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Impact of Overland Flow on Soil Characteristics in Třebsín Experimental Plots

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Abstract

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This paper describes the continuation of simulated outcomes from the plots No. 4 and No. 5 with two different soils, using the KINFIL model to assess the runoff from extreme rainfall. The KINFIL model is a physically-based, parameter-distributed 3D model that has been applied to the Třebsín experimental station in the Czech Republic. This model was used for the first time in 2012 to simulate the impact of overland flow caused by natural or sprinkler-made intensive rains on four of the nine experimental plots. This measurement of a rain simulator producing a high-intensity rainfall involves also hydraulic conductivity, soil sorptivity, plot geometry and granulometric curves to be used for the present analysis. However, since 2012, the KINFIL model has been amended to provide a more effective comparison of the measured and computed results using the values of new parameters such as storage suction factor and field capacity on plot 4 and plot 5. The KINFIL model uses all input data mentioned above, and it produces the output data such as gross rainfall, effective rainfall, runoff discharge hydraulic depths, hydraulic velocities and shear velocities as well as shear stress values depending on the soil particle distribution. These processes are innovative, physically based, and both the measured and the computed results fit reliably.

Keywords: hydrological model; water erosion; infiltration; kinematic wave

Soil and water resource protection is crucial for productive agriculture and sustainable environments. Soil erosion and sediment redistribution are processes to be presently studied using measurement tools, modelling tools, and management (Owens & Collins 2006; Kirkby 2011). Earlier models were not developed for predicting event erosion, but for an assessment of soil loss, using the Universal Soil Loss Equation (USLE, Wischmayer & Smith 1978). Current research on erosion modelling is concerned with soil-physics parameters that reflect their properties in a non-homogeneous space. Recent erosion simulation models like WEPP (Flanagan & Nearing 1995) and EUROSEM (Morgan *et al.* 1998) require a considerable amount of data and operate on the rainfall-runoff event basis. The KINFIL model is a physical 3D model, based on a combination of infiltration and transformation of direct runoff. In 2011 (Kovář & Vaššová 2011), this model was used for the first time to simulate the impact of overland flow caused by natural or sprinkler-made intensive rains on various experimental plots. A pair of technical devices (the RISWC Rain Simulator and the KINFIL model) produced the results presented in this paper. The devices compile records of rainfall and the corresponding overland flow discharges, and also hydraulic variables such as depths, velocities, shear stress and shear velocities, which are presented for a comparison with measured overland flow discharges. The intensive effective rainfall causes direct runoff, which is calculated by the Green and Ampt method (Green & Ampt 1911) adapted by Morel-Seytoux

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(Morel-Seytoux & Verdin 1981). The rest of the flow infiltrates down to be subtracted from the direct runoff, or alternatively according to the SCS CN method, which was developed by the U.S. Soils Conservation Service (SCS 1972, 1986) and by the U.S. Army Corps of Engineers (HEC-HMS, USACE 2015). In this study, we use the Green and Ampt method, which is suitable for small areas. Changes in land use and farm/land management can also be tested (Kovář & Hrádek 1994; Kovář *et al.* 2011, 2012).

MATERIAL AND METHODS

This paper describes the continuation of simulated outcomes from the article published in SWR Vol. 7, No. 3, using the KINFIL model to assess the runoff from extreme rainfall. The KINFIL model is currently used for simulating erosion processes and for predicting the vulnerability of soil to water, inasmuch as surface runoff and water erosion are closely related. In the calculation, we designed rainfall events on experimental plots 4 and 5 in Třebsín, which are located close to the nearest rainfall recording gauge at Benešov. These rainfall-runoff events were reduced from 15 to 20-minute critical periods of high-intensity rainfall on recurrence interval between 2 years and 100 years. However, this is only to assess rainfall parameters (depth and intensity) close to 80-years measurement (Šamaj *et al.* 1983). Using a rain simulator (RISWC), we measured the area of the rainfall-runoff simulations A = 30 m^2 (i.e. length L = 10.0 m, width W = 3.0 m) on two plots, using mainly experimental plots No. 4 and No. 5.

The KINFIL model takes into account the physical-geographical characteristics of the experimental areas or small catchment-plots and the soil hydraulic properties which can be obtained by direct measurement. The model is primarily designed to derive peak flows during simulations of variants with different input conditions, e.g. a change in land use (deforestation, urbanization, etc.). The model is based on a combination of infiltration theory (INFIL) and transformation of the runoff by a kinematic wave (KIN). The current version of the KINFIL model can be combined with a GIS interface (Kovář *et al.* 2011; Kovář & Vaššová 2011; Dostál *et al.* 2014). The KINFIL model is based on the Green and Ampt theory of infiltration, and also introduces the concept of production according to Mein and Larson (1973) and Morel-Seytoux (Morel-Seytoux & Verdin 1981; Morel-Seytoux 1982):

$$K_s\left(\frac{z_f+H_f}{z_f}\right)=(\theta_s-\theta_i)\frac{dz_f}{dt},\quad S_f=(\theta_s-\theta_i)\times H_f,\quad t_p=\frac{S_f}{i\left(\frac{i}{K_s}-1\right)} \tag{1}$$

where:
K_s – saturated hydraulic conductivity (m/s)
z_f – depth of infiltration (m)
θ_s – saturated soil moisture (–)
θ_i – initial soil moisture (–)
H_f – suction below the infiltration depth (m)
i – rain intensity (m/s)
S_f – storage suction factor (m)
t_p – ponding time (s)
t – time (s)

The infiltration process is investigated on the basis of the Green and Ampt theory in the organization as adapted by Morel-Seytoux, based on a calculation of ponding time t_p. At this point, we have simplified the computational programme to introduce directly $S(\theta_{FC})$ for S_f. The soil sorptivity for field water capacity (m/s$^{0.5}$) is then given by:

$$S(\theta_{FC})=\sqrt{2K_s\times S_f} \tag{2}$$

from the Green and Ampt equation (Green & Ampt 1911):

$$v_f=K_s\times\left[i+\frac{(\theta_s-\theta_i)\times H_f}{W}\right] \tag{3}$$

where:
W – cumulative infiltration (m)

The kinematic wave sub-model is a part of the model with distributed parameters that can be used for a variety of geometric shapes, e.g. for a cascade of flat planes, convergent or divergent segments, or for sections of concentrated runoff in catchments.

Water flows on a flat plane or on convergent/divergent segments and can be expressed as a kinematic wave equation:

$$\frac{\partial y}{\partial t}+\frac{\partial q}{\partial x}=i_e(t),\quad q=\alpha\times y^m \tag{4}$$

where:
q – flow rate per unit width of the slope (m^2/s)
$i_e(t)$ – intensity of the effective rain (m/s)
α, m – hydraulic parameters
t, x – time coordinates (s) and position coordinates (m)

By combining the equations, we get:

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$$\frac{\partial y}{\partial t}+m\alpha y^{m-1}\frac{\partial y}{\partial x}=i_e(t) \qquad (5)$$

The kinematic wave model with an explicit numerical scheme provides a solution (Lax & Wendroff 1960) to the depth of the water flow:

$$\begin{aligned} y_j^{i+1} = y_j - \frac{\Delta t}{2\Delta x}\times\left(\alpha y_{j+1}^m - \alpha y_{j-1}^m - 2\Delta x\left(i_e\right)_j\right) + \frac{(\Delta t)^2}{4\,(\Delta x)^2}\times \\ \times\left(\alpha m y_{j+1}^{m-1} + \alpha m y_j^{m-1}\right)\times\left(\alpha y_{j+1}^m - \alpha y_j^m - \Delta x\times(i_e)_j\right) - \\ -\frac{(\Delta t)^2}{4(\Delta t)^2}\times\left(\alpha m y_j^{m-1} + \alpha m y_{j-1}^{m-1}\right)\times\left(\alpha y^m\right)_j - \left(\alpha y^m\right)_{j-1} - \\ -\Delta x\times(i_e)_j + \frac{\Delta t}{2}\left[(i_e)_j^{i+1} - (i_e)_j\right] \end{aligned} \qquad (6)$$

In this equation, all variables that are not marked with superscript $i + 1$, are considered to be running with a time step of $i(i + \Delta t = t + \Delta t)$. Subscript j denotes the surface step $x(j + \Delta x = x + \Delta x)$. In order to solve other hydraulic variables, the hydraulic depths y_j^{i+1} have to be used as the most important starting variables (Eq. (6)), which is applied further for the hydraulic velocities v_j^{i+1}, the shear velocity $(v^*)_j^{i+1}$ and the shear stress τ_j^{i+1}. All the following three additional variables have been computed from the hydraulic depths y_j^{i+1}:

$$v_j^i = \alpha_j \times (y_j^i)^{m-1},\ (v^*)_j^i = \sqrt{g\times Y_j\times y_j^i},\ \tau_j^i = \rho\times g\times Y_j\times y_j^i \qquad (7)$$

where:
α_j, m_j – hydraulic parameters
Y_j – slope of the land (–)
g – acceleration of gravity (m/s^2)
ρ – density of water (kg/m^3)

The KINFIL model can be used as a hydrologically-based instrument for determining the hydrological characteristics when designing technical erosion control measures (Kovář *et al.* 2012, 2016).

The experimental area is located about 40 km south-east of Prague, close to the village of Třebsín (49°51'15''N, 14°27'49''E). The experimental research location is operated by the Research Institute for Soil and Water Conservation in Prague-Zbraslav. The average slope of the plots is about 7° to 8°. There are soils with different hydraulic properties (Table 2). The scheme of the experimental runoff areas is illustrated in Figure 1. A field rain simulator was used to simulate rainfall (Figure 2). It is made from duralumin, and stands 3 m above the terrain. The tubes are provided with nozzles (FullJet spraying system) (Flanagan & Nearing 1995) with a wide range of spray droplet sizes (104° at a pressure of 34.5 kPa), approaching natural driving rain. The size of the water drops is close to the size of natural rain drops.

The average values for saturated hydraulic conductivity K_S and for sorptivity $S(\theta_{FC})$ were obtained by the infiltrometer method (double cylinders) for a saturated state.

RESULTS AND DISCUSSION

The rainfall data was produced by an RISWC rainfall simulator and also by a tipping bucket system. For dry land, data from 30/7/2008 and from 1/8/2009 was assessed and, for wet soil, data from 13/7/2009 and from 12/8/2009 was also assessed. Basic information on the runoff situation, together with the hydrological parameters, is presented in Table 1.

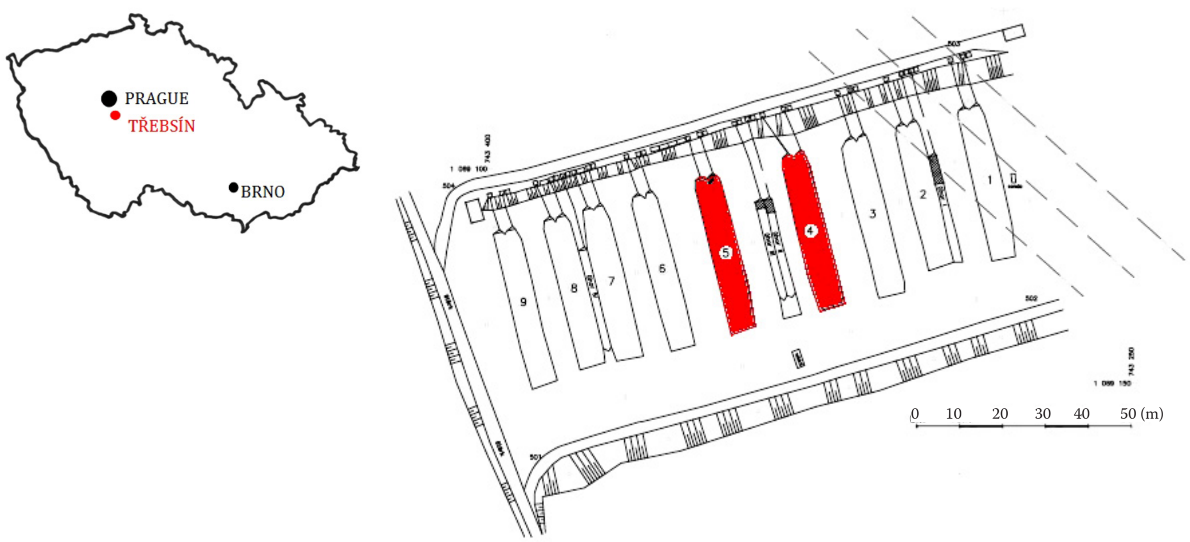

Figure 1. Plan of the experimental runoff plots in Třebsín

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Figure 2. Rain simulator

The effective rainfall was calculated using the KINFIL model, into which the following information was entered: saturated hydraulic conductivity, soil sorptivity, rainfall, time, and the Curve Number (CN) value. Then after the INFIL part, the effective rainfall model is automatically completed by the KIN part. The overland flow was calculated using the kinematic wave hydrological parameters (α, *m*), granulometric curves or Manning's roughness (*n* in our case), surface plots, and time. The effective rain and the overland flow are shown in Table 2. Figures 3 and 5 show the effective rainfalls during simulator sprinkling. The hyetograph rises rapidly in the first minutes, then the levels stabilize. Finally, the levels decrease more slowly than they had risen at the beginning of the process. There is a delay of about 2 min before runoff begins. The model shows how the effective rainfall and the corresponding runoff hydrographs reflect the state of the soil, especially its ability to infiltrate rainwater. The values of the computed hydraulic parameters K_s and S_f (or $S(\theta_{FC})$) were recorded in 2008 and 2009. Figures 4 and 6 present the values of the hydraulic depths, the hydraulic velocities and the shear velocities. The measured and computed hydrographs were compared using the Nash and Sutcliffe efficiency coefficients (Nash & Sutcliffe 1970), see Eq. (8) and Figures 3 and 5:

$$EC = 1 - \left(\sum_{i=1}^{N}(Q_i - QC_i)^2\right) / \left(\sum_{i=1}^{N}\left(Q_i - \bar{Q}\right)^2\right) \quad (8)$$

where:

Q_i – measured discharge (l/s)

QC_i – computed discharge (l/s)

Q^- – average measured discharges (l/s)

N – number of discharge ordinates (–)

Their goodness of fit is very satisfactory and all efficiency coefficients (*EC*) are well acceptable (0.77 < *EC* < 0.85).

Table 1. Basic information on rainfall-runoff simulated events (15 min)

Plot No.	Date		Nash-Sutcliffe coefficient (–)	Rainfall	Runoff measured	Runoff computed
				(mm)		
4	30/07/2008	D	0.80	13.66	9.37	9.26
4	13/07/2009	W	0.77	13.83	8.37	8.22
5	01/08/2009	D	0.85	13.21	5.77	5.57
5	12/08/2009	W	0.78	13.21	6.17	5.99

D – dry; W – wet

Table 2. Plot geometry, crop and soil hydraulic parameters

Site No.	Slope (%)	Area (m^2)	Crop	Saturated hydraulic conductivity (K_s, mm/min)	Sorptivity ($S(\theta_{FC})$, mm/min$^{0.5}$)	Storage suction factor (S_f, mm)
4	14.3	30	maize	4.36	4.64	2.47
5	13.5	30	maize	1.65	4.13	5.17

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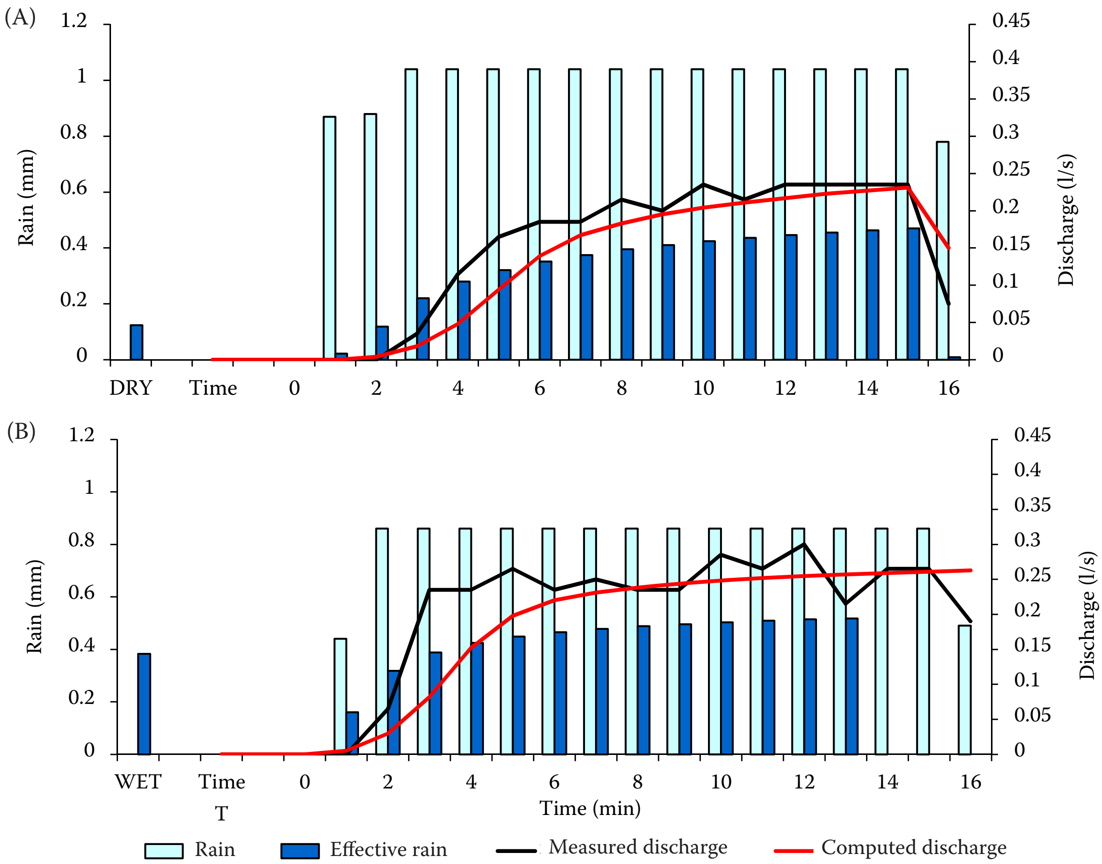

Figure 3. Simulated rainfall-runoff events – Třebsín Plot 4: (A) 30/7/2008, maize, condition of land: dry, DT = 1 min, (B) 13/7/2009, maize, condition of land: wet; DT = 1 min; DT – duration

Table 1 provides *EC* values. According to the measured and computed runoff values in the last two columns of Table 1 it seems that their differences are negligible. However, if compared in Figures 3 and 5, the measured discharges are more jagged than the computed hydrographs. The absolutely perfect *EC* goodness of fit is 1.0 (–), acceptable values are greater than 0.75 (–). The data from plot 4 and plot 5 was applied in the KINFIL model for the same rainfall duration td = 20 min.

CONCLUSIONS

A reliable RISWC rainfall simulator, including appropriate devices for overland flow measurements that also set up the parameters of the model, provided useful

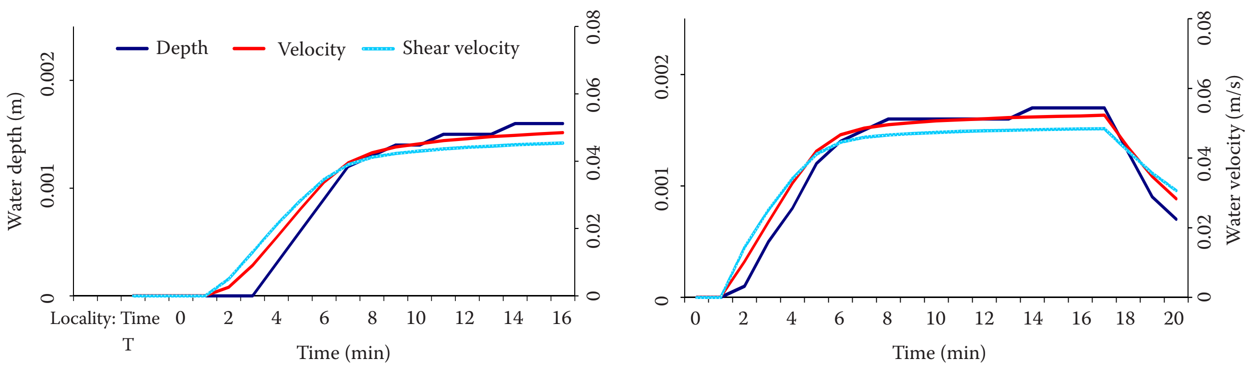

Figure 4. Left: Třebsín Plot 4, hydraulic variables date: 30/7/2008, maize, condition of land: dry, DT = 1 min; right: Plot 4, hydraulic variables date: 13/7/2009, maize, condition of land: wet, DT = 1 min; DT – duration

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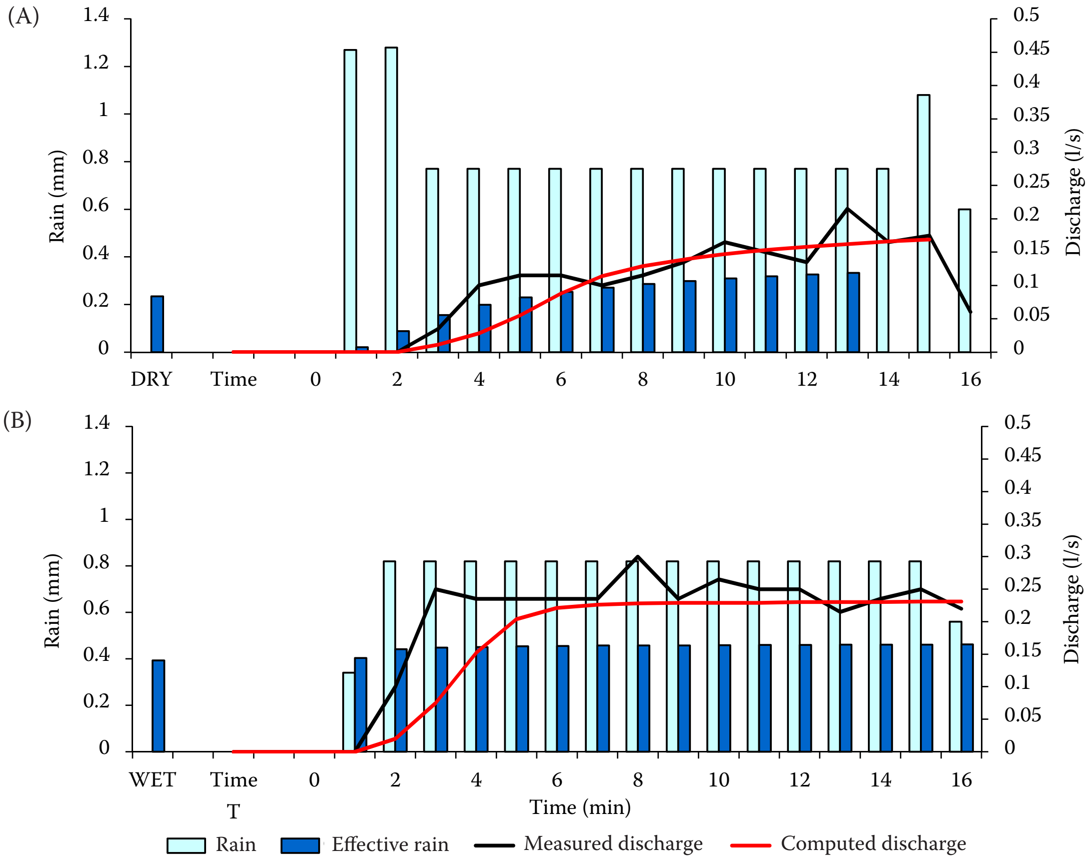

Figure 5. Simulated rainfall-runoff events – Třebsín Plot 5: (A) 1/8/2009, maize, condition of land: dry, DT = 1 min; (B) 12/8/2009, maize, condition of land: wet, DT = 1 min; DT – duration

physical equipment for studying the runoff processes. Table 2 describes both experimental plots No. 4 and No. 5, each of which is 30 m^2 in area. The KINFIL model evidently has a broad range of applicability (Kovář *et al.* 2012). The complete set of devices, which the KINFIL model comprises, enables the user to calibrate the parameters of the model, i.e. saturated conductivity *Ks* and storage suction factor *Sf*, Manning's roughness coefficients *n*, geomorphology and granulometry. This set corresponds to the devices and the model structures (Amore *et al.* 2004; Morgan & Nearing 2011). The characteristics of soil hydrology are different. The most important parameters are hydraulic conductivity *Ks* and storage suction factor *Sf*. The resultant variables are

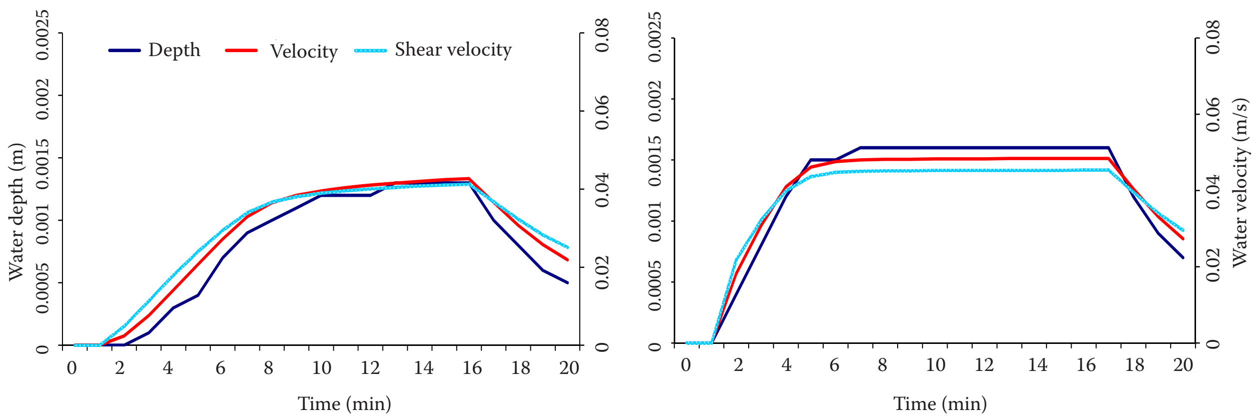

Figure 6. Left: Plot 5, hydraulic variables date: 12/8/2009, maize, condition of land: dry, DT = 1 min; right: Plot 5, hydraulic variables date: 12/8/2009, maize, condition of land: wet, DT = 1 min; DT – duration

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overland flow discharges, hydraulic variables, e.g. depths, velocities, shear stress and shear velocities, measured accurately enough to be compared with the measured overland flow discharges, changes in land use and farmland management. In conclusion, it may be stated that the joint application of the KINFIL model and the RISWC rainfall simulator has the following advantages: firstly, it provides results from a physically-based scheme and, secondly, it provides a way to calibrate model parameters for the simulation of a natural rainfall-runoff event. For a subsequent computation of the soil loss we can start with granulometry of the soils to distinguish between the effects of inter-rill erosion and rill erosion on the critical shear stress values and the revetment role of biotechnical measures.

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