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Using WaTEM/SEDEM and HEC-HMS models for the simulation of episodic hydrological and erosion events in a small agricultural catchment

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Abstract: A careful analysis of rainfall-runoff events and patterns of sediment and pollution load to water bodies is crucial for the proper management of agricultural land. This study simultaneously employed the WaTEM/SEDEM long-term erosion model and the HEC-HMS episodic hydrological and erosion model to describe the runoff and sediment load evoked by extreme rainfall events in a small agricultural catchment in Czechia, using the long-term monitoring discharge and water quality episodic data. WaTEM/SEDEM helped to delineate the runoff and sediment critical source areas, subsequently incorporated into HEC-HMS. The acquired results showed that the spatial distribution of land use is a fundamental factor in the protection of watercourses from diffuse pollution sources and the transport and delivery of sediment profoundly depends on the status of crop cover on arable land near a watercourse. Integrating both models, it was shown that the tabulated Curve Number (CN) values as well as the average C-factor values had to be lowered for the majority of the modelled events to match the monitored data. A noticeable role of catchment runoff response most probably played tile drainage, which appeared to profoundly modify the episodic runoff pattern. This study showed a promising approach for the simulation of different rainfall-runoff responses of small agricultural catchments and could be applied for the delineation of areas where soil conservation measures or protective management is of high priority. The results further revealed the obvious need to revise the CN values for tile-drained catchments.

Keywords: CN method; modelling; runoff; sediment transport; soil erosion

Soil erosion is a natural process which has, however, been markedly accelerated in the present epoch by the activities of man, in particular by intensive farming. In the context of climate change, a more frequent extreme rainfall pattern is anticipated in Europe (Walling 2009). In the Czech Republic (CR), more than 50% of farmland is threatened by soil erosion (Dostál *et al*. 2006). This is, besides the intense rainfall and intrinsic geomorphological characteristics of farmland in CR, especially associated with the increased soil erodibility due to the degradation processes and farming of large blocks of arable land (Janků *et al*. 2016; Žížala *et al*. 2017).

The pollution of surface water bodies is directly linked with the quick runoff and erosive processes on the agricultural land. The severity of the impact of

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runoff and soil erosion on the quality of the surface water in the CR was pointed out by several studies (e.g., Van Rompaey *et al*. 2007; Svoboda *et al*. 2016). Despite the long-term efforts of researchers on the practical implementation of knowledge dealing with soil and water conservation measures (e.g., Konečná *et al*. 2017; Karásek *et al*. 2018) the negative impacts of soil erosion remain an extensive, repeated and deepening problem in the CR.

The aforementioned status of agricultural land also pertains to the Czech's largest drinking water reservoir basin on the Želivka River (Kronvang *et al*. 2005). Here, the biological and technical retention measures apparently remain insufficient for the farmland (Kvítek *et al*. 2017) and this situation is generally similar at numerous other catchments in the CR. To achieve a favourable shift, advanced progress knowledge of the erosive processes and their impact in various specific conditions is essential.

Research of erosive and transport processes in agricultural catchments is usually based, in particular, on monitoring the rainfall, the runoff and the pollutant concentrations in the water (e.g., Bishop *et al*. 2004; Pavlík *et al*. 2012). Among many others, hydrological and hydrochemical monitoring at small catchments represents a suitable approach. Large catchments are less homogenous and information on the rainfall, erosion and runoff dynamics can be hidden or, partially suppressed by the variability of the naturally and anthropically influenced processes (Laudon & Sponseller 2018). Therefore, characterisation of the rainfall-runoff and erosion processes based on detailed long-term monitoring data gained at small catchments, followed by modelling is irreplaceable for the proper description of this phenomena.

To simulate the delivery of suspended solids into the water bodies from a single rainstorm, complex knowledge about both the hydrologic and erosion response of the catchment is necessary. A wide range of applicable software exists, based on different principles and methods (the overview, e.g., Singh *et al*. 2005 or Pak *et al*. 2015). However, most of them were developed to simulate a specific part of the rainfall-runoff-erosion-transport-sedimentation process only. Simply, a single mathematical model to simulate the complete process is basically missing. This paper provides a new approach of the simultaneous use of two frequently used and well established soil erosion models; an event-based hydrological model, HEC-HMS, and a long-term erosion model, WaTEM-SEDEM, to simulate the runoff and soil erosion, taking the advantages of both. Despite the fact that the HEC-HMS model is a quite powerful event-based rainfall-runoff simulation tool, the lumped approach of its erosion module blurs the spatial variation of some catchment parameters and its use for the description of soil erosion processes is questionable (Van Rompaey *et al*. 2006). To substitute this disadvantage, the WaTEM/SEDEM model was used in this study. The long-term erosion model is, in general, unsuitable for event modelling, but it considers the spatial variation of the land use, relief and soil properties, which are crucial parameters for the simulation of the erosion. This paper uses both models simultaneously which is not frequent. Information on the source areas of the suspended solids, provided by WaTEM/SEDEM, was used to calibrate the HEC-HMS erosion module. The approach was applied based on the results of multiyear intensive monitoring of rainfall-runoff events and sediment delivery in the Kopaninský stream catchment.

MATERIAL AND METHODS

Study area. To study the impact of the land-use pattern and farm management on rainfall-runoff events and the associated surface water quality, a small subcatchment of the Kopaninský stream catchment, called Na Hřebelci (75.1 ha), was selected and analysed. The land-use consists of 48% of arable land, 3.5% of permanent grassland and 48.5% of forest. The Na Hřebelci catchment is located in the area of the Bohemian-Moravian Highlands (Figure 1), at an altitude of 575 m a.s.l. The bedrock is made up of crystalline rocks – gneiss and locally quartzite. The soil cover is predominantly composited from Cambisols. Lighter-textured soils with high potential infiltration are situated in the morphologically highest catchment parts, whereas moderate-textured soils are located at the bottom of the slopes. The climatic region is moderately temperate, humid, with an average annual temperature of 6.5°C and an average annual total rainfall amount of 700 mm (Uhlířová *et al*. 2009; Fučík *et al.* 2015). In the catchment, there are 4.8 ha of tile drainage systems (Figure 1) located in the valley along the monitored water course.

Monitoring. Since 2005, the systematic monitoring of the hydrological and erosive processes resulting from extreme rainfall-runoff events, as well as evidence of farm management, have been carried out in the catchment. The catchment outlet (Figure 2)

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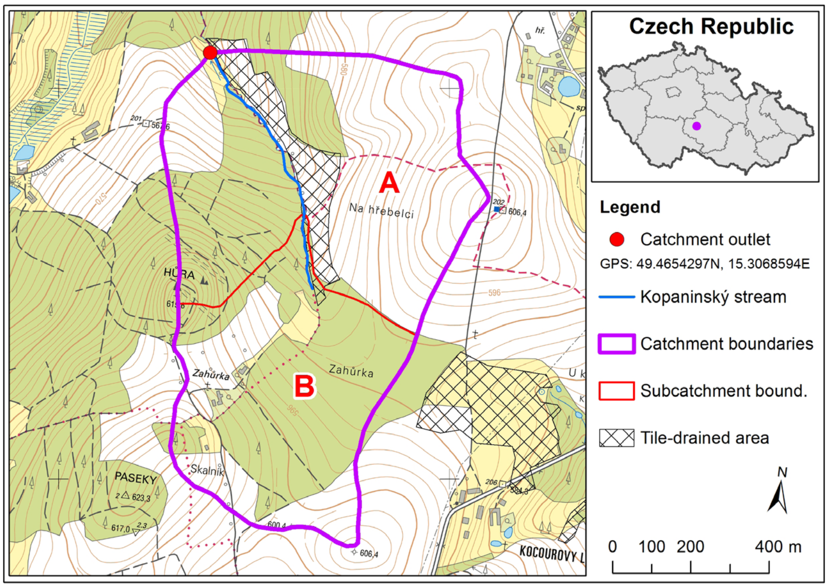

Figure 1. The monitored catchment at Na Hřebelci

was equipped for the measurement of the continual runoff. Water levels were measured using a calibrated Thomson weir with automatic ultrasound probe connected to a datalogger (Fiedler-Magr) with 10 min (1 min at events) recording. For the water and sediment sampling, a passive sampler (Janeček 1981) was used. It consists of a plastic box, embedded in a stream bank. There is a set of eight bottles, placed above each other, which fill automatically as a flood wave rises. For each bottle, the average runoff and time of filling was empirically established based of the outlet runoff curves, according to the particular height of the bottle throat inlet (equidistant vertical interval = 80 mm). Using these values, the analysed sediment concentration was then converted to the volume of the transported suspended solids. The meteorological station (which provides data on the local rainfall in 1 mm resolution) is located 200 m from the catchment outlet.

Figure 2. The gauging site and equipment at the catchment outlet

The falling flood limb was not sampled continually and this fact was taken into account for the modelling runoff and sediment transport as described below. Generally, the decreasing runoff limb is associated with the declining sediment concentrations (Zabaleta *et al.* 2007 or Bača 2008). Based on our own manual sampling from several flood waves, the sediment transport from the decreasing part of the flood limb varied between 78 and 100%. In accordance with safety principles usually implemented in erosion control studies, we considered the maximum measured amount of the sediment transport during the falling flood limb as 100% of the rising limb. Due to the rocky nature of the stream bed, the influence of bottom erosion was neglected here (Nagle & Ritchie 2004; Uhlířová *et al.* 2009). A terrain survey also documented the stability of the banks and no side wall collapse was proved during the recent campaigns.

The number of rainfall events which caused soil erosion and the transport of the suspended solids in the catchment outlet differed between the individual years. The summary of the data from the years 2005 to 2017 is presented in Table 1, where the total mass of the suspended solids M is the sum of the individual erosion events in each year (based on the gauged data for the rising limb of every flood wave).

From the long-term series of measurements, five extreme rainfall-runoff events were selected (Table 2). The measured data was then used to calibrate the

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Table 1. Annual transport of the suspended solids resulting from the captured erosion events

Year	No. of extreme events	Suspended solids (kg)	
		M	M + 100%
2005	6	503 231.4	1 006 462.8
2006	5	40 266.2	80 532.4
2007	0	0.0	0.0
2008	0	0.0	0.0
2009	1	110.7	221.4
2010	3	3 727.5	7 455.0
2011	5	35 589.0	71 178.0
2012	3	37 813.8	75 627.6
2013	3	4 744.2	9 488.4
2014	0	0.0	0.0
2015	1	6.3	12.6
2016	2	1 579.1	3 158.2
2017	2	2 105.1	4 210.2
Average	2.4	48 397.9	96 795.9
SD	1.9	132 186.4	264 372.9

M – transported amount at the rising part of a flood wave; SD – standard deviation

episodic HEC-HMS model. Selected events represented both, the long-term rainfall (2–6 h) with relatively low intensity as well as the heavy, short (0.5–1.5 h) rains. The criteria for the selection of the events were: the complete and errorless data set, the obvious erosion effect and the properly recorded transport of soil particles in the stream, the representative character of the events in the catchment. The type and rotation of the crops on the arable land were gained from the farmers, the crop coverage was estimated according to the vegetation stage at the time of the selected events (Figure 3).

Long-term model. The long-term average soil loss due to water erosion was calculated with the Universal Soil Loss Equation (USLE) in the ArcGIS (Ver. 10.6, 2018) environment, using the USLE 2D software and the routing algorithm (flux decomposition) (Konečná *et al.* 2017). The DMR 4G digital relief model with a resolution of 5 × 5 m/pixel was used. The USLE factors were set according to the currently valid methodology for the assessment of the soil erosion threat in the CR (Janeček *et al.* 2012). The recommended rainfall erosivity factor value of R = 400 MJ/ha·mm/h (i.e., 40 MJ/ha·cm/h) was applied, since it is a reliable and, in the CR, widely used value calculated by experts from 31 meteorological stations over a ten year long data series (Janeček *et al.* 2013). The method also contains values of the revised K factor for the main soil units (Vopravil *et al.* 2007). The C factor indicates the protection of the soil by the crop as related to a particular crop and its phase and was determined on the basis of the crop rotation for the period 2005–2017, provided by the local farmers. The long-term average crop rotation in the catchment was as follows: cereals 51%, maize 25%, oilseed rape 18%, potato 2%, others 4%.

The WaTEM/SEDEM model (2006) was used for the calculation of the long-term average transport of the suspended solids to the catchment outlet. For the calculation of the average annual soil loss, the model applies the Revised Universal Soil Loss Equation (RUSLE) (Renard *et al.* 2000). When processing the WaTEM/SEDEM model, the same input data from the USLE 2D model was used. The used model parameters settings were: the LS factor McCool algorithm, PTEF coefficients (arable soil = 0; forest = 75; permanent grassland = 75), parcel connectivity for arable land = 40, for the transition forest/pasture = 75. For the transport process, the following coefficients, kTc low = 35 and kTc high = 55 were used (Krasa *et al.* 2019). As these adjusted values were applied, the WaTEM/SEDEM model gave detailed, spatialised information on the erosion threat degree for all the assessed field

Table 2. Transport of the suspended solids in the selected rainfall-runoff events at the rising limb of a flood wave

Event No.	Date	Q_{max} (l/s)	Suspended solids		Causal rainfall		
			C (g/l)	M (kg)	total (mm)	max. int. (mm/10 min)	duration (min)
1	23/5/2005	667.0	263.6	344 137.8	79.0	17.0	130
2	12/9/2005	648.9	96.5	32 897.8	48.6	12.8	60
3	3/5/2012	650.0	44.0	36 274.4	76.4	3.6	90
4	24/7/2016	89.5	2.7	459.0	27.4	4.5	380
5	31/7/2016	502.0	3.7	1 120.1	16.5	12.9	30

Q_{max} – maximum outflow; C – average concentration; M – transported amount

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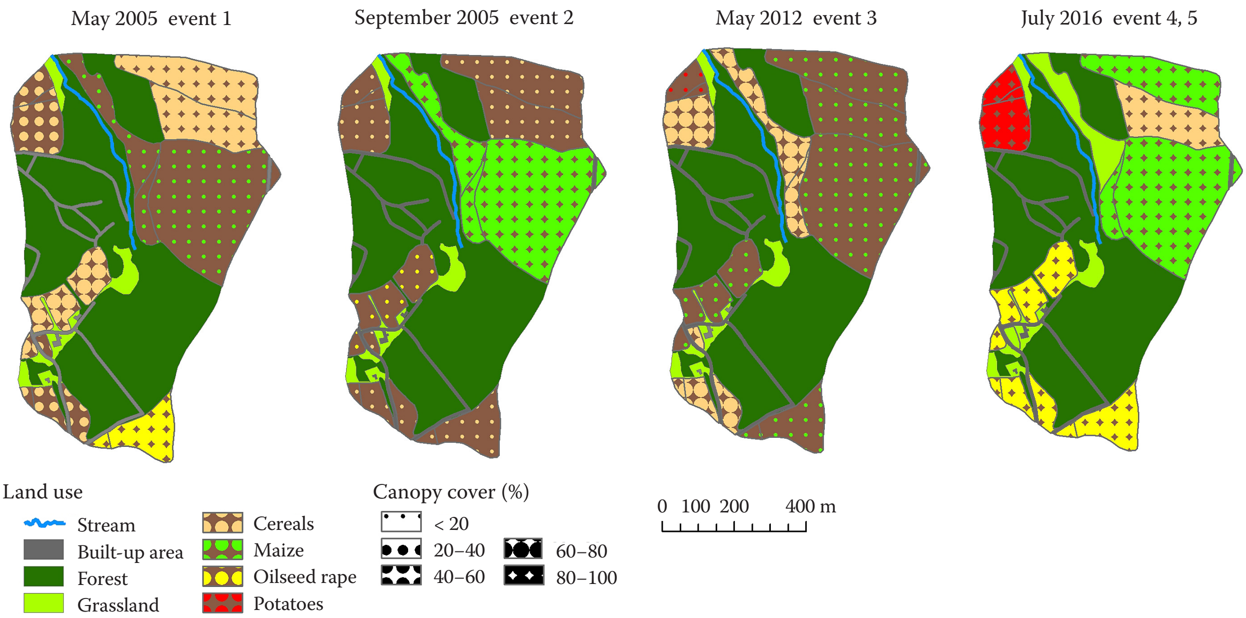

Figure 3. The state of the land use and crop cover during the selected evaluated events

block parts in 5 × 5 m resolution (Lieskovský & Kenderessy 2014).

Episodic model. To evaluate the individual rainfall-runoff and erosion events and to assess the water quality in a catchment, the HEC-HMS model (USACE 2013) was applied, specifically version 4.0 with an added erosion module (Pak *et al*. 2015). In the model, the hydrological cycle is separated into several independent sub-processes: infiltration losses, the transformation of the excess precipitation, the baseflow and the transformation of the flood waves in the channels. Every aforementioned part is represented by an independent mathematical model. For each model, several calculation methods can be chosen. The methods selected for this study are summarised in Table 3. The process of soil erosion was calculated by the empirically-derived method of the Modified Universal Soil Loss Equation (MUSLE) (for the CR, in Janeček *et al*. 2012). The model is based on the lumped principle of the spatial distribution of the input parameters. The results are provided as the runoff (m/s) and sediment mass (kg) time curves for the catchment outlet.

To quantify the response of a catchment to the causal rainfall, a model has to be properly calibrated. As a prerequisite of successful soil erosion modelling, the runoff model has to simulate direct runoff accurately. The Na Hřebelci catchment was divided into two subcatchments, A and B (Figure 1). The initial parameters were derived on the basis of spatial analysis of the DMR 4G 5 × 5 m digital terrain model and real land use for the modelled episodes in ArcGIS. The Curve Number (CN) method was applied, adjusted for the Czech conditions by Janeček *et al*. (2012), according to the soil hydrological groups, land use and current catchment hydrological conditions. Soils in the catchment were classified to the hydrological groups according to their type. Regarding the character of applied tillage, the runoff-related hydrological conditions were considered as a good indicator.

Table 3. The calculation methods used in the HEC-HMS model for the simulation of the hydrological and erosive response of the catchment

Model	Method	Characteristic
Runoff-volume model	SCS curve number	event, lumped, empirical, fitted parameter
Direct runoff model	Clark's Unite Hydrograph	event, lumped, empirical, fitted parameter
Baseflow model	exponential recession	event, lumped, empirical, fitted parameter
Routing model	Muskingum Cunge	event, lumped, quasi-conceptual, measured parameter
Sediment model	MUSLE	event, lumped, empirical, fitted parameter

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The average or typical values of the input parameters for the whole subcatchment (Table 4) were entered into the model. The calibration parameters of the runoff part of the HEC-HMS influencing the resulting hydrograph were as follows:

(1) the initial loss of rainfall water (Ia), which stands for the interception, detention, evaporation and initial infiltration,

(2) the CN value, expressing the degree of infiltration and direct runoff,

(3) the concentration time (Tc), the time the water needs to travel from the furthest point in the catchment to the catchment outlet, and

(4) the storage coefficient (Sc), the time of the temporary retention of the water in the catchment.

After the setup of the runoff part of the HEC-HMS model, the erosion module was calibrated. The first model runs revealed the lower subcatchment A (Figure 1) predominantly contributed to the event runoff response in the catchment outlet. Therefore, it was crucial to find the suitable parameter settings for this subcatchment. The protective influence of the cover management factor C was chosen as a calibration parameter. For all the assessed events, the following average values of the other input parameters were implemented: LS factor = 2.055, K factor = 0.352, P factor = 1.

The reliability of the calibration process was evaluated by standard statistical indicators, which were the percent bias (PBIAS), the root mean square - observations standard deviations ratio (RSR) and the Nash-Sutcliffe efficiency (NSE). The PBIAS (Eq. (1)) measures the average tendency of the simulated data to be larger or smaller than their observed counterparts (Lefrancq *et al.* 2017). The optimal value of PBIAS is 0, with low magnitude values indicating an accurate model simulation. Positive values indicate a model underestimation bias, negative ones indicate a model overestimation bias.

$$\text{PBIAS} = 100 \times \frac{\sum_{i=1}^{n}(X_{i\text{sim}} - X_{i\text{obs}})}{\sum_{i=1}^{n} X_{i\text{obs}}} \tag{1}$$

RSR (Eq. (2)) is calculated as the ratio of the root mean square error (RMSE) and the standard deviation of the measured data ($\text{STDEV}_{\text{obs}}$). It applies the benefits of normalisation of the RMSEs of different model runs on a comparable scale so that, unlike with the RMSE, the model's performance under different rainfall and catchment conditions can be compared (Singh *et al.* 2005). The RSR varies from an optimum value of 0, which indicates a zero RMSE or a residual variation and, therefore, a perfect model simulation, to a large positive value. The lower the RSR, the better the model simulation performance is (Moriasi *et al.* 2007).

$$\text{PSR} = \frac{\text{RMSE}}{\text{STDEV}_{\text{obs}}} = \frac{\sqrt{\sum_{i=1}^{n}(X_{i\text{obs}} - X_{i\text{sim}})^2}}{\sqrt{\sum_{i=1}^{n}(X_{i\text{obs}} - \overline{X_{\text{obs}}})^2}} \tag{2}$$

NSE (Eq. (3)) is a normalised statistic that determines the relative magnitude of the residual variance ("noise") compared to the measured data variance ("information"). It can range from −∞ to 1. An efficiency of 1 corresponds to a perfect match of the modelled to the observed data. An efficiency of less than zero occurs when the observed mean is a better predictor than the model.

$$\text{NSE} = 1 - \frac{\sum_{i=1}^{n}(X_{i\text{obs}} - X_{i\text{sim}})^2}{\sum_{i=1}^{n}(X_{i\text{obs}} - \overline{X_{i\text{obs}}})^2} \tag{3}$$

According to Moriasi *et al.* (2007) reviewing many studies, using the above described statistical indicators, a model performance can be judged as:

Table 4. Calibration parameters of the HEC-HMS model – the initial values and values after calibration; the values after calibration are given in original units with % of the initial value in parenthesis

Event No.	Ia (mm)		CN (–)		Tc (h)		Sc (h)		Cf (–)	
Subcatchment	A	B	A	B	A	B	A	B	A	A
Initial value	21	40.7	70.7	55.5	6.1	7.8	0.9	1.5	–	–
1 – 23/05/2005	9 (42.8)	38 (95.8)	15 (21.2)	20 (35.6)	0.17 (2.7)	5 (65.1)	0.1 (10.6)	2 (130.1)	0.640 (206.5)	0.31
2 – 12/09/2005	5 (23.8)	38 (93.5)	24 (33.9)	8 (14.4)	0.17 (2.7)	0.3 (3.8)	0.08 (9)	0.2 (13)	0.276 (100)	0.276
3 – 03/05/2012	12 (58.5)	38 (93.5)	15 (21.1)	8 (14.4)	0.17 (1.7)	0.3 (3.8)	0.08 (9)	0.2 (13)	0.152 (38.4)	0.396
4 – 24/07/2016	8 (39)	12 (29.5)	30 (42.1)	30 (54)	0.7 (11.6)	1 (12.8)	0.1 (10.6)	2 (130.1)	0.032 (19)	0.168
5 – 31/07/2016	5 (24.4)	9 (22.1)	75.5 (106)	60 (108)	0.17 (1.7)	0.3 (3.8)	0.08 (9)	0.5 (32.5)	0.011 (6.3)	0.168

Ia – initial abstraction; CN – curve number; Tc – time of concentration; Sc – storage coefficient; Cf – crop cover-management factor

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– satisfactory if the PBIAS is ± 25% for the streamflow and ± 55% for the sediment, the RSR < 0.70 and if the NSE > 0.5,
– good if the PBIAS is ± 15% for the streamflow and ± 30% for the sediment, the RSR < 0.60 and if the NSE > 0.65,
– very good if the PBIAS is ± 10% for the streamflow and ± 15% for the sediment, the RSR < 0.50 and if the NSE > 0.75.

RESULTS AND DISCUSSION

Based on the long-term catchment monitoring data, the heaviest erosion rich events years appeared to be 2005 and 2006. Conversely, the years 2007, 2008 and 2014 were relatively dry, without any significant storms (Table 1). The highest measured annual total of transported suspended solids (in the rising part of the runoff waves) in 2005 (= 503 231 kg) was more than ten times the average transport (48 398 kg). The episodic model results indicated that for the entry of the suspended solids into the water, the timing of the torrential downpours throughout the year was more crucial than the total precipitation amount. As an example, the events in 2005 can be mentioned. While the peak runoff was comparable for both events, the sediment transport was ten-times higher in May (event No. 1) due to the low crop cover on the maize fields, compared to September (event No. 2) when the maize was fully developed.

Long-term model. The calculated long-term average soil loss due to erosion on the farmland in the studied catchment was 14.3 t/ha/year. Relating this value to the area of the farmland in the catchment (38.3 ha) gave a long-term average soil loss of 547.7 t/year. A substantial portion of the eroded particles most probably settled at the foot of the slopes or was placed in the catchment accumulation zones or in the permanent vegetation (grass or forest). The WaTEM/SEDEM model assessed the average long-term sediment load at the catchment outlet to be 116.0 t/year.

Based on the measured data, including an estimate of the declining part of the wave (= M + 100%), the long-term annual average was calculated as 97 t per year (Table 1). In accordance with the findings of other authors (e.g., Lieskovský & Kenderessy 2014; Krása *et al.* 2015), the mathematical model showed a tendency to overestimate the amount of erosion in comparison with the measured data. The spatial analysis (Figure 4) revealed that the dominant source of sediment was the lower subcatchment, in particular the right (eastern) slope which directly touches the bank of the stream. The arable land, which is separated from the stream by a wide belt of forest, played a minimal role as a source of the sediment. The knowledge of the spatial distribution of the erosion-transport-sedimentation process in the catchment given by WaTEM/SEDEM was used for the HEC-HMS erosion module calibration.

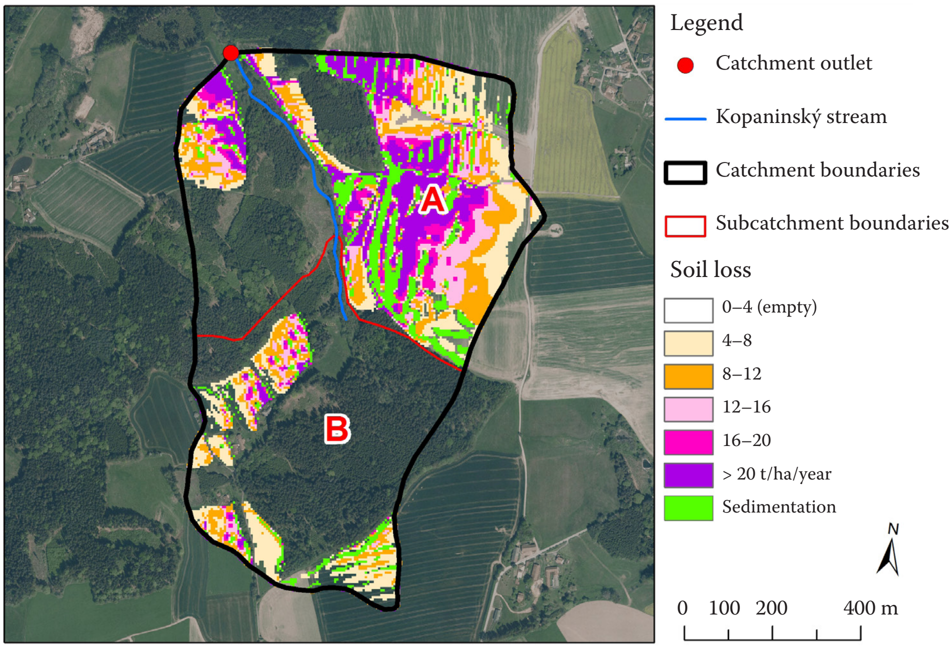

Figure 4. The WaTEM/SEDEM model output

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Episodic model. The final calibration parameter values for each episode are given in Table 4 as a percentage of the initial value. To match the monitored runoff data, the model parameters controlling the course over time of the culmination wave Tc and Sc were reduced to a minimum and the CN values were far below the normally used values suggested according to the methodology (Janeček *et al.* 2012). Episode No. 5 from 31/7/2016 marked an exception. The initial values given by the methodology corresponded to the real behaviour of the catchment. Compared to the other ones, this episode was extremely intense and short, and while the rainfall volume was by far the lowest, the maximum runoff was similar to the strongest episodes. Either the rainfall intensity exceeded the infiltration rate, or the initial conditions such as the soil crusting or hydrophobicity significantly decreasing the infiltration rate, were developed. The initial loss of precipitation I_a was similarly far below the value recommended according to the CN methodology (Janeček *et al.* 2012; Verma *et al.* 2017). The model values however corresponded to the findings, which confirm that the rather lower values match the real conditions (e.g., Noori *et al.* 2012).

It was also possible to identify the differing behaviour of the lower-situated, mostly agriculturally used subcatchment A and the predominantly forested subcatchment B. Subcatchment A reacted to the rainfall substantially faster than subcatchment B (Tc 10–42, resp. 18–300 min, Sc 5–6 resp. 12–120 min), had a lower infiltration capacity (CN 15–75, resp. 8–60) and a lower initial loss (Ia 5–12, resp. 9–38 mm). The difference between the subcatchments corresponded to the structure of their vegetation cover and the general properties of the arable and the forested land.

The calibration process of the erosion module supported the findings from the WaTEM/SEDEM, that the slopes of the arable land immediately adjacent to the watercourse were the main sources of the sediment. The initial value of the C factor, which is a weighted average for the entire subcatchment, and, thus, blurs the spatial distribution of the land use, had to be modified according to the actual crop state in the field on the right stream bank. In the May events (1 and 3), the average C factor was fairly high (0.31–0.4) due to the low and sparse canopy of the maize and potatoes grown in the catchment. In 2005, the maize was grown on this field and the overall C factor was more than twice as large. Conversely, in 2012, the winter barley with a dense canopy cover was cultivated in the field and the average C factor was reduced to 38% of the original value. During the September event in 2005 (No. 2), the maize was already fully grown and the C factor of the field corresponded to the overall average C factor. The model's results with this setting showed the best agreement with the measured data. The events in 2016 (No. 4 and 5) took place with a gap of one week, and in a period when there was good crop cover on all the fields. The C factor for the field adjacent to the stream was substantially lower than the average due to the cultivation of the grass-clover mixture. To achieve adequate erosion modelling results, it had to be reduced to 19%, or respectively to 7% of the average value.

The ability of the model to simulate the course of events is documented in Table 5 and Figure 5 for the runoff and Table 6 and Figure 6 for the suspended solids. According to Moriasi *et al.* (2007), on the basis of statistical indicators, the model showed satifactory calibration results. For the runoff, the

Table 5. Statistical evaluation of the HEC-HMS runoff simulations

Rainfall event	Volume sim (%)	Q_{max} sim (%)	PBIAS	RSR	NSE
1 – 23/05/2005	85.9	100.4	0.4	0.40	0.846
2 – 12/09/2005	105.8	100.0	–0.9	0.44	0.813
3 – 03/05/2012	102.9	101.2	–2.9	0.15	0.975
4 – 24/07/2016	100.9	96.8	–1.5	0.18	0.969
5 – 31/07/2016	114.7	100.5	–12.3	0.90	0.012

sim – simulated; Q_{max} – maximum outflow; PBIAS – percent bias; RSR – root mean square error and observations standard deviations ratio; NSE – Nash-Sutcliffe efficiency

Table 6. Statistical evaluation of the HEC-HMS suspended solids simulations

Rainfall event	Total sediment in the rising limb (%)	PBIAS	RSR	NSE
1 – 23/05/2005	96.3	–3.2	0.30	0.908
2 – 12/09/2005	99.9	132.2	1.18	–0.54
3 – 03/05/2012	100.0	37.7	0.45	0.777
4 – 24/07/2016	100.7	2.8	0.51	0.701
5 – 31/07/2016	99.2	30.3	0.43	0.793

PBIAS – percent bias, RSR – root mean square error and observations standard deviations ratio, NSE – Nash-Sutcliffe efficiency

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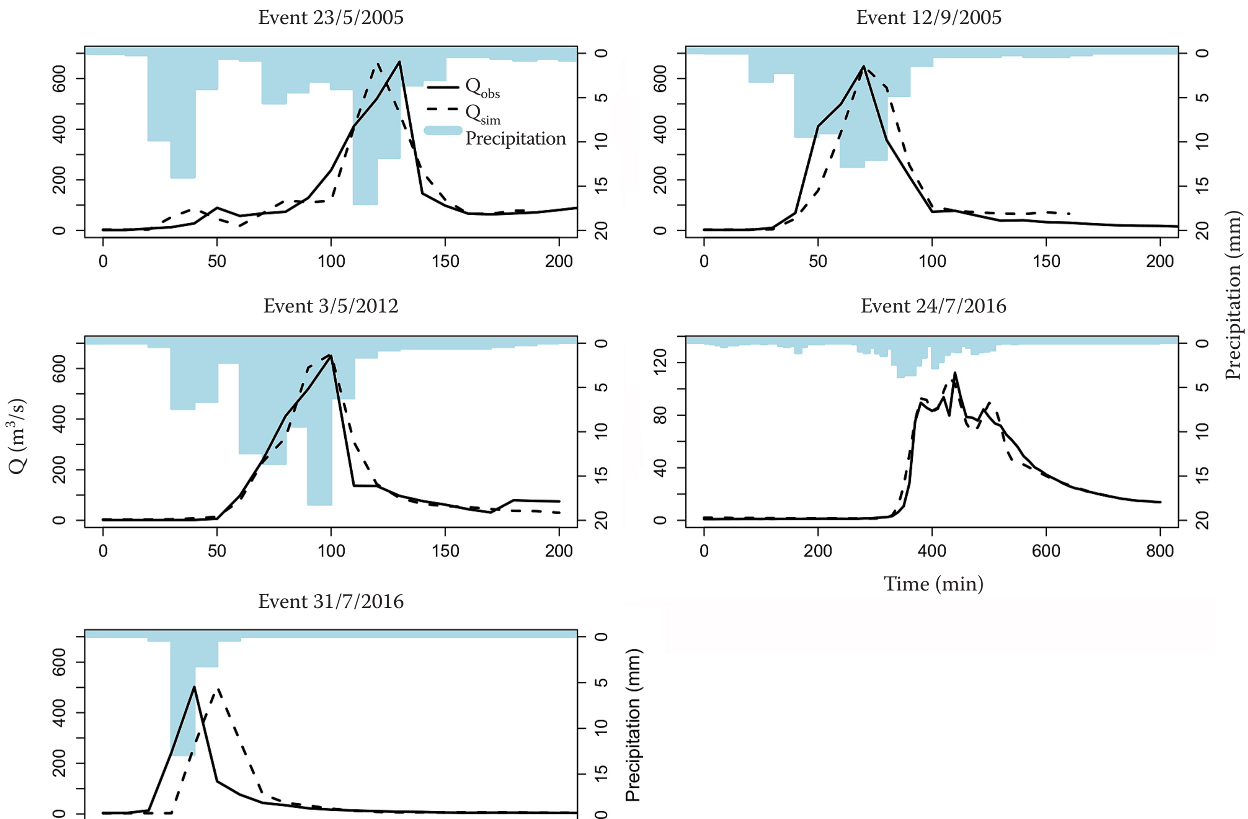

Figure 5. Calibration of the runoff for the selected events

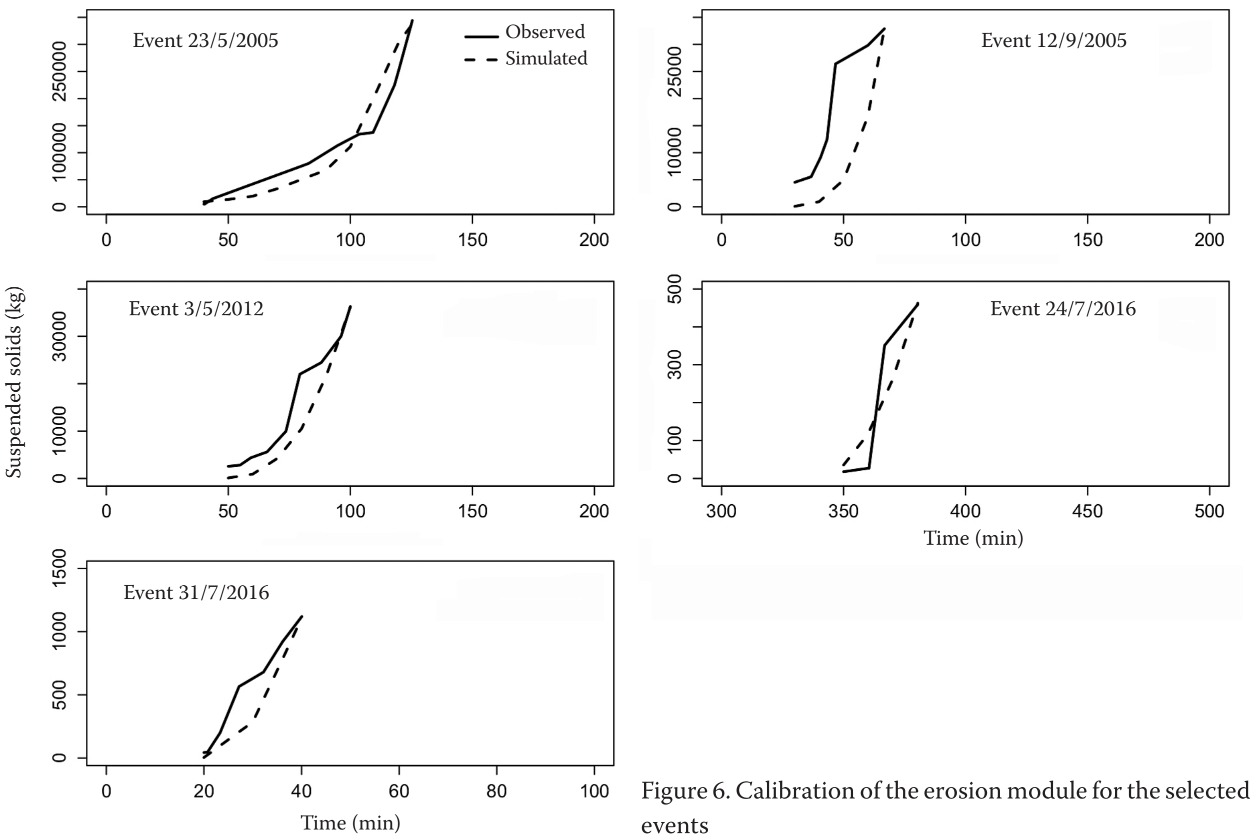

Figure 6. Calibration of the erosion module for the selected events

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calibration results can be seen as very good for all the events aside from the extremely rapid and short event No. 5. The model delayed it by one time step in the simulation (10 min), which, in an overall duration of 30 min, led to the unsatisfactory values of the statistical indicators. However, the model captured the course, volume and peak flow of the wave very well. For suspended solids, the results can be seen as ranging from staisfactory to very good in all the events except for No. 2. Here, the model did not manage to interpret the high initial volume of the suspended solids and the decrease in their transport during the culmination of the runoff.

Generally, the catchment reacted extremely rapidly to the rainfall and demonstrated a high infiltration capacity. The erosive response of the catchment and the input of the suspended solids into the watercourse was significantly dependent on the current state of the crop cover on the fields in the vicinity of the stream.

The results indicated that during the rainfall-runoff events, the infiltration of the water into the soil was probably partly influenced by the tile drainage system. Farmland of an area of 4.8 ha on the right bank of the stream is tile-drained with a systematic drainage network connected to the stream. The drainage most probably (in relation to the current moisture conditions in the catchment and rainfall characteristics) modifies the course of the surface runoff (King *et al.* 2014), or respectively, in the initial phase, generally flattens the rising limb of the hydrograph. This also confirms the earlier results of the modelling from this catchment (Žlábek *et al.* 2002) and other work (Lefrancq *et al.* 2017), which indicated a need to generally reduce the CN values for the drained agricultural land. However, our modelling results demonstrated that the land drainage in the area helped to accelerate the runoff response to the rainfall episodes.

CONCLUSION

This study proved that the simultaneous use of a lumped episodic model and a distributed long-term model is capable of carrying out a detailed analysis of the hydrological and erosion processes in a catchment. Furthermore, the applied approach enabled one to disentangle the influence of the land use pattern and the current crop and tillage state in terms of the suspended solids delivery into a stream for the different rainfall events. For the simulated catchment, the WaTEM/SEDEM model revealed that the main sources of the sediment load were areas of arable land in the immediate vicinity of the stream. The sediment produced in the field parts at a greater distance from the stream with a different type of land use, which interrupted or slowed the runoff, was captured before it reached the watercourse and did not significantly influence the water quality (which corresponds with other findings, e.g., Konečná *et al.* 2017; Kvítek *et al.* 2017). The conclusion was supported by the HEC-HMS model with an adjusted C factor, modified according to the current crop stages.

The results suggested that a lumped approach for the modelling of the soil erosion episodes, where the input parameters of the model are determined by a weighted average for the entire catchment, is fundamentally inappropriate. The key issues for the successful modelling seem to be to incorporate detailed information on the soil management as well as the current crop and vegetation stages during the event as well as the advanced knowledge of the calibration-validation process of a given model. The study showed the promising possibility for the use of a long-term distributed model as a tool for the setting the parameters of a lumped episodic model.

The studied small catchment manifested an extremely rapid runoff response for the analysed events and, simultaneously, a relatively high soil infiltration capacity. This may be the result of considerable hydrological connectivity of the lower-situated subcatchment with the watercourse and also most probably due to the presence of a drainage system in this part of the catchment. When simulating the rainfall-runoff relationships in a tile drained catchment, special attention has to be paid to the influence of the systematic drainage in the CN method, since the drainage hydrology appears to be significant.

The presented approach seems to be suitable for the identification of the main sources of the sediment transported from the farmland to streambed as well as for the design of effective erosion control measures in small catchments.

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