surfaces. Finally the soil runoff coefficient is compared with surface cover runoff coefficient. The relation of these two coefficients serves as base factor for the evaluation of the specific combination of underlying soil and surface cover.

The infiltration model – basic approach

The infiltration model of ROSS simulates the percolation of rainwater into the soil. Because some processes are very difficult to parameterise some model simplifications are particularly necessary. An important simplification used in the ROSS model is the representation of the soil matrix as a rigid body which is particularly not affected by any changes over time. Such changes, which may have a decisive impact on infiltration rate, could be the result of biotic activity (e.g. earthworm burrows) or climatic impacts (e.g. freezing/thawing cycle).

The infiltration process consists of a stationary i_1 and an instationary (dynamic) component i_2. The stationary component i_1 is a function of the gravitational potential Ψ_g:

$$i_1 = k \cdot \frac{\Delta\Psi_g}{x_{f_1}} = k \cdot g \qquad (1)$$

where i_1 ... infiltration rate of the stationary component [kg (m^2 s)$^{-1}$], k ... hydraulic conductivity of the transport zone [(kg s) m^{-3}], Ψ_g ... gravitational potential [(N m) kg^{-1}], x_{f1} ... depth of the wetting front of the stationary component [m], g ... gravity [m s^{-2}], 9.81.

The instationary component i_2 is a function of the matric potential Ψ_m:

$$i_2 = k \cdot \frac{\Delta\Psi_m}{x_{f_2}(t)} \qquad (2)$$

where i_2 ... infiltration rate of the instationary component [kg (m^2 s)$^{-1}$], k ... hydraulic conductivity of the transport zone [(kg s) m^{-3}], Ψ_m ... matric potential [(N m) kg^{-1}], $x_{f2}(t)$ ... depth of the wetting front of the instationary component [m] at time t.

The infiltration model assumes a continually-advancing wetting front that moves downward through the soil profile. The water volume infiltrating into the soil during a particular time interval can then be calculated by multiplying the penetration velocity of the wetting front with the difference between the initial and the saturated soil water content.

Hence the stationary component i_1 can be calculated by the following equation:

$$i_1 = k \cdot g = \rho_f \cdot \Delta\Theta \cdot \frac{dx_{f_1}}{dt} \qquad (3)$$

with $\Delta\Theta = \Theta_s - \Theta_0$

where i_1 ... infiltration rate of the stationary component [kg (m^2 s)$^{-1}$], k ... hydraulic conductivity of the transport zone [(kg s) m^{-3}], g ... gravity [m s^{-2}], 9.81, ρ_f ... fluid density [kg/m^3], x_{f1} ... depth of the wetting front of the stationary component [m] at time t, t ... time [s], Θ_s ... saturated water content [m^3 m^{-3}], Θ_0 ... initial water content [m^3 m^{-3}].

Similarly, the instationary component i_2 given by:

$$i_2 = k \cdot \frac{\Delta\Psi_m}{x_{f_2}(t)} = \rho_f \cdot \Delta\Theta \cdot \frac{dx_{f_2}}{dt} \qquad (4)$$

with $\Delta\Theta = \Theta_s - \Theta_0$

$\Delta\Psi_m = \Psi_{m0} - \Psi_{ms}$

where i_2 ... infiltration rate of the instationary component [kg (m^2 s)$^{-1}$], k ... hydraulic conductivity of the transport zone [(kg s) m^{-3}], ρ_f ... fluid density [kg m^{-3}], $x_{f2}(t)$ ... depth of the wetting front of the instationary component [m] at time t, t ... time [s], Θ_s ... saturated water content [m^3 m^{-3}], Θ_0 ... initial water content [m^3 m^{-3}], Ψ_{mo} ... matric potential related to the initial water content Θ_0 [N m kg^{-1}], Ψ_{ms} ... matric potential related to the water content of the transport zone Θ_s [N m kg^{-1}].

Under the assumption of nearly saturated conditions within the transport zone the simplification $\Psi_{ms} \approx 0$ can be made, so that $\Delta\Psi_m \approx \Psi_{m0}$ and $k \approx k_s$.

By rearranging and integrating eqn. (4) and (5), the depth of the wetting front x_{f1} at time t for the stationary component i_1 is obtained by:

$$x_{f_1} = \frac{k_s \cdot g \cdot t}{\rho_f \cdot (\Theta_s - \Theta_0)} \tag{5}$$

x_{f1} ... depth of the wetting front of the stationary component [m], k_s ... saturated hydraulic conductivity [(kg s) m^{-3}], g ... gravity [m s^{-2}], 9,81, 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}].

and, for the instationary component i_2 by

$$x_{f_2} = \sqrt{\frac{2k_s \cdot \Psi_{m0} \cdot t}{\rho_f \cdot (\Theta_s - \Theta_0)}} \tag{6}$$

x_{f2} ... depth of the wetting front instationary component [m], k_s ... saturated hydraulic conductivity [(kg s) m^{-3}], Ψ_{mo} ... matric potential related to the initial water content Θ_0 [N m kg^{-1}], t ... time [s], ρ_f ... fluid density [kg m^{-3}], Θ_s ... saturated water content [m m^{-3}], Θ_0 ... initial water content [m^3 m^{-3}].

Hence x_{f1} (eqn. 5) can be inserted into eqn. 1 and x_{f2}: (eqn. 6) into eqn.2:

$$i_1 = \frac{\Delta\Psi_g}{\dfrac{g \cdot t}{\rho_f \cdot (\Theta_s - \Theta_0)}} = k_s \cdot g \tag{7}$$

$$i_2 = k_s \cdot \frac{\Psi_{m0}}{\sqrt{\dfrac{2k_s \cdot \Psi_{m0} \cdot t}{\rho_f \cdot (\Theta_s - \Theta_0)}}} \tag{8}$$

Now the infiltration rate can be calculated as the sum of the stationary i_1 and the instationary component i_2:

$$i = i_1 + i_2 = k_s \cdot g + k_s \cdot \frac{\Psi_{m0}}{\sqrt{\dfrac{2k_s \cdot \Psi_{m0} \cdot t}{\rho_f \cdot (\Theta_s - \Theta_0)}}} \tag{9}$$

where i ... infiltration rate [kg (m^2 s)$^{-1}$], i_1 ... infiltration rate of the stationary component [kg (m^2 s)$^{-1}$], i_2 ... infiltration rate of the instationary component [kg (m^2 s) $^{-1}$], k_s ... saturated hydraulic conductivity [(kg s) m^{-3}], g ... gravity [m s^{-2}], 9.81, Ψ_{mo} ... matric potential related to the initial water content Θ_0 [N m kg^{-1}], 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}].

The independent variables of this equation can either be directly estimated from field measurements (i.e. the initial water content Θ_0), or be derived from basic soil parameters by applying the following pedotransfer functions:

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

$$\textit{with} \quad b = \left(10^{-3} \cdot D\right)^{-0{,}5} + 0{,}2 \cdot \delta_p \qquad \textit{(Campbell, 1985)}$$

k_s ... saturated hydraulic conductivity [(kg s) m^{-3}], ρ_b ... bulk density [kg m^{-3}], T ... clay content [kg kg^{-1}], U ... silt content [kg kg^{-1}], b ... parameter [-], D ... mean diameter of soil particles [m], σ_P ... standard derivation of the mean diameter of soil particles [-].

$$\Psi_{m*} = \frac{\left[\left(\dfrac{\Theta_s - \Theta_r}{\Theta_o - \Theta_r} - 1\right) \cdot \dfrac{1}{\alpha^n}\right]^{\frac{1}{n}}}{100 \cdot \rho_b} \qquad \text{(van Genuchten, 1980)} \tag{11}$$

where Ψ_{m0} ... matric potential related to the initial water content Θ_0 [N m kg^{-1}], ρ_b ... bulk density [kg m^{-3}], Θ_0 ... initial water content [m^3 m^{-3}], Θ_r ... residual water content [m^3 m^{-3}], Θ_s ... saturated water content [m^3 m^{-3}], α, n ... parameter [-].

Because the theoretical concept presupposes a rigid soil matrix time variable soil structures such as macropores due to shrinking and biological activities (cracks, rootholes, wormholes etc.) have to be considered by an empirical factor, called skin factor. This factor allows calibration of the saturated hydraulic conductivity k_s according to eqn. (10) on the basis of measured data.

Experimental work
For characterizing the permeability of surface covers ROSS uses an integrated database, which was developed on the basis of extensive experimental research on different types of urban surfaces (Figure 1). Beside the type of surface cover also the age of the covers and the texture/structure of the base layers were considered. The experiments were accomplished with a transportable rainfall simulator (Figure 2, Schramm *et al.* in Breuste, 1995).

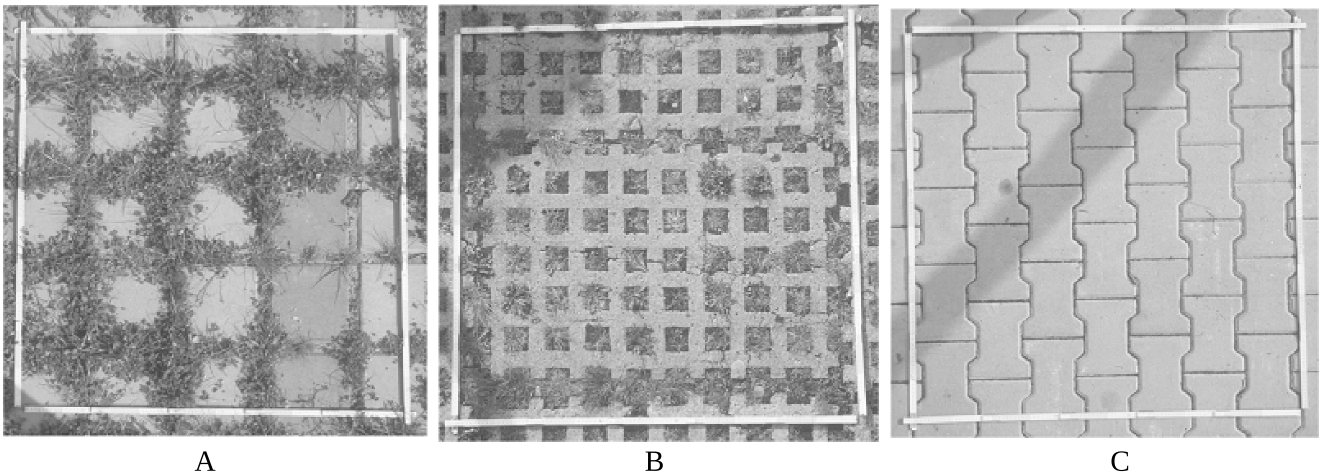

Figure 1. Examples for different types of surface cover: (a) bricks with grassed openings, (b) concrete plate with drainage openings, (c) brick pavement

Figure 2. Measuring the permeability of a sealed soil covered by concrete plates with drainage openings using a portable rainfall simulator

Results and Discussion

Figure 3 presents some of the infiltration curves achieved by the simulated rainfall experiments on different cover types but similar soil type. Obviously some cover types result in a dramatic decrease of infiltration capacity. Surprisingly similar cover types do not necessarily produce similar infiltration rates, as can be recognized by the two examples of brick cover with grassed openings in Figure 3. While on the one site high infiltration rates were measured, the other site shows extremely low infiltration rates, despite of the similar cover type. The main reason for these differences was found in the cover age as well as in the texture/structure of the base layer. Generally it was found, that with increasing cover age the permeability of the surface cover material decrease due to the clogging of drainage openings by fine dust, tire abrasion and other substances. Only in case of intensive vegetation within the drainage openings the permeability can be kept on a high level due to the activity of earth worms and other soil life. However, such conditions can only exist if the surface is only rarely covered up by vehicles. When the site is used more frequently there is not enough sunlight in order to keep a permanent vegetation within the drainage openings.

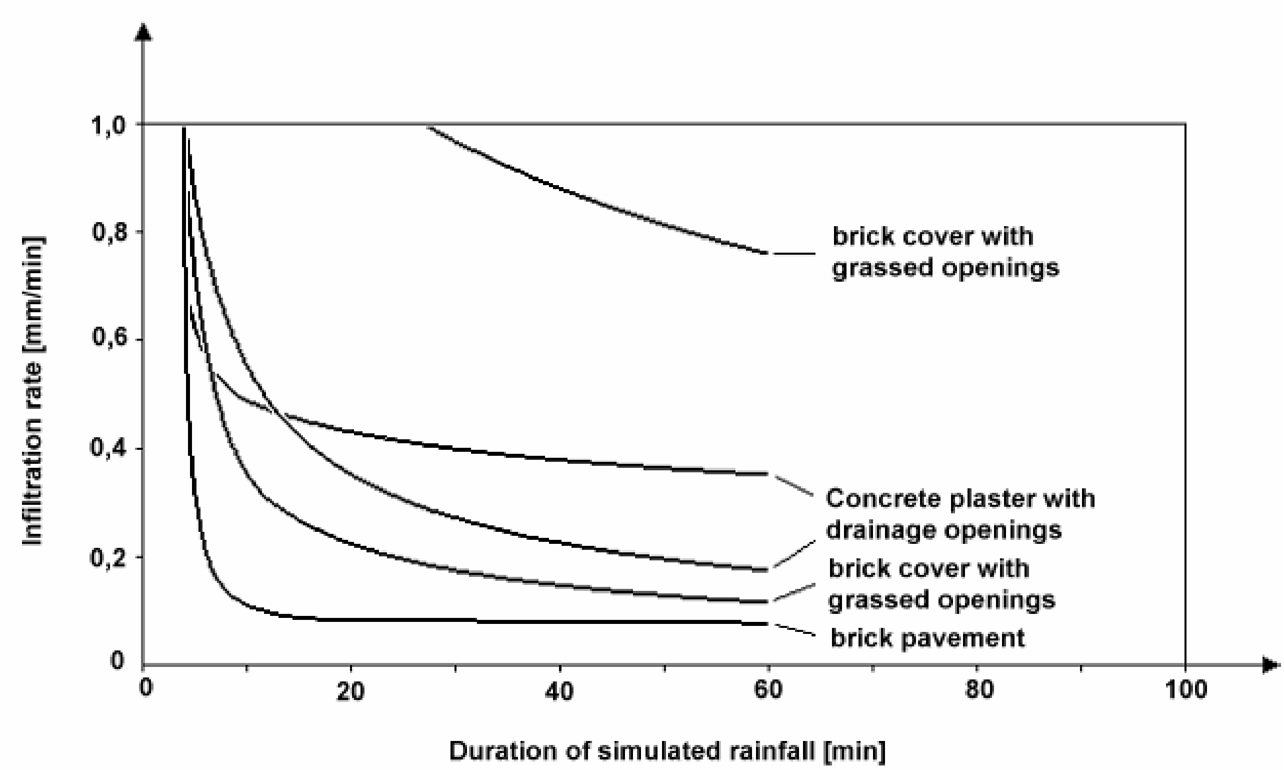

Figure 3. Experimentally derived infiltration rates of sealed soils as a function of cover type

The ROSS model produces two output curves as displayed in Figure 4. The upper curve displays the infiltration rate of the covered soil whereas the lower curve represents the infiltration rate of the uncovered soil. For comparison purposes cumulative infiltration is calculated from both curves. Using the cumulative infiltration data the runoff coefficients can be determined for the covered and the uncovered soil on the basis of a reference rainfall. Figure 5 shows the original ROSS output window, in which the computed data are displayed. Taking these coefficients into account an appropriate estimation of the hydrologic effects of soil sealing can be achieved.

Conclusions

Taking the model results into account an appropriate estimation of the hydrologic effects of soil sealing can be achieved. The evaluation of alternative surface cover materials or the dimensioning of drainage and compensation measures can be quoted as examples for the practical application of the ROSS model. Further development of the model is in progress. The major goal is the extension of the existing site specific model to a surface-related model.

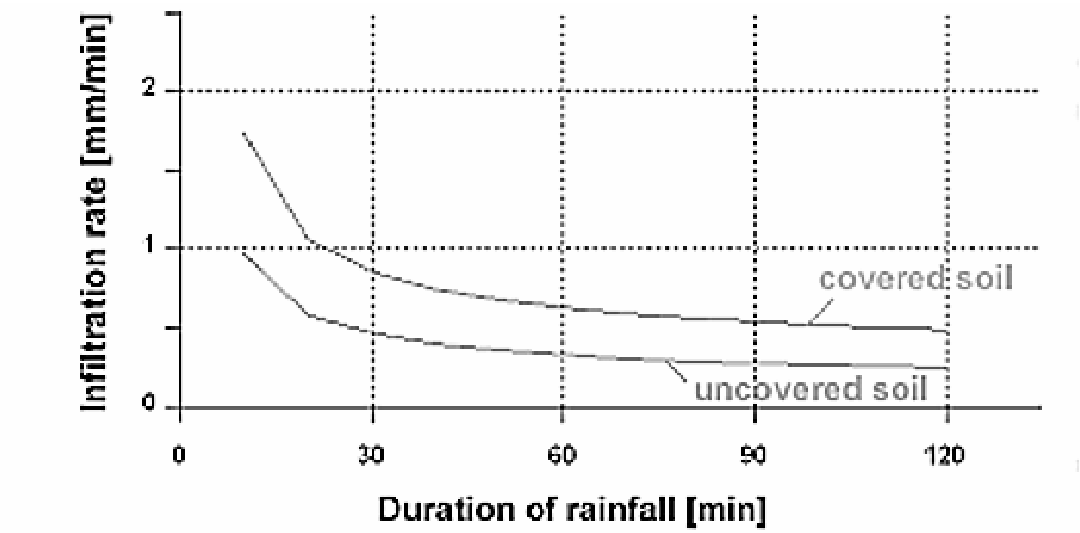

Figure 4. Infiltration rates of a sandy soil with and without a permeable surface cover as simulated by the ROSS model

Ergebnisse

Niederschlagssumme [mm]	120,000
kum. Infiltration o. Belag [mm]	80,556
kum. Infiltration m. Belag [mm]	46,939
Abflussbeiwert o. Belag	0,329
Abflussbeiwert m. Belag	0,609

Figure 5. ROSS output window showing: total precipitation of reference rainfall, computed cumulative infiltration without surface cover, computed cumulative infiltration with surface cover, runoff coefficient without surface cover, runoff coefficient with surface cover

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