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Use of Terraces to Reduce Overland Flow and Soil Erosion, Comparison of the HEC-HMS Model and the KINFIL Model Application

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Abstract

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In our study, a system of seven natural terraces interspersed with six field belts situated at the Knínice locality (the Ore Mts., North-West Bohemia) was selected as the experimental catchment area. Overland flow was computed using two different methods: the kinematic wave method and the SCS dimensionless Unit hydrograph (UH). For the kinematic wave method calculations the KINFIL software was used; for SCS dimensionless hydrograph the HEC-HMS software was applied. The results compare hydrographs with *N*-year recurrence of rainfall-runoff time, where *N* = 10, 20, 50, and 100 years. The comparison provides hydraulic results with terraces and without terraces computed using both mentioned software products. Although two different methods of overland flow computation were performed, the input data obtained from geodetic and hydrological measurements were identical. Results of the comparison are presented and discussed.

Keywords: extreme rainfall; infiltration; kinematic wave; soil protection; Unit hydrograph

In many mountainous parts of the Czech Republic there are locations with agricultural hedgerows, agricultural terraces, walls, because these measurements allow fields to be founded even on steep slopes. Usually terrace consists of flat part, which could be used as field and the slope part. However, considerable part of the hedgerows was, in the long term, excluded from cultivation.

Typical terraces have a high diversity of vegetation. The described location is characterised by grass areas in combination with stony hedgerows between them. The borderlines are underlined by trees and shrubs. Terraces serve as an effective barrier for surface runoff, thanks to the stone design with different diameters showing high water permeability, thereby reducing the hydraulic speed.

Currently, there are ongoing discussions about the character and applicability of the model of kinematic waves. This paper deals mainly with the question whether the kinematic wave model can alternatively replace other proven methods of runoff generation, such as a dimensionless Unit hydrograph, for calculating the overland flow in mountainous regions with a historical system of terraces.

MATERIAL AND METHODS

Experimental area. The experimental catchment area at Knínice constituted by seven terraces interspersed with six field belts is much larger (8.80 ha) than the Libouchec Experimental Runoff Area (ERA) sizing 2.21 ha. The experimental area is described in Figure 1 showing a map of standard geographical situation with marginal views (on the left), where the terraces are covered by trees and shrubs which, from above, look like hedgerows. On the right side there

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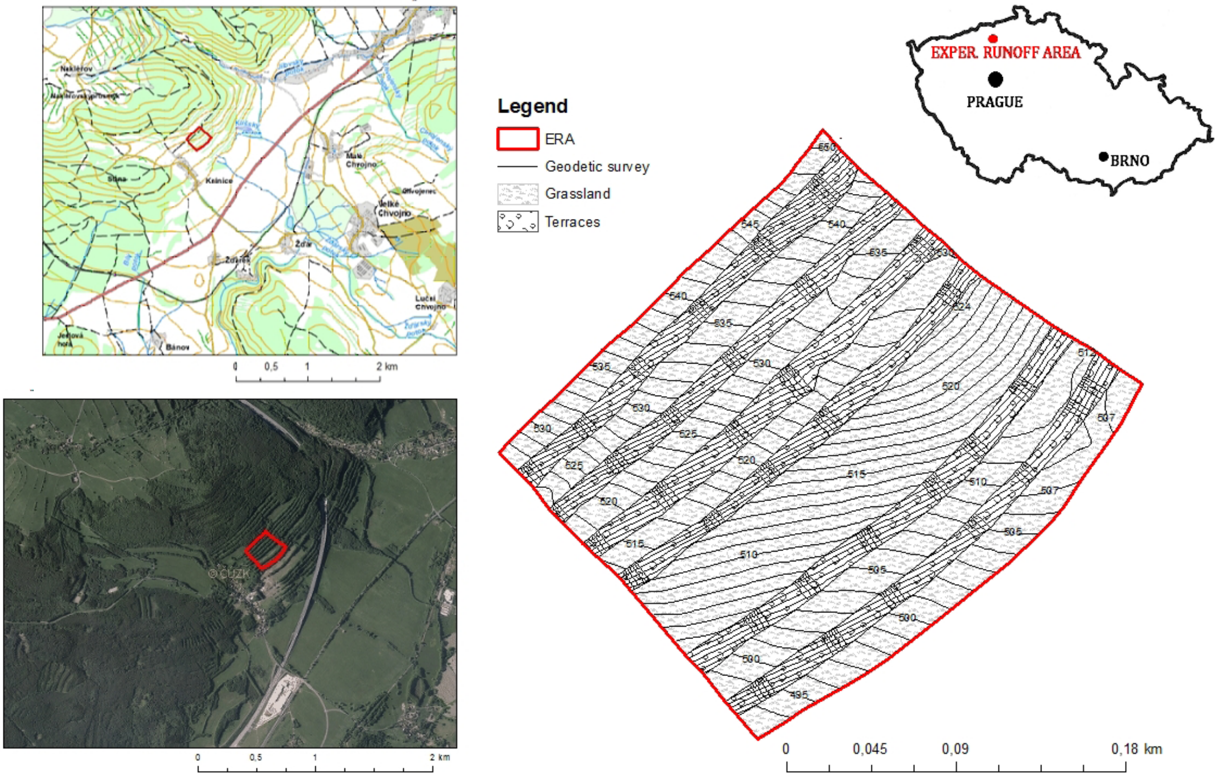

Figure 1. Location of the Knínice village and the Experimental Runoff Area (ERA) and a scheme of terraces protecting field belts against soil erosion

is the village of Knínice on the map of the Czech geodetic survey. Figure 2 provides the schematic placement of typical stone terraces that serve as measures in support of infiltration and for mitigating overland flow discharges, and gives a detailed view of two neighbouring terraces. Terraces serve as an effective barrier for the surface runoff, which thanks to the stone design and different diameters are highly water permeable, thereby reducing the hydraulic velocity. Typical terraces have a high diversity of two-level vegetation (shrubs and trees).

The Libouchec ERA in the Knínice region in the Ore Mts. is well protected, and its terraces still provide good soil erosion control in this area.

The average elevation of the catchment is 517.0 m a.s.l. The catchment ends with an open contour line profile which is about 400 m wide. Slope variation downstream within the catchment on arable land (this part of land is permanently overgrown with grass) is J_{PG} = 0.04 to 0.12, and on the terraces the slope variation is J_{TER} = 0.35 to 0.61. The complete longitudinal profile of the whole system of field belts alternating with protective terraces is depicted in Table 1.

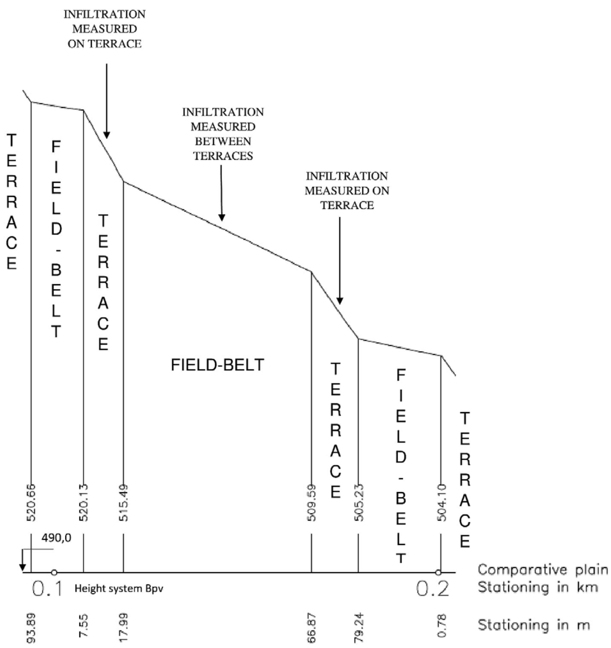

Figure 2. Section of the scheme of terraces protecting field belts against soil erosion; longitudinal profile of the terraces and the field belt system (1:1000/250); infiltration parameters are measured on both terraces and on field belts

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Table 1. Parameters of individual terraces (1–7) and field belts constituting the Knínice catchment area

		1	2	3	4	5	6	7
Terraces	length (m)	11.3	10.7	13.9	10.4	12.4	10.7	
	slope (–)	0.36	0.43	0.37	0.45	0.35	0.34	
Fields	length (m)	6.0	20.6	17.9	13.7	48.5	21.5	19.4
	slope (–)	0.04	0.07	0.06	0.04	0.12	0.05	0.04

Climate is mild-warm and humid. Long-term annual precipitation average is 650–750 mm. The average annual temperature is 6.5–7.0°C. Geological structure of the ERA is mainly of pleistocene orthogenesis and quaternary stony and stony-loam sediments prevail. The dominant soil types are mesotrophic to entropic Cambisols, which can be characterized as water-permeable silt loam and sandy loam.

Field measurements. For the measurement of geodetic data we used a Trimble total station with GNSS options. Data were processed by a Geodimeter System 640 using the polar method. Mapping was carried out within the KOKES system, version 1250. The final mapping was amended in the ATLAS system.

For the infiltration measurement, the procedure of the Richards equation (Kutílek & Nielsen 1994) and the Philip solution for non-steady flow infiltration (Philip 1957) are crucial. The shortened Philip equation for the infiltration intensity into the soil (v_f), calculated with the saturated hydraulic conductivity K_s (m/s) and sorptivity S (m/s$^{1/2}$), is as follows (Eq. (1)):

$$v_f(t) = \frac{1}{2} S \ .t^{-1/2} + K_s \qquad (1)$$

Table 2. Hydraulic values measurements on fields and terraces

	Average	No. of measurements			
		1	2	3	4
Fields					
S (mm/h$^{0.5}$)	19.8	17.0	22.4	19.4	20.3
K_s (mm/h)	7.0	5.0	9.0	6.0	8.0
S_f (mm)	28.0	28.9	27.9	31.4	25.8
Terraces					
S (mm/h$^{0.5}$)	34.6	34.2	33.5	32.6	38.0
K_s (mm/h)	30.0	29.0	32.0	26.0	33.0
S_f (mm)	20.0	20.2	17.5	20.4	21.9

S – sorptivity; K_s – hydraulic conductivity; S_f – storage suction factor

Both parameters K_s and S were computed using the method of non-linear regression (Kovář *et al.* 2011; Štibinger 2011). Table 2 provides the results of hydraulic conductivity K_s and sorptivity S measurements, each carried out four times in four terraces and four fields. Table 2 shows also the average values of K_s and S, and the storage suction factor S_f (mm) calculated according to Eq. (2):

$$S_f = \frac{S^2}{2K_s} \qquad (2)$$

The final values of calculated parameters are given in Table 2. The average storage suction factor S_f is 28.0 mm for the fields and 20.0.mm for the terraces. The K_s value for the terraces is about 4.3 times higher than for the field belts. The S value for the terraces is about 1.7 times higher than for the field belts.

Extreme rainfall assessment. The Knínice catchment uses the rainfall data from the Ústí nad Labem – Kočkov station situated 9 km apart. This rain gauge provides daily rainfall data with a return period N = 2, 5, 10, 50, and 100 years (Table 3). Because the Knínice catchment represents a small catchment area, the periods of critical rainfall duration were selected just for time t_d = 10, 20, 30, and 60 min and a return period of N = 10, 20, 50, and 100 years. The DES_RAIN software was used for computing the reduction in daily rainfall depths $P_{t,N}$ (Kovář & Vaššová 2011). This procedure is based on regional

Table 3. The maximum of the extreme rainfall depths $P_{t.N}$ of short duration in the station Ústí n. L. (in mm)

N (years)	$P_{t.N}$ (min)	t (min)			
		10	20	30	60
2	30.6	10.1	12.4	14.0	16.3
5	41.8	14.7	18.2	20.7	24.8
10	49.0	17.6	22.4	15.7	30.7
20	56.5	21.5	27.4	31.6	38.0
50	65.7	26.3	33.8	39.2	47.5
100	79.2	32.5	42.1	49.1	59.4

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parameters *a* and *c,* derived following the methodology of Hrádek and Kovář 1994. The results of data simulation are presented in Table 3. $P_{t,N}$ is the maximum extreme rainfall depth (mm) less than 1 day duration and return period *N* years.

The HEC-HMS (Hydrologic Modeling System) software is a new generation product of the Hydrologic Engineering Center within the U.S. Army Corps of Engineers (USACE 2013). It is designed to simulate the precipitation-runoff mechanisms of dendritic drainage basins and it is a replacement for HEC-1, which has long been considered a standard for hydrologic simulation (Zhang *et al*. 2013). The new HEC-HMS is capable of almost similar simulation, but it is more advanced in numerical analysis, which is a significant advantage of the modern faster desktop computers. It also has a number of features that were not included in HEC-1, such as continuous simulation and grid cell surface hydrology. The graphical user interface makes the software more user-friendly.

The runoff from any size basins is calculated using four processes of flow from the catchment area, taking into account the division or merger of the channel. The runoff hydrographs are computed using data of rainfall, excess loss (infiltration), Unit hydrographs or kinematic wave, and the baseflow. Any mass or energy flow in the cycle can then be described with a mathematical model. Several model choices are usable for describing each flow in most cases. Each mathematical model included in the software is relevant for different environments and under different conditions.

The loss can be computed using the SCS Curve Number, Green and Ampt, Deficit and Constant, Exponential, Initial and Constant, Smith Parlange, Soil Moisture Accounting methods. The Unit hydrograph can be made based on Clark Unit Hydrograph, Kinematic Wave, ModClark, SCS Unit Hydrograph, and user-specified S-Graph and Unit Hydrograph methods. The baseflow decreases logarithmically with the set value of hydrograph recession curve or is calculated on the basis of soil moisture. Averaged catchment rainfall can be calculated by precipitation at certain points by using standard weighing method or probability criterion of maximum rainfall, or on the basis of gridded radar precipitation data. The methods of hydrograph calculation also include Muskingum, Muskingum-Cunge, Kinematic Wave, and Modified Puls methods. The Modified Puls method is used primarily for reservoirs. The model can be made both on the confined parts of a basin or on the spatially distributed gridded basins. Internal calculations are performed in the metric system, input and output data can be both in metric and U.S. Customary unit systems.

The HEC-HMS software Unit hydrograph method was successfully used for modelling runoff in Romania as was discussed in the study of Györi and Haidu (2011). The HEC-HMS Rainfall-Runoff model was computed for flow simulation on three basic models: the climatic model, the catchment model, and the control indices. The loss method calculates an effective rainfall with the input hyetograph, the results are transformed in a function that converts the excess precipitation into runoff at the subwatersheds outlets.

Soil Conservation Service dimensionless hydrograph. The dimensionless unit hydrograph has been developed by the Soil Conservation Service (SCS) from the Unit hydrographs for a high number of basins of different sizes and for many different environments. The SCS dimensionless hydrograph is a synthetic Unit hydrograph in which the discharge is described as a ratio of discharge (q) to peak discharge (q_p) and the time by the ratio of time (t) to time of peak of the Unit hydrograph (t_p). The Unit hydrograph can be determined from the synthetic dimensionless hydrograph for the given basin given the peak discharge and the lag time for the duration of the excess rainfall (Ramírez 2000).

The dimensionless Unit hydrograph can be expressed in terms of an equivalent triangular hydrograph as suggested by the SCS. Using this simplified triangular Unit hydrograph the values of q_p and t_p can then be estimated. The height of the simplified Unit hydrograph in this case is equal to q_p and time base t_b is equal to 2.67 t_p (SCS 1972). In SCS, time is usually expressed in hours (h), and the discharge in $m^3/s/cm$ (or cfs/in). The SCS recommends recession duration of 1.67 t_p after the analysis of a high number of Unit hydrographs. It can be shown that:

$$q_p = C \times A/t_p \qquad (3)$$

because the volume of direct runoff must equal 1 cm, where $C = 2.08$ (483.4 in the British system) and A is the drainage area in square kilometres (square miles).

The basin lag is

$$t_l = 0.6t_c \qquad (4)$$

from a study of many large and small rural watersheds, where t_c is the time of concentration of the watershed.

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The time to peak (t_p) is then equal to $t_r/2 + t_l$ (SCS 1972).

The data required by the SCS hydrograph method include mostly hydrological data as channel depth, length, and rainfall data. In order to receive the SCS dimensionless Unit hydrograph it is necessary to estimate the lag time for a given basin. The timing parameter considerably affects the values of the Unit hydrograph, but it is somewhat difficult to estimate and rather subjective (Chow 1959).

The 3D KINFIL is a physically based model, it covers two parts of the hydrological process. The first part describes the infiltration of rainfall to build rainfall excess, and the second part expresses the overland flow presentation from rainfall excess and its conversion into a final runoff hydrograph. The model also delivers marginal results, e.g. hydraulic depths and velocities. Since 2002 it has been applied for simulating rainfall-runoff processes in gauged and ungauged catchments (Kovář *et al.* 2002). Later the model has been improved to simulate hydraulic processes needed for shear stress values to compute erosion when soil calibration is at disposal (Kovář et al. 2012).

The overland flow part of the KINFIL model uses the kinematic equation and can be described by Eq. (5) (Kibler & Woolhiser 1970; Maidment 1992; Beven 2006):

$$\frac{\partial y}{\partial t}+\alpha\times m\times y^{m-1}\times\frac{\partial y}{\partial x}=r_e(t) \quad (5)$$

where:

$r_e(t)$ – rainfall excess intensity (m/s)

y, t, x – ordinates of the depth of water, time, and position (m, s, m)

α, m – hydraulic parameters

The infiltration part of the KINFIL model is based on the Green and Ampt theory of infiltration, using the principle of ponding time and the storage suction factor S_f (Morel-Seytoux & Verdin 1981; Morel-Seytoux 1982):

$$v_f=(\theta_s-\theta_t)\frac{d_{zf}}{dt}=K_s\left[\frac{z_f+H_f}{z}\right] \quad (6)$$

The right side of Eq. (6) expresses the Green-Ampt theory (Rawls & Brakensiek 1983), the left side describes the Darcy concept for the process of infiltration $v_f(t)$. K_s is the hydraulic conductivity (m/s), H_f is the capillary suction on the infiltration front (m), is the difference between the saturated soil moisture content and actual content (–), z_f is the depth of the infiltration front (m), and z is the vertical ordinate (m) (Kovář *et al.* 2016).

RESULTS AND DISCUSSION

The question if the kinematic wave method can replace the Unit hydrograph methods still remains open due to the huge fundamental differences of these two methods. Researchers and practitioners have reported both on the success and failures of the kinematic wave model (e.g. Hromadka & DeVries 1988; Syed *et al.* 2012). The kinematic wave method for overland flow is a deterministic and physically based, distributed-parameter, hydraulic-data-intensive method (requiring geometric and frictional parameters), which is primarily applicable to small catchments, for which the perfectionism of the mathematical modelling can be applied in practice, when high detailization can actually reveal the processes occurring in the experimental area. From a number of the kinematic wave models we have selected the KINFIL model.

The dimensionless Unit hydrograph performs the typical shape of Unit hydrographs charted in dimensionless terms. The discharge ordinates of this hydrograph are divided by the maximum discharge, and the time ordinates are divided by the time from 10% of peak flow to peak flow to obtain the dimensionless Unit hydrograph. The 10% time is subjective and was used to reduce the long build-up time when the discharge is small (Bender & Roberson 1961).

The Unit hydrographs were originally designed for large catchments (Sherman 1932), but later the method was found to be primarily applicable to midsize catchments. Nevertheless, with catchment subdivision, the applicability of the Unit hydrograph can be extended also to large catchments (Wałęga 2013). Due to the fact that the overland flow kinematic wave method is primarily used for small catchments, and the Unit hydrograph is primarily applicable to midsize catchments, it seems these two methods should overlap to a small extent (Ponce *et al.* 1978).

The simulations by the both models were computed for all events in the return periods of their duration t_d = 10, 20, 30, and 60 min for the basic scenario without terraces and with terraces. The sub-catchment areas were fragmented to reflect the fact that each field belt has one biotechnical protective measure in the form of a terrace. The geometric dimensions of the terraces correspond to the real situation. The final results are shown in Figure 3.

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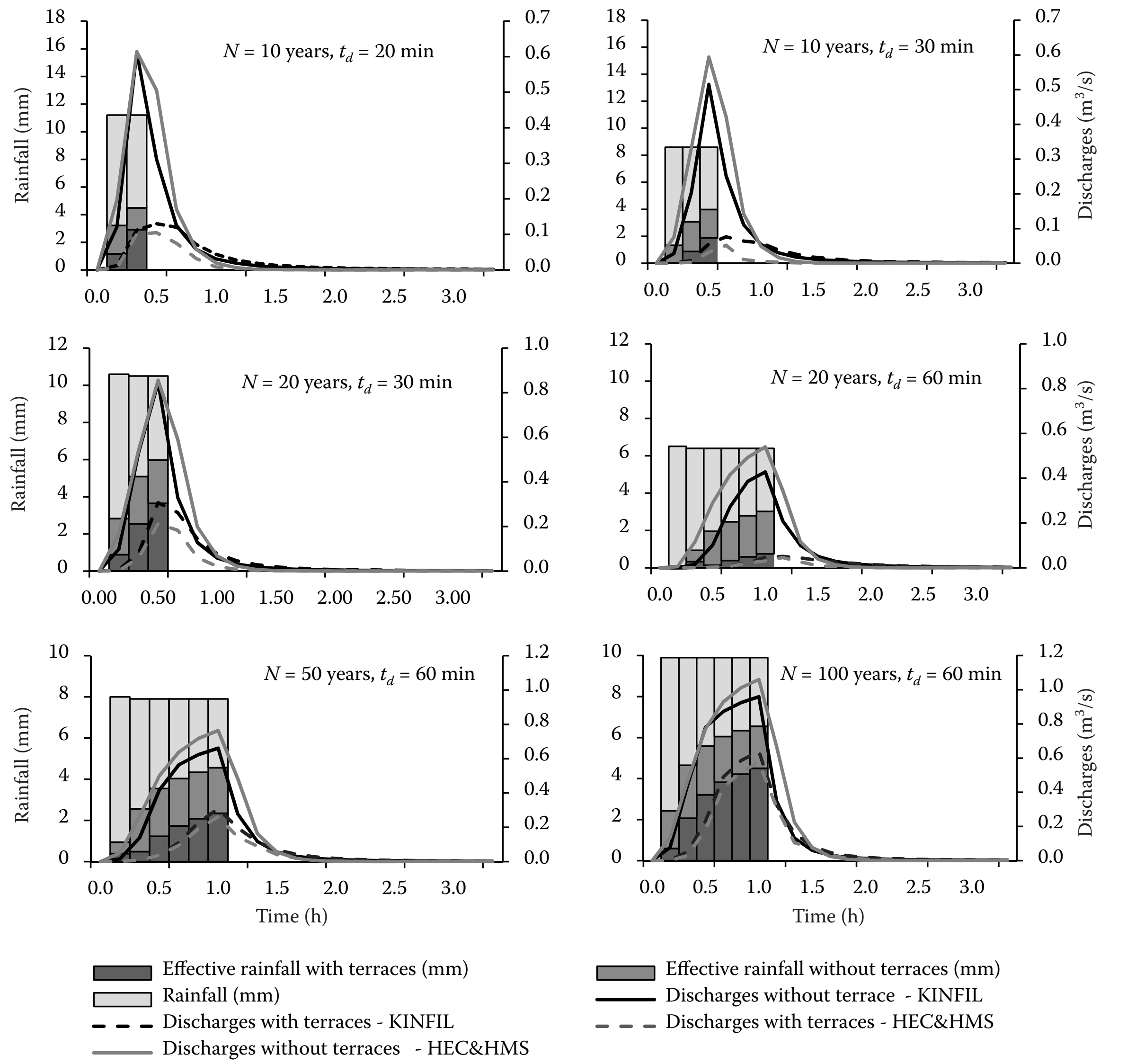

Figure 3. Comparison of hydrographs for the Knínice catchment with and without the terraces for extreme rainfalls of various return periods N and duration periods t_d

CONCLUSION

The dispute which method is better or more accurate has no simple answer. Both methods require different input data, they are of different nature and are not readily comparable. The HEC-HMS software is undoubtedly easier to use even by an unexperienced user, the interface is simplified and can be used intuitively, which is a big advantage of the HEC software. The KINFIL interface is not so user friendly, the kinematic wave method itself requires more data, but it provides more accurate results, as presented in Figure 3. The hydrographs calculated by the kinematic wave method are sharper in shape, which is more natural under given conditions for small catchments. The results yielded by the SCS Unit hydrograph also attain higher values for natural cases, e.g. without terraces, however, the difference in discharges is not very significant, especially for N = 10 and 20 years it is less than 0.1 m^3/s.

A significant benefit of the kinematic wave method is that it can describe roughness coefficient and rainfall variations. The model provides also marginal results, e.g. hydraulic depths and velocities. The kinematic wave method increases in accuracy as the catchment size decreases; and the Unit hydrograph methods increase in applicability with the increasing catchment scale.

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So, in cases where the scale can be logically negotiated, the kinematic wave model should provide better specification in a future simulation of flood flows.

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