Surface Runoff Simulation to Mitigate the Impact of Soil Erosion, Case Study of Třebsín (Czech Republic)

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Abstract: The relation between soil erosion and its redistribution on land strictly depends on the process of surface runoff formation during intensive rainfall. Therefore, interrupting and reducing continuous surface runoff, using adequate conservation measures, may be implemented in order to reduce the shear stress of flowing water. This paper describes the outcomes of the KINFIL model simulation in assessing the runoff from extreme rainfall on hill slopes. The model is a physically based and parameter distributed 3D model that was applied at the Třebsín experimental station in the Czech Republic. This model was used for the first time to simulate the impact of surface runoff caused by natural or sprinkler-made intensive rains on four of the seven different experimental plots. The plots involved in the analysis contain a variety of soils which are covered with different field crops. At this stage, the model parameters comprise saturated hydraulic conductivity, field capacity, sorptivity, plot geometry and surface roughness reflecting the Třebsín experimental plots. These parameters were verified on observed data. All seven plots had the same slope angle, but two of them were vulnerable to surface runoff due to their soil hydraulic parameters. There were rapidly increasing depths and velocities which consequently caused a higher shear stress for splashing soil particles downstream. The paper provides further information and data concerning the relationships between the depth of water and its velocity on the slopes of certain roughness. It also provides information concerning shear stress and shear velocity values, compared with their critical values depending on the soil particle distribution. This approach is more physically based than the traditional method of Universal Soil Loss Equation (USLE).

Keywords: hydrological model; shear stress; shear velocity; soil loss

The first set of erosion simulation models that adopted Wischmeier's approach was used to generate surface runoff and transport of soil including examples like ANSWERS (Beasley *et al*. 1980), CREAMS (Knisel 1980) and later AGNPS (Young *et al*. 1989) and KINEROS (Woolhiser *et al*. 1990). The last three models allowed a choice between daily simulations based on the US SCS Curve Numbers and coefficients which describe the soil, slope, land cover, and storm simulations where runoff is calculated as the excess of rainfall intensity over the infiltration rate of soil. This generation of erosion models was process-based as regards the simulation of runoff and sediment, but relied on the factors of the Universal Soil Loss Equation – USLE (Wischmeier & Smith 1978; Janeček 2004) to describe soil erodibility (K), slope length (L), cropping (C) and management (P) effect (Morgan & Nearing 2011).

Current research on erosion modelling is concerned with replacing the coefficients related to soil, slope and land cover with parameters that reflect their properties and which take into account variations in both time and space. The outcome is that erosion models have become more complex to describe the catchment rainfall-runoff behaviour including surface runoff and erosion (Owens & Collins 2006).

Recent erosion simulation models like WEPP (Flanagan & Nearing 1995), EUROSEM (Morgan *et al.* 1998) or EROSION3D (Schmidt *et al.* 1999; Schmidt 2000), which are more detailed process-based ones, operate on storm basis and it is possible to change the input parameters regularly over time to take in account changes. Such models require a lot of data on, for example, interrill erodibility, rill erodibility, shear stress, surface roughness, plant density, etc. These data sets are more complex than hydrological data (Flanagan & Nearing 1995; Váška 2000).

Therefore, we have recently adopted the KINFIL model (Kovář 1992; Kovář *et al.* 2002, 2011), which simulates infiltration and surface runoff processes in small catchments, for erosion process simulation supplementing it by the soil erosion subroutines.

MATERIAL AND METHODS

KINFIL model

The KINFIL model in its recent version (3D, 2011) is physically based and it was used formerly for hydrological simulation of significant rainfall-runoff events (2008–2010) either for prediction or for simulations of various scenarios. It has the infiltration part as well as the surface runoff transformation part. The infiltration part of the model is based on the Morel-Seytoux equations (Morel-Seytoux & Verdin 1981) using the Green-Ampt concept and distinguishing pre- and post-ponding infiltration from constant or variable rainfall. The Green-Ampt method presumes that above the infiltration front there is a zone of saturated soil moisture content θ_S and the conditions for a saturated flow hold. The infiltration rate v_f under these conditions can be expressed as follows:

$$v_f = K_S\left[1 + \frac{(\theta_S - \theta_0)\times H_f(\theta_0)}{V}\right] \qquad (1)$$

where:

K_S – coefficient of saturated hydraulic conductivity

θ_S – saturated soil moisture

θ_0 – initial soil moisture

$H_f(\theta_0)$ – soil capillary drive just under the infiltration front

V – cumulative infiltration.

Mein and Larson (1973) introduced ponding time $t = t_p$ occurring when $\theta_0 = \theta_S$ and infiltration rate v_f equals rainfall intensity i. Then cumulative infiltration V_p at ponding time t_p equals $V_p = i \times t_p$. Substituting it into Eq. (1):

$$i = K_S\left[1 + \frac{(\theta_S - \theta_0)\times H_f(\theta_0)}{i \times t_p}\right] \qquad (2)$$

After rearrangement of this equation, we can get:

$$t_p(i^2 - K_S \times i) = K_S(\theta_S - \theta_0)\times H_f(\theta_0) \qquad (3)$$

If we define the normalized rainfall intensity according to the coefficient of saturated hydraulic conductivity K_S, $i_* = i/K_S$, then the ponding time t_p can be expressed explicitly like this:

$$t_p = \frac{(\theta_S - \theta_0)\times H_f(\theta_0)}{\frac{i}{K_S}(i - K_S)} = \frac{(\theta_S - \theta_0)\times H_f(\theta_0)}{i(i_* - 1)} \qquad (4)$$

Equation (4) was derived by Mein and Larson (1973). If $\theta_0 = \theta_S$, t_p comes immediately, the drier the soil, the longer the ponding time. If $i < K_S$ ($i_* < 1$), the ponding time is not reached and Eq. (4) ceases. This equation can be altered by introducing the storage suction factor S_f defined as:

$$S_f = (\theta_S - \theta_0)\times H_f(\theta_0) \qquad (5)$$

after substituting S_f in Eq. (4):

$$t_p = \frac{S_f}{i(i_* - 1)} \qquad (6)$$

The terms for infiltration velocity and cumulative infiltration were derived by Morel-Seytoux (Morel-Seytoux & Verdin 1981; Morel-Seytoux 1982). The final forms of the resulting equation for constant rainfall intensity after reaching the ponding time, i.e. $t \geq t_p$, can be written as follows:

$$v_f = \frac{1}{2}S(\theta_0)\frac{i_*}{i_* - 1}\times\frac{1}{\sqrt{t - t_p + \frac{1}{2}\left(\frac{i_*}{i_* - 1}\right)\times t_p}} + K_S \qquad (7)$$

where:

$S(\theta_0)$ – sorptivity

Cumulative infiltration can be expressed by integration of Eq. (7) within integration limits t_p, t:

$$V = V_p + K_s(t - t_p) + S(\theta_0) \times \\ \times \frac{i_*}{i_* - 1}\left(\sqrt{t - t_p + CA} - \sqrt{CA}\right) \tag{8}$$

where:

$$CA = \frac{1}{2} \times \left(\frac{i_*}{i_* - 1}\right)^3 \times t_p \tag{9}$$

Adequate equations were derived for a generic case of variable intensity rain (Morel-Seytoux 1982; Kovář 1992). Herein, the final forms of equations are given. For the ponding time we can write:

$$t_p = t_{j-1} + \frac{1}{i_j}\left(\frac{S_f}{i_{*j-1}} - \sum_{k=1}^{j-1} i_k(t_k - t_{k-1})\right) \tag{10}$$

where:

j – time step subscript

k – subscript of rainfall ordinates to which the individual rainfall depths in time steps are summarized up to the step t_j

The cumulative infiltration after reaching the ponding time is as follows:

$$V = V_p + K_s(t - t_p) + \sqrt{\frac{2K_S(S_f + V_p)^2}{S_f}} \times \\ \times \left(\sqrt{t - t_p + CB} - \sqrt{CB}\right) \tag{11}$$

where:

V_p – cumulative infiltration at ponding time

$$CB = \frac{1}{2} \times \frac{(S_f + V_p)^2}{K_S \times S_f\left(\frac{t_p}{K_S} - 1\right)^2} \tag{12}$$

where:

i_p – ponding rainfall intensity

Infiltration velocity from variable rainfall intensity is:

$$v_f = \frac{1}{2}\sqrt{\frac{2K_S(S_f + V_p)^2}{S_f}} \times \frac{1}{\sqrt{t - t_p + CB}} + K_S \tag{13}$$

From the above analysis it is evident that this procedure requires the knowledge of soil hydraulic parameters and initial conditions of soil moisture content of the upper soil zone. The values of θ_S, θ_0, K_S, $S(\theta_0)$ or S_f need to apply the infiltration procedure which is the essence of the infiltration part of the KINFIL model. In particular, when we know the values of S_f and K_S, we can solve equations (6), (7), and (8) for constant rainfall, and equations (10), (11), and (13) for variable rainfall.

The first part of the KINFIL model computes infiltration rates $v_f(t)$ from rainfall ordinates for each time step and subtracts them from rainfall intensity ordinates $i(t)$ in order to get the effective rainfall hyetograph $ie(t)$:

$$ie(t) = i(t) - v_f(t) \tag{14}$$

The second part of the KINFIL model is the surface runoff component using the kinematic wave equation (Kibler & Woolhiser 1970; Singh 1996):

$$ie(t) = \frac{\partial y}{\partial t} + \alpha m y^{m-1}\frac{\partial y}{\partial x} \tag{15}$$

where:

$ie(t)$ – excess rainfall intensity

y, t, x – ordinates of depth, time and position

α, m – hydraulic parameters

Equation (15) describes non-steady flow, approximated by kinematic wave on a plane or a cascade of planes or segments. It is computed using the finite differences method implementing the explicit scheme (Lax & Wendroff 1960) of the second order. Thus the depths of flow (3D) are computed according to the following scheme:

$$\begin{aligned} y_j^{i+1} = {} & y_j - \frac{\Delta t}{2\Delta x}[(\alpha y^m)_{j+1} - (\alpha y^m)_{j-1} - 2\Delta x \times ie_j] + \\ & + \frac{\Delta t^2}{4\Delta x^2}[(\alpha m y^{m-1})_{j+1} + (\alpha m y^{m-1})_j] \times \\ & \times [(\alpha y^m)_{j+1} - (\alpha y^m)_j - \Delta x \times ie_j] - \\ & - \frac{\Delta t^2}{4\Delta x^2}[(\alpha m y^{m-1})_j + (\alpha m y^{m-1})_{j-1}] \times \\ & \times [(\alpha y^m)_j - (\alpha y^m)_{j-1} - \Delta x \times ie_j] + \\ & + (ie_j^{i+1} - ie_j) \times \frac{\Delta t}{2} \end{aligned} \tag{16}$$

In Eq. (16) and then in Eq. (17) all variables not indicated by superscript $i + 1$ are considered in the present time step i, ($i + \Delta t$ is $t + \Delta t$), subscript j indicates the position step x ($j + \Delta x$ is $x + \Delta x$). The upper boundary condition is $y(x, 0) = 0$ for all x. The lower boundary condition $j = jj$ is defined by the difference scheme of the first order (Singh 1996):

$$y_{ij}^{i+1} = y_{ij} + \Delta t\left(-\alpha \frac{y_{ij}^m - y_{ij-1}^m}{\Delta x} + ie_{ij}\right) \tag{17}$$

The numerical stability of computation assumes the following criterion of both time and position step:

$$\frac{\Delta t}{\Delta x} \leq \frac{1}{\alpha m y^{m-1}} \tag{18}$$

For a catchment subdivision the computation scheme can be used for more detailed fragmentation to a cascade of planes and convergent or divergent segments (Heřman *et al.* 2001).

Besides the computation of y_j^i the present version of the KINFIL model for surface runoff – soil erosion events provides the computation of hydraulic velocities of surface flow (interrill flow):

$$v_j^i = \alpha_j \times (y_j^i)^{m_j - 1} \tag{19}$$

water shear velocities:

$$v_* = \sqrt{g \times Y_j \times y_j^i} \tag{20}$$

and shear stress on the soil surface by surface runoff:

$$\tau_j^i = \rho \times g \times Y_j \times y_j^i \tag{21}$$

where:

α_j, m_j – hydraulic parameters
Y_j – slope gradient
g – gravity acceleration
ρ – water density

Experimental area and field measurement

The experimental area is located about 40 km from Prague in south-east direction, close to the village of Třebsín (49°51'15''N, 14°27'49''E). There are nine experimental plots, each covering a surface of 7 × 36 m. The size of each plot can be reduced according to the rainfall simulator capacity and measuring device. The average slope of the plots is about 7°. They are situated on arable land with a variety of crops grown on each plot, depending on the cropping systems and the required tests. The research location is operated by the Research Institute for Soil and Water Conservation in Prague-Zbraslav (RISWC Prague), where experimental testing has been conducted since the beginning of the 1990's. The area belongs to a mildly warm region, with annual mean precipitation of 517 mm, average temperature of 6.5°C and an altitude of 340–350 m a.s.l. The natural soil composition is originally a gneiss substrate and is mostly of Haplic Cambisol type, belonging to the soil group of silty loam.

Runoff from natural rains was measured at automatic measuring stations on the downstream side of the rectangular shape of parcels (by measuring flume) of the area of A = 252 m^2 (7 × 36 m). Rainfall simulation was used on the reduced size of the parcel area A = 30 m^2 (3 × 10 m). Parcels where tests were carried out to provide the data used in this paper were selected on the basis of a broad spectrum of soil hydraulic parameters. In particular, parcels No. 6 and No. 9 had anthropic soils, with applications of less permeable soil (loamy clay). The scheme of experimental runoff plots

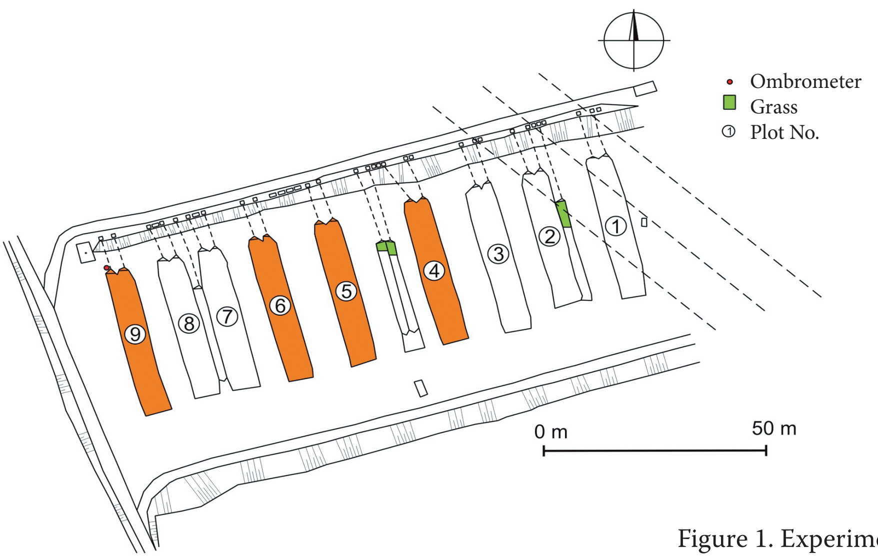

Figure 1. Experimental runoff plots in Třebsín

Table 1. Plot geometry, crop and soil hydraulic parameters

Site No.	Slope (%)	Area (m^2)	Crop 2008/09	Saturated hydraulic conductivity K_S (mm/min)	Sorptivity $S(\theta_0)$ ($mm/min^{0.5}$)	Storage suction factor S_f (mm)
4	14.3	10.0	maize	4.36	4.64	2.47
5	13.5	10.0	maize	1.65	4.13	5.17
6	12.8	10.0	maize	0.18	1.20	4.07
9	11.0	10.0	maize	0.21	1.06	2.63

is depicted in Figure 1, the soil characteristics of plots and their hydraulic parameters are shown in Table 1. Granulometric curves for all plots are represented in Figure 2.

The average values of saturated hydraulic conductivity K_S and sorptivity $S(\theta_0)$ were obtained by the infiltrometer method (double cylinders) for saturated state. It is evident from Table 1 that plot 4 has a high value of K_S, plot 5 an average value, and plots 6 and 9 have a low value of infiltration rate.

A rainfall simulator, belonging to RISWC Prague, was used for the experiment. Its self-supporting construction is made of aluminium pipes 3.0 m in height. The pipes are connected with tubes ended with a wide-angle spraying system, covering an area of 104° at a pressure of 34.5 kPa (fulljet type). The size of water drips is close to the size of natural rain drops. The equipment can cover an area of 30 m^2 from three nozzles. The water pump, powered by a 12 V battery, supplies water from a 600 l tank. The spraying intensity can vary from 0.5 to 2.0 mm/min and it can be regulated by an electronic device. The rainfall simulator can be seen in Figure 3.

RESULTS AND DISCUSSION

Rainfall data produced by the rainfall simulator was measured by two parallel devices: firstly, by a flowmeter which is a part of the simulator, and secondly by a tipping-bucket system on the plot area. The discharges are registered by a discharge measurement device located in the special flume at the downstream outlet of the plot. The tests were carried out on four plots in the years 2008 to 2009. Two tests on each plot were carried out in order to show how the KINFIL model (formerly a hydrological tool) can also be adopted in soil erosion research.

At the beginning, tests on each experimental plot were carried out on dry soil, and for the same rainfall duration t_d = 15 min. The second run took place when the soil was still wet, just after the first run.

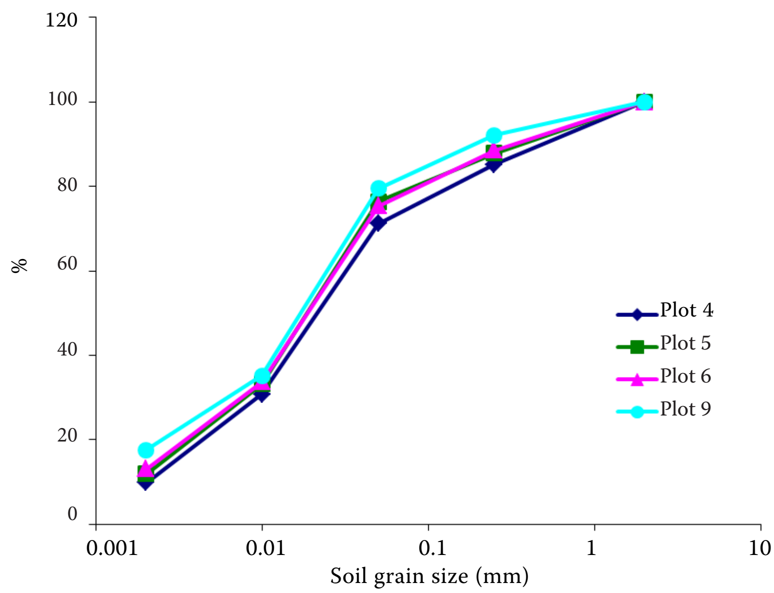

Figure 2. Granulometric curves of experimental plots in Třebsín (2006)

Figure 3. Left: rainfall simulator (RISWC Prague); right: discharge/sediment load measuring device (2009)

This data was applied for the KINFIL model. The infiltration part of the KINFIL (INFIL) computes with parameters K_S, S_f and rainfall data the ponding time, pre- and post-ponding infiltration and effective rainfall. The latter is then automatically integrated in the transformation part of the KINFIL (KIN), which computes the kinematic wave using plot geometry data, hydraulic parameters (α, m) and Manning n for the outflow hydrograph. At the same time, 3D-hydraulic variables, depths and velocity of flow, shear velocity and shear stress are also computed. These last four hydraulic variables are computed at each 2.0 m distance downstream in the length of 10.0 m (five values). On the entire 10.0 m distance, both rill development and flows do not usually appear. Table 2 shows the basic information on particular rainfall-runoff simulation events. Table 3 documents the maximum values of the hydraulic variables at the downstream end of all four experimental plots, No. 4, 5, 6 and 9.

These are the values of depths $\max(y_j^i)$, velocities $\max(v_j^i)$, shear velocities $\max(v_{*j}^i)$ and shear stress

Table 2. Basic information on rainfall-runoff simulation events

Plot No.	Date	Dry (D) or wet (W)	Soil moisture content (%)	Rainfall (mm)	Runoff measured (mm)	Runoff computed (mm)	Coefficient of determination (–)	Coefficient of variation (–)
4	13/07/09	D	23.5	12.4	2.9	2.8	0.67	0.39
		W	38.3	13.8	3.7	3.5	0.77	0.28
4	12/08/09	D	23.2	8.6	2.1	2.0	0.51	0.63
		W	32.6	9.5	3.1	2.8	0.57	0.41
5	30/07/08	D	12.4	16.1	2.6	2.5	0.85	0.31
		W	38.7	15.5	4.1	3.9	0.82	0.25
5	13/07/09	D	20.3	13.4	1.5	1.2	0.75	0.38
		W	38.8	12.7	3.4	3.2	0.48	0.50
6	30/07/08	D	9.7	15.1	6.1	6.4	0.82	0.33
		W	34.1	15.8	9.9	9.3	0.72	0.34
6	13/07/09	D	20.7	12.7	4.2	4.4	0.87	0.26
		W	41.4	12.2	6.9	6.8	0.88	0.22
9	26/08/09	D	14.0	11.7	5.3	5.2	0.91	0.24
		W	29.0	11.5	6.7	6.5	0.50	0.43

Table 3. Maximum values of hydraulic variables at downstream outlets of plots, Třebsín 2008–2009

Plot No.	Date	Dry (D) or wet (W)	Hydraulic depth $\max(y_j^i)$ (m)	Hydraulic velocity $\max(v_j^i)$ (m/s)	Shear velocity $\max(v_{*j}^i)$ (m/s)	Shear stress $\max(\tau_j^i)$ (Pa)
4	13/07/09	D	0.0015	0.0487	0.0460	2.117
		W	0.0017	0.0523	0.0485	2.354
4	12/08/09	D	0.0013	0.0435	0.0423	1.792
		W	0.0015	0.0474	0.0451	2.037
5	30/07/08	D	0.0016	0.0485	0.0454	2.060
		W	0.0018	0.0521	0.0479	2.294
5	13/07/09	D	0.0012	0.0392	0.0387	1.500
		W	0.0015	0.0469	0.0443	1.963
6	30/07/08	D	0.0019	0.0538	0.0489	2.387
		W	0.0022	0.0586	0.0521	2.713
6	13/07/09	D	0.0016	0.0480	0.0449	2.016
		W	0.0018	0.0517	0.0475	2.254
9	26/08/09	D	0.0017	0.0464	0.0429	1.843
		W	0.0019	0.0496	0.0451	2.038

$\max(\tau_j^i)$. These values consistently illustrate the runoff process. Many experimental tests were carried out with the physical rainfall simulator and subsequently mathematically simulated by the adopted KINFIL model. The results from selected plots (No. 4, 5, 6 and 9) are shown in Figures 4 to 7. The accuracy of fits during measured and computed events was statistically analysed and the corresponding results, in

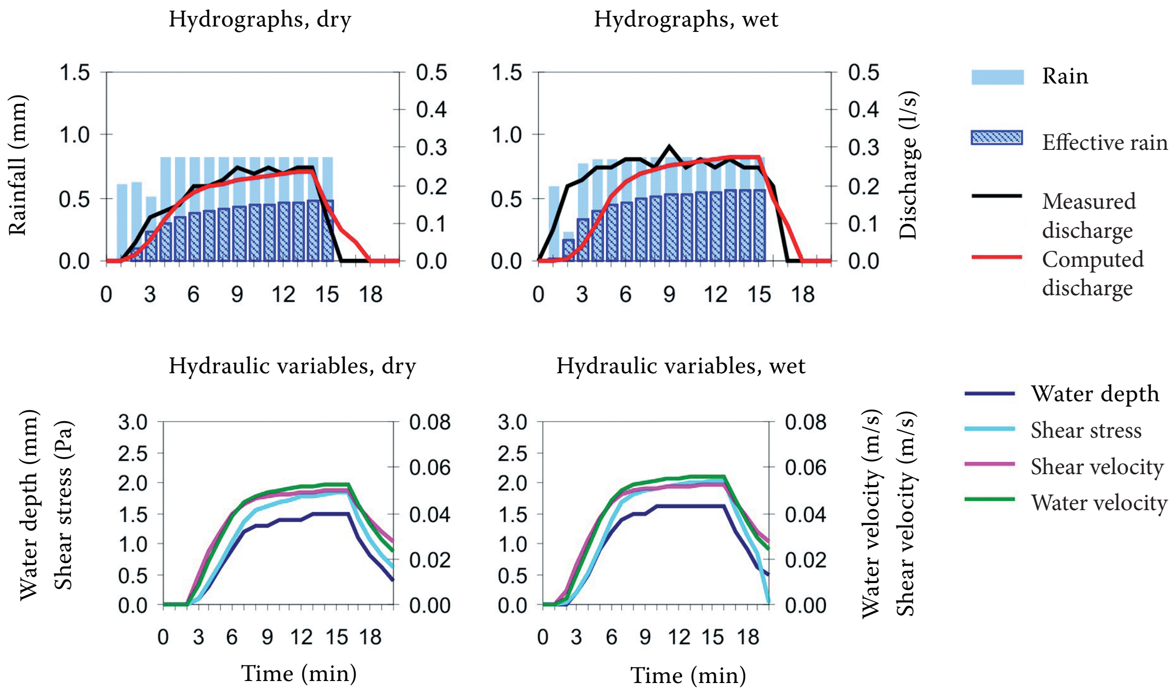

Figure 4. Graphs of measured and simulated rainfall-runoff values and computed hydraulic variables for dry and wet initial conditions, Třebsín, plot 9, 26/8/2009

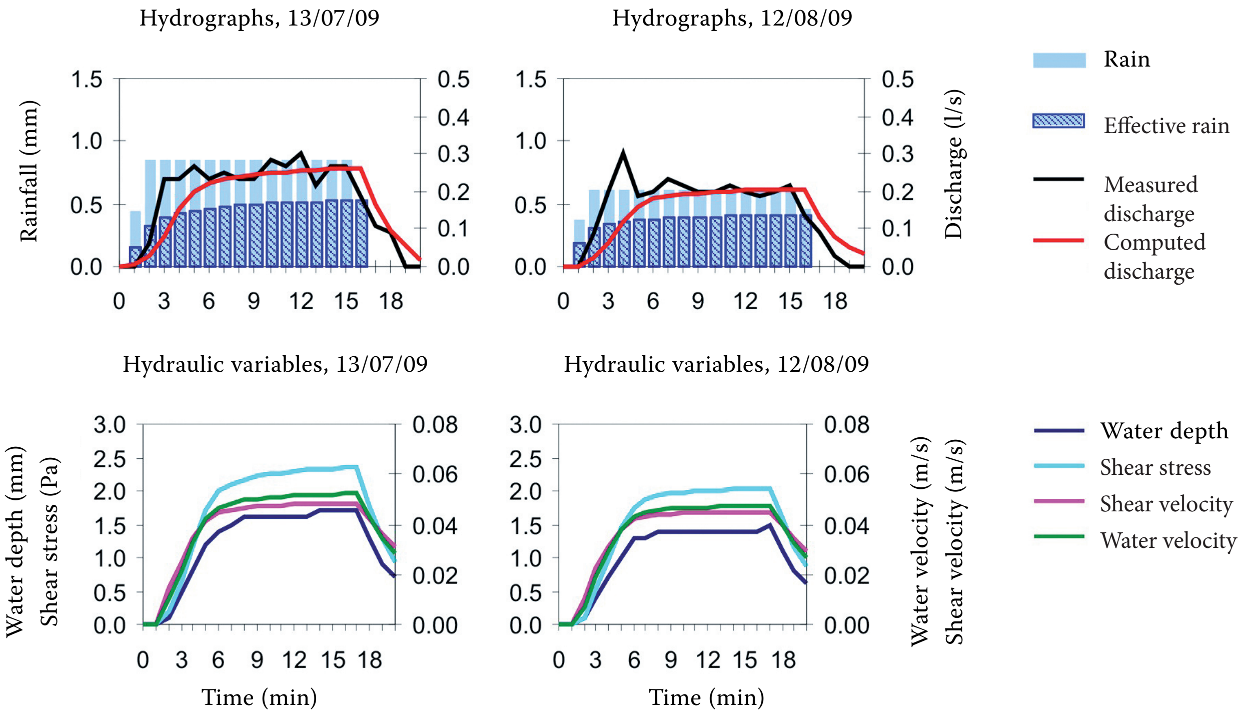

Figure 5. Graphs of measured and simulated rainfall-runoff values and computed hydraulic variables for two events with wet initial conditions, Třebsín, plot 4, 13/7/2009 and 12/8/2009

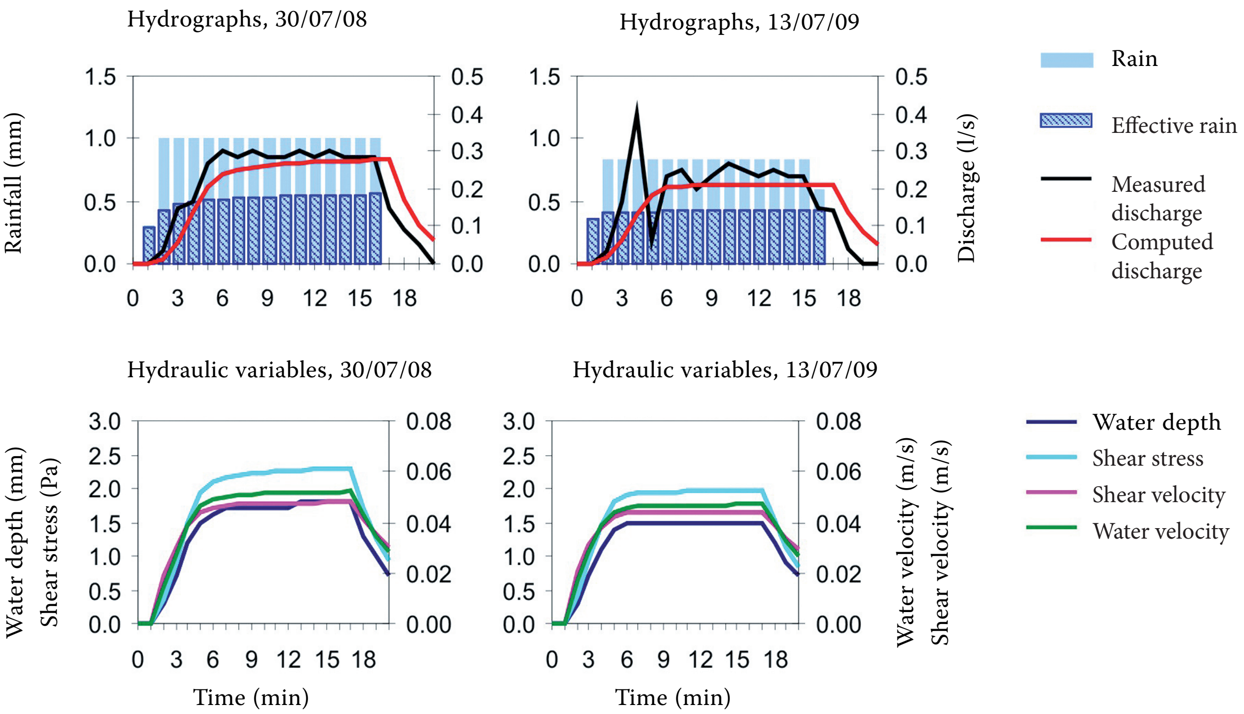

Figure 6. Graphs of measured and simulated rainfall-runoff values and computed hydraulic variables for two events with wet initial conditions, Třebsín, plot 5, 30/7/2008 and 13/7/2009

the form of coefficients of determination (similarly like in Nash & Sutcliffe 1970) and coefficient of variation, are shown for all pairs in Table 2.

The values of the progressing hydraulic variables during runoff processes (depths, velocities and shear stresses) measured on all plots are graphi-

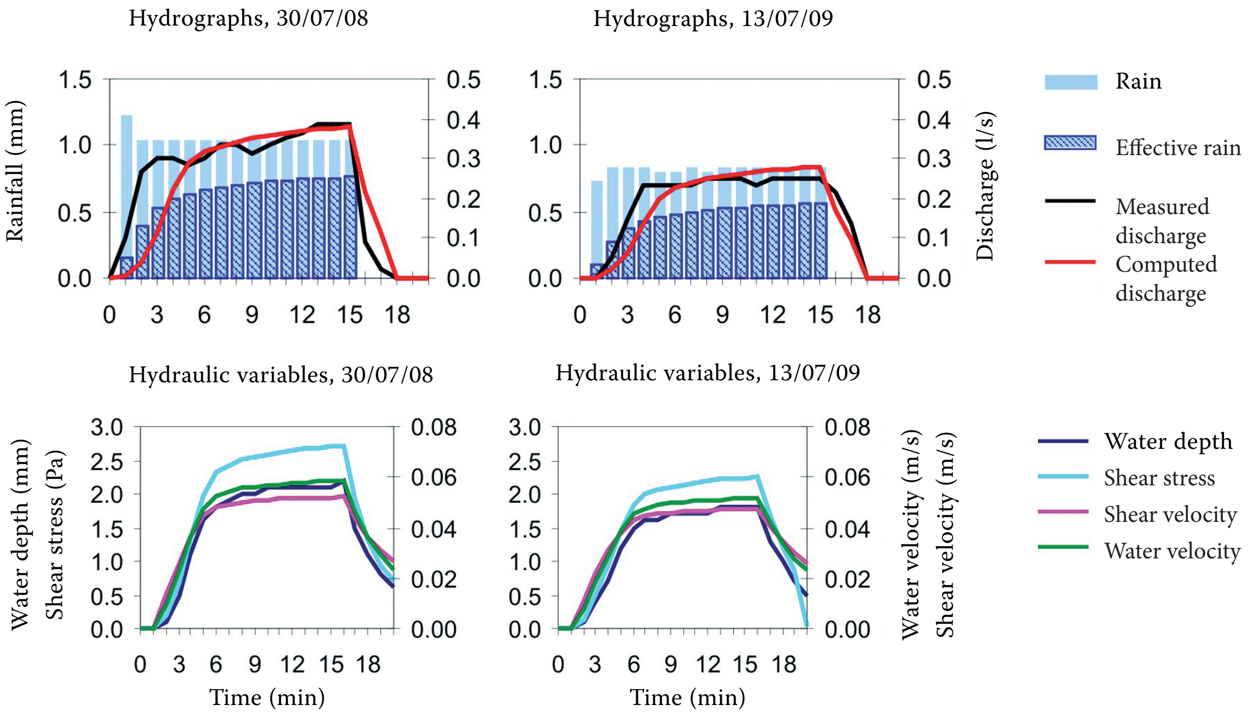

Figure 7. Graphs of measured and simulated rainfall-runoff values and computed hydraulic variables for two events with wet initial conditions, Třebsín, plot 6, 30/7/2008 and 13/7/2009; plot 6 (wet initial conditions)

cally represented in Figures 8 to 11, in a streamflow distance step of 2 meters (L = 0 to 10 m) for the initial wet conditions.

The shear stress values, after comparing their critical values according to the granulometric curves, can be used to identify where and when a soil loss event starts and stops (Kovář & Vaššová 2010). Such comparative assessments and soil loss computations will also be carried out in the future and their outcomes will be published in one of the next SWR papers.

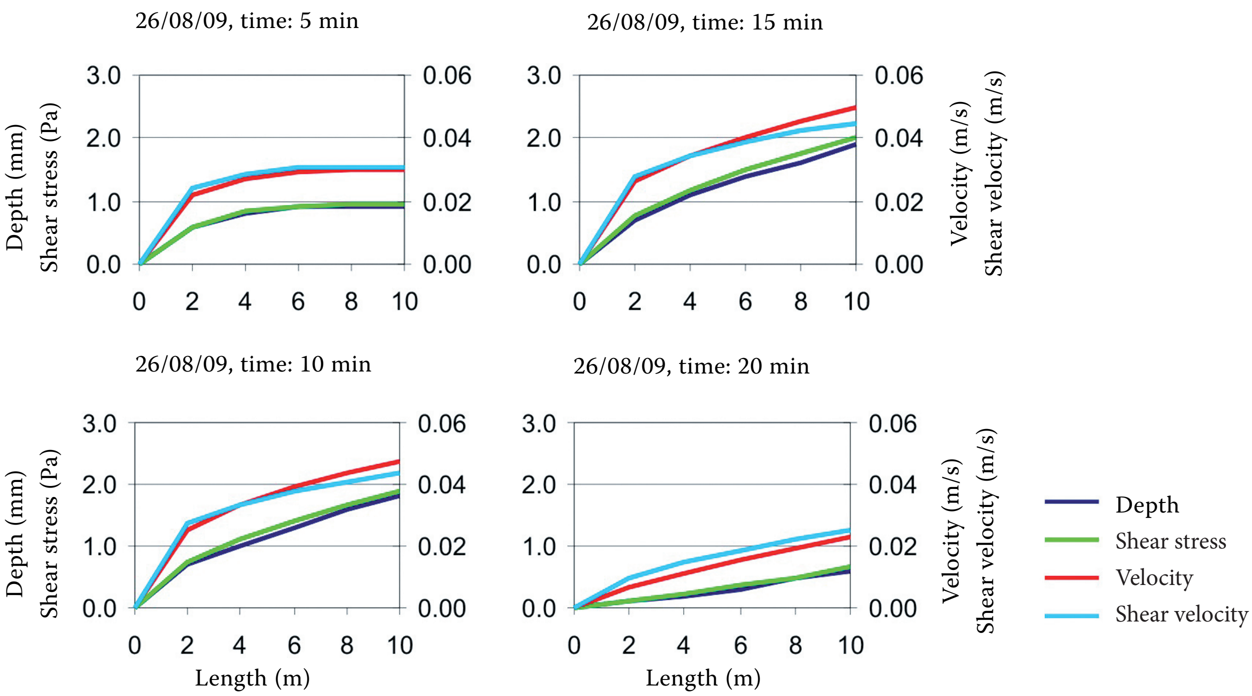

Figure 8. Graphs of progressing hydraulic variables (depth, velocity, shear stress) on Třebsín plot 9 (wet initial conditions)

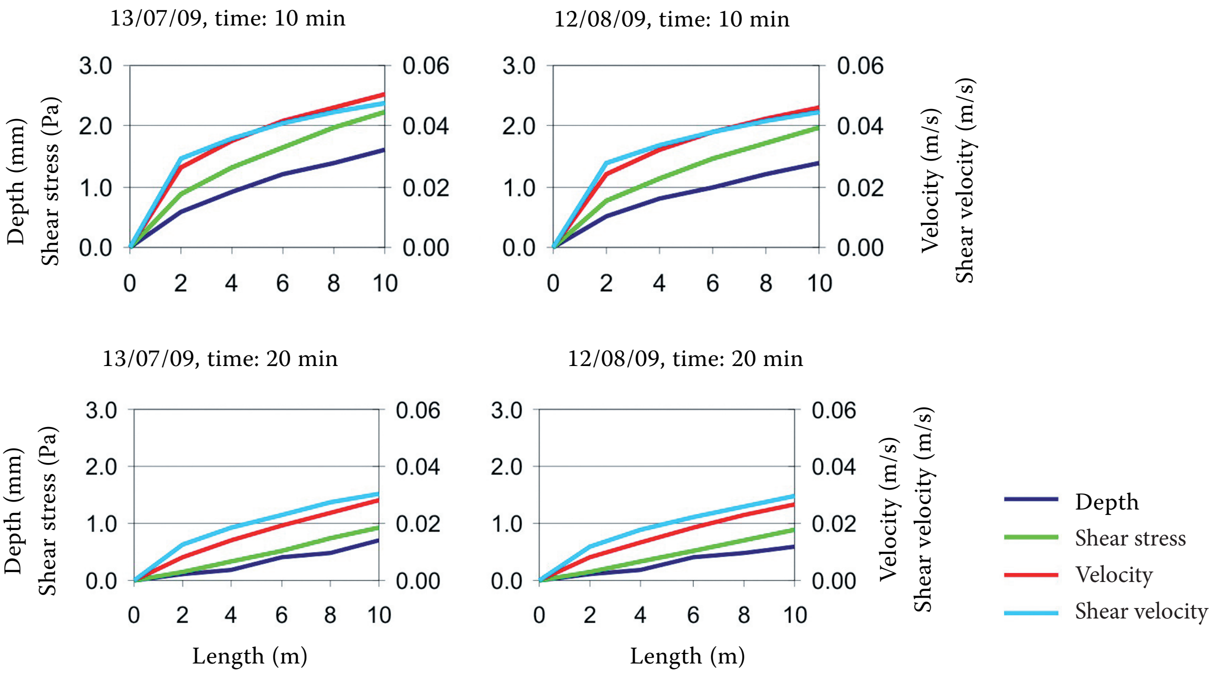

Figure 9. Graphs of progressing hydraulic variables (depth, velocity, shear stress) on Třebsín plot 4 (wet initial conditions)

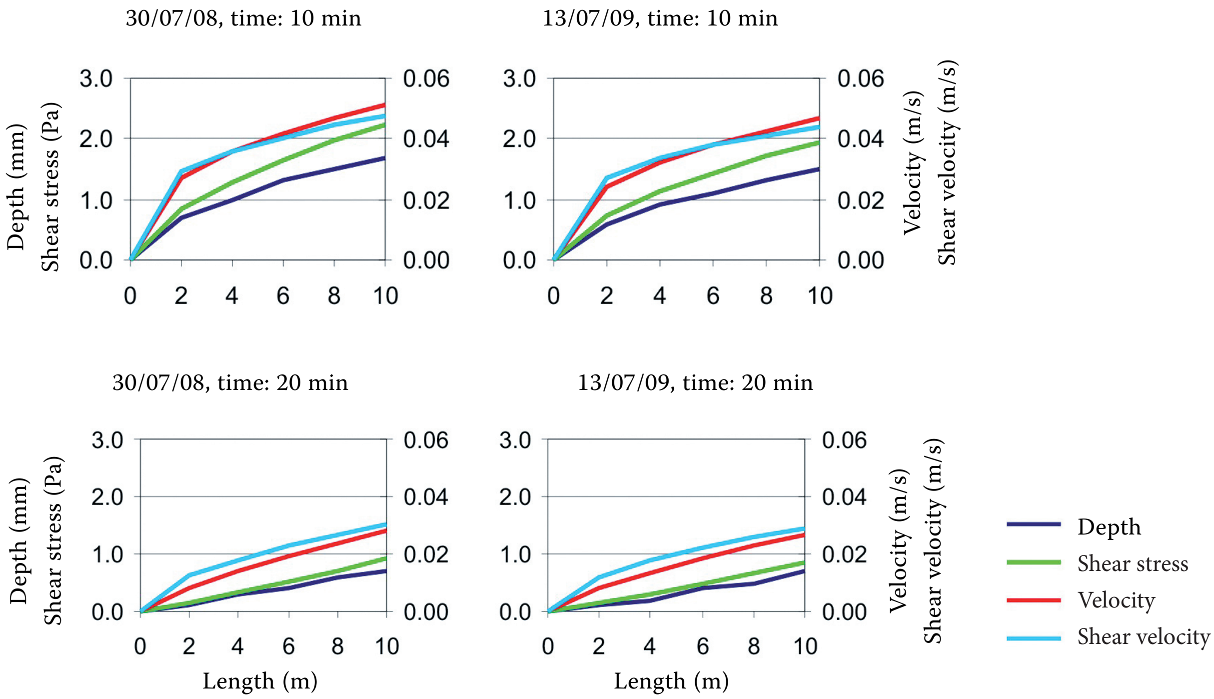

Figure 10. Graphs of progressing hydraulic variables (depth, velocity, shear stress) on Třebsín plot 5 (wet initial conditions)

CONCLUSIONS

The KINFIL model, formerly conceived only for simulation of rainfall-runoff events, has been adapted through detailed hydraulic subroutines for 3D computation of water depth, velocity and shear stress values. This new model adaptation was successful and it also provides a good tool for "erosion hydraulics"

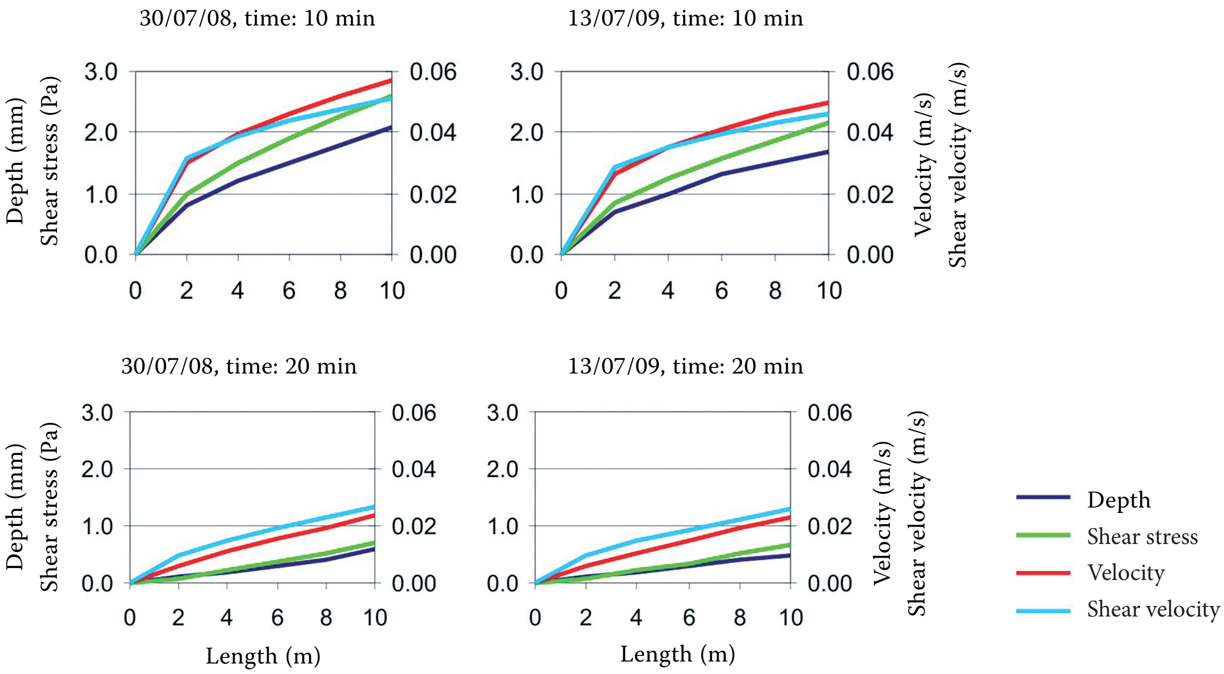

Figure 11. Graphs of progressing hydraulic variables (depth, velocity, shear stress) on Třebsín

simulation. A reliable and functional physical rainfall simulator, including appropriate measuring devices, has been shown to be useful equipment for studying runoff processes in detail on four experimental plots, with areas not exceeding 30 m^2. The necessary prerequisite was to measure and set up the model parameters, in particular the coefficient of saturated conductivity K_S and sorptivity $S(\theta_0)$, Manning n, geometry, geomorphology and granulometry.

Experimental plots 4, 5, 6 and 9 at Třebsín have the same area, similar slope but different soil hydraulic properties. The model evidently shows a broad spectrum of applicability. In conclusion it may be stated that the joint application of the KINFIL model and the RISWC rainfall simulator offers the following advantages:

– It provides results from a physically-based scheme.
– It provides possibilities to calibrate model parameters also for natural rainfall-runoff event simulation.
– It simulates surface runoff discharges, depths, velocities and shear stress accurately enough to be compared with measured discharges, using the rain simulation equipment.
– It also simulates the change in land use and farmland management.

For subsequent computation of soil loss we can start with granulometry of soils to distinguish interrill and rill erosion and a revetment role of the canopy.

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