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Use of the KINFIL Rainfall-Runoff Model on the Hukava Catchment

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Abstract: The paper reports on the flood events on the forested Hukava catchment. It describes practical implementation of the KINFIL rainfall-runoff model. This model has been used for the reconstruction of the rainfall-runoff events and thus for the calibration of its parameters. The model was subsequently used to simulate the design discharges with an event duration of t_d = 30, 60, and 300 min in the period of recurrence of 100 years, and during the scenario simulations of the land use change when 40% and 80% of the forest in the catchment had been cleared out and then replaced by permanent grasslands. The implementation of the KINFIL model supported by GIS proved to be a proper method for the flood runoff assessment on small catchments, during which different scenarios of the land use changes were tested.

Keywords: rainfall-runoff model; GIS; design discharges; land use changes

Recent trends in the climate changes often cause torrential rainfalls that have clearly led to a rise in the frequency of hydrological extremes, floods in particular (Grešková 2001). The catchment management, including the land use, plays an important role in the rainfall-runoff relationships. The implementation of hydrological models allows a better analysis of the flood situations, with particular reference to the direct runoff processes in the context with the changes caused by human activities (Halmová 2000). The simulation of the design discharges on small catchments under the influence of these activities is a key task for hydrometeorological institutes. However, in the case of small catchments, the reliability of these data varies, and one possible way to improve it is the use of hydrological models. One of these models, simulating the direct runoff from ungauged catchments, is the KINFIL model (Kovář 1992), which can be easily utilised by hydrologists.

Recent development in hydrological modelling provides modern methods of runoff forecasting and techniques for the prediction of design discharges impacted by human activities. These N-year design discharges caused by the design rainfalls play a significant role in the new investments as they significantly influence the extent of the flood control measures and consequently their cost (Beven 2006). However, this paper describes a case study of the impact of a special land use change – deforestation. The role of forests in controlling the hydrograph peaks has long been debated in hydrology (Swank & Crosley 1988; McCulloch & Robinson 1993). In general, the impact of deforestation is likely to be associated with some uncertainty. It does not involve only a change of vegetation but also changes in forest roads, soil structure, and ditching (Beven 2006). The direct runoff simulation has been computed using the kinematic wave sub-model (i.e. KINFIL model part, Kovář *et al.* 2002) respecting the catchment topography. Topographical characteristics of the Hukava catchment were processed by the ARC/INFO system. Our purely deterministic approach does not consider the possible uncertainty in estimating the model parameters. The reliability of these modern methods of hydrological modelling and their GIS interface is relevant for an adequate mathematical description of the rainfall-runoff process and for the extent and quality of the data.

MATERIALS AND METHODS

Characteristics of the KINFIL model

The KINFIL model uses the Curve Number method (U.S. SCS 1986) but suppresses its weak theoretical background by substituting the physically-based infiltration theory for a common empirical CN approach. The correspondence between CN values and soil parameters, such as the saturated hydraulic conductivity (K_S) and sorptivity (S_f), was derived through a correlation technique of these parameters with the design rainfalls. To discover the best fitting correspondence between the CN and (K_S, S_f) – pairs for all major textural soil groups and the rainfall data of a wide intensity – duration spectrum, a correlation method was used. This analysis was then performed with 10 major textural classes (Brakensiek & Rawls 1981) (compatible with the Kopecký classification with 7 classes) and 62 rainfall stations in the Czech Republic, each for a duration of 30, 60, 90, 120, 180, and 300 min, derived from the daily (24 h) rainfalls with a return period of 1, 2, 5, 10, 20, 50, and 100 years. Thus more than 22 thousand data pairs provided the best fitted CN – (K_S, S_f) relations for the average antecedent soil moisture conditions (i.e. AMC II) that roughly correspond to the field capacity saturation (Kovář 1992). The resulting regression coefficients were used for further simulation of historical rainfall-runoff events, implementing the KINFIL model also in typical mountain catchments. The infiltration part of the model is based on the Morel-Seytoux equations (Morel-Seytoux 1982), based on the Green-Ampt concept, distinguishing the pre- and post-ponding infiltrations from the constant or variable rainfalls. As it had been derived for the Czech Republic territory (Kovář 1992), we carried out a test to see if regression coefficients can be applied also for the Slovak hydrological conditions. It is always disputable if the Green-Ampt approximation is adequate to simulate the infiltration process on forested mountainous catchments. However, the KINFIL model uses this approximation in combination with the SCS Curve Number method based on the Morel-Seytoux approach mentioned above. Thus, the hydraulic properties of soil (K_S and S_f) are related to CN values and they get conceptual values rather than the purely physical ones.

The second basic component of the KINFIL model is the simulation of the runoff. This process is based on a kinematic wave approximation of the model. The runoff mechanism considers a direct runoff (i.e. surface runoff plus interflow) when its interflow part appears alternatively either as a surface runoff or a shallow subsurface flow going mostly through the system of preferred gravity pores. This approach is not theoretically fully correct but is a part of the kinematic wave approximation that has been often used in the forest hydrology for heavy rainfall events or for the design floods determination (e.g. Tani & Abe 1987). In the cases of high rainfall intensities as it is always in the design floods when those are often higher that 2 mm/min and their depth is over 50 mm, the conditions for using a kinematic wave are mostly feasible (Overton & Meadows 1976). For the numerical solution, the explicit Lax-Wendroff finite difference scheme was implemented. Three simulation components, a cascade of planes, converging or diverging segments, and channel reaches can be used, in principle, in the model implementation to simulate the topography of a catchment. A more detailed model structure is described elsewhere (Kovář *et al.* 2002). A recent innovation in the geometrisation of a catchment is to take consistently into account the hierarchy of sub-catchments in the flow direction. This version assumes that the individual small sub-catchments are substituted by a system of serial/parallel cascades of planes arranged according to the flow direction. However, this system should not go into too great a topographic detail but put emphasis on slopes and roughness conditions. A real current runoff mechanism in the Hukava catchment is undoubtedly very complex and the likely runoff source areas are not homogenous all over the catchment. However, in the significant rainfall-runoff events due to the steep slopes in the Hukava catchment direct runoffs (described above) have been assumed, and their routing has been approximated by a kinematic wave in the KINFIL model (Overton & Meadows 1976). In addition, it should also be stated that the infiltration part of the KINFIL model has two parameters, K_S and S_f, strictly dependent on the CN values which are not subjected to a change through calibration. However, each of these partial areas has its own CN-value characterising the rainfall excess conditions. The routing part of the model has two groups of parameters – geometrical parameters of partial sub-catchments (at least the width and length of rectangles, or segment parameters) that have to be used, and the Manning roughness to be adjusted according to the natural runoff conditions. There is no automatic optimisation of these parameters. This model version was used for the Hukava catchment data. Table 1 shows the land use in this catchment.

Table 1. Land use in the Hukava catchment

Land use	Area (km^2)	Percentage (%)
Coniferous forest	2.81	26.06
Deciduous forest	1.64	15.18
Mixed forest	5.24	48.56
Shrubbery	0.06	0.50
Meadows and permanent grasslands	0.91	8.47
Urbanised areas	0.01	0.03
Road network	0.13	1.20

GIS implementation

Geographical Information Systems (GIS) allow not only the processing of spatial geo-data but they also enable an analysis of these data with further information provided by hydrological models. GIS also allows visualisation of the input/output data from various perspectives.

GIS tools for a catchment identification in the form of DTM including the topographical characteristics, soil groups, land use, and water drainage pattern in this paper, were used. All these characteristics are given in Table 2.

Table 2. Basic physiographic characteristics of experimental Hukava catchment

Catchment area (km^2)	S_p	10.80
Forested catchment area (km^2)	S_L	9.84
Forestation (%)	l	90.14
Length of river(km)	L	6.438
Length of inflows (km)	ΣL_{pi}	9.263
Catchment perimeter (km)	O	14.905
Length of talweg (km)	$L_{\text{ú}}$	6.834
Max. catchment altitude (a.s.l.)	H_{maxp}	1458
Min. catchment altitude (a.s.l.)	H_{minp}	569
Average catchment altitude (a.s.l.)	$H\O$	909.86
Average width catchment (km)	B_p	1.580
Average river slope (%)	I_t	15.75
Average talweg slope (%)	$I_{\text{ú}}$	12.34
Average catchment slope (%)	I_s	31.15

The spatial properties of the Hukava catchment are characterised in the raster maps based on the topographical maps 1:25 000. Graphical inputs/outputs were made in GIS ArcView and ArcGIS (version 9.0). The vectorising procedure of the topographical maps 1:25 000 rasters was conceived, distinguishing different land use patterns (forest, permanent grassland, arable land, water areas, and urbanised patches) Figure 1.

The next step was to derive the Curve Number values of different subcatchments. There was a usual routine in the case of the agricultural land; however, in the case of the forest soils, the classification of the geological substrate method was used (ČHMI 2006).

Characteristics of the Hukava catchment

The studies of the catchment of the Hukava River (see Figure 1) classify it according to the torrent coefficient as a moderate torrent. The catchment spreads in the orographic region of the Slovak Central Mountains Massive of Poľana (CHKO).

From the hydrological typology point of view, the surveyed river is part of the main catchment SVP-IX-Hron, partial catchment Slatina. The closing profile is at an altitude of 569 m, the highest point of the catchment being Poľana (1458 m a.s.l.), at

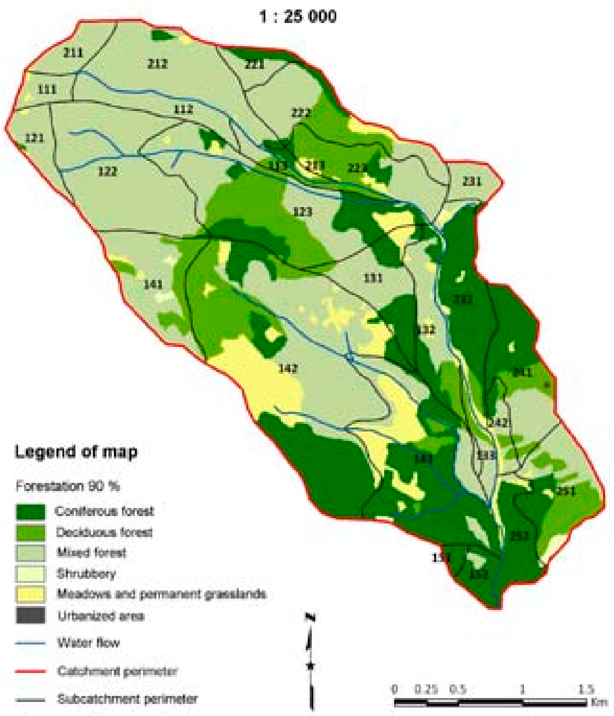

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Figure 1. Land use in the Hukava catchment

the watershed. The mean inclination of the slopes in the catchment is 31.15%.

The dominating type of the rock formations belongs to the petrography variety of Andesine, more than Ryodasits and Diorite. The most common types of soil are Cambisol (71.47%) and brown Andosol (26.88%). The dominating soil variety in the catchments is Loamy Sand in 100%. The soil types are represented by Cambisols (71.5%), brown Andosols (26.8%), Regosols (1.1%), and grey Andosols (0.6%). Table 1 provides the land use distribution on the Hukava catchment.

Average yearly temperatures vary between 6°C and 2.5°C. Average yearly precipitations amount to 957 mm and 1300 mm. The forested areas in the catchment grow in four forest vegetation categories: 4. beech, 5. fir-beech, 6. spruce-fir-beech and 7. spruce. Tree species are: 45.44% spruce; 34.91% beech; 7.33% mountain maple, and 6.12% slim ash. Other species represent 6.20%.

As concerns the outlines for schematisation, the borders between the cascades are waterdivides. These borders within one cascade were derived from the slopes respecting, the land use. All planes were transferred to the same area rectangles. According to the average width and real subcatchment area, the plane theoretical length was computed. All these operations were carried out using GIS ARC/INFO.

The principle of numbering is as follows:

1xx	right part
2xx	left part
x1x–x7x	cascade number
xx1–xx3	plane number in cascade (downslope)

RESULTS AND DISCUSSION

Reconstruction of the events observed

When the first flood (Wave 1) came, the catchment had been moderately saturated with the previous precipitations to the level of antecedent moisture conditions AMC II, during the second wave (Wave 2) the catchment was extremely saturated (level AMC III), as a consequence of which the culmination inflow was higher, even though the precipitation was much lower in this case (Table 3). The AMC I to III are classified according to the U.S. Soil Conservation Service Method (U.S. SCS 1986) to distinguish between the levels of saturation with precipitation depths during five previous days (AI to 36 mm, AII from 36 to 53 mm, and AIII more than 53 mm). These sudden intensive rainfalls caused floods which, with their peaks of 2.485 m^3/s and 3.050 m^3/s, may be classified in the category of the recurrence time N = 2 years (according to the calculations of the Slovak Hydrometeorological Institute).

Table 3 describes the basic characteristics of these flood waves.

Table 3. Basic information on rainfall-runoff events in the Hukava catchment

Hukava	Wave 1	Wave 2
Beginning of causal rainfall	16. 07. 2001 18:00	11. 08. 2002 15:00
End of causal rainfall	17. 07. 2001 06:00	12. 08. 2002 01:00
Peak flow (m^3/s)	2.485	3.050
Total depth of causal rainfall (mm)	81.10	18.60
Total depth of effective rainfall (mm)	8.13	9.05

Each sub-catchment was differentiated mainly according to the parameters of the slope inclination and the soil and land use. The cascades were determined with 2–3 elements with the help of GIS. In total, 10 basic sub-catchments were identified in the runoff processes, while the runoff process was identified in 26 runoff elements, i.e. in 26 sub-catchments.

In the geometric procedures of the topographic areas the attention was mainly focused on the parameters of inclination and the Manning roughness. All sub-catchments were reoriented towards rectangular elements of the cascade in the same area. This procedure is schematically represented in Figure 1 and Table 4, which both indicate the geometric parameters of each sub-catchment.

The results of the reconstruction of the observed waves are statistically assessed in Table 5 and in Figures 2 and 3. The coefficient of determination (i.e. Nash-Sutcliffe efficiency coefficient) for the best fit should be 1.0, and coefficient of variation should be 0.0 for the same.

Design flood runoff simulation

After the reconstruction of the rainfall-runoff events concerned and the calibration of the model parameters, the simulation was undertaken of the

Table 4. Scheme of the Hukava catchment (according to Figure 1)

Cascade	Area (km^2)	Plane No.	Area (km^2)	Average width (km)	Length (km)	Slope (–)
DP 11	0.418	111	0.102	3.248	0.031	0.320
		112	0.216		0.067	0.360
		113	0.100		0.031	0.195
DP 12	2.148	121	0.170	2.961	0.057	0.304
		122	0.863		0.291	0.434
		123	1.115		0.376	0.316
DP 13	0.831	131	0.377	2.426	0.155	0.286
		132	0.362		0.149	0.254
		133	0.092		0.038	0.337
DP 14	3.600	141	0.474	3.938	0.120	0.348
		142	2.081		0.528	0.317
		143	1.045		0.265	0.278
DP 15	0.146	151	0.036	0.418	0.086	0.276
		152	0.110		0.263	0.363
DP 21	0.811	211	0.153	2.733	0.056	0.280
		212	0.618		0.226	0.377
		213	0.040		0.015	0.172
DP 22	0.994	221	0.126	0.821	0.153	0.218
		222	0.479		0.583	0.350
		223	0.389		0.474	0.329
DP 23	0.598	231	0.115	1.794	0.064	0.344
		232	0.483		0.269	0.288
DP 24	0.569	241	0.455	0.379	1.200	0.161
		242	0.114		0.301	0.364
DP 25	0.680	251	0.438	1.127	0.389	0.179
		252	0.242		0.215	0.320

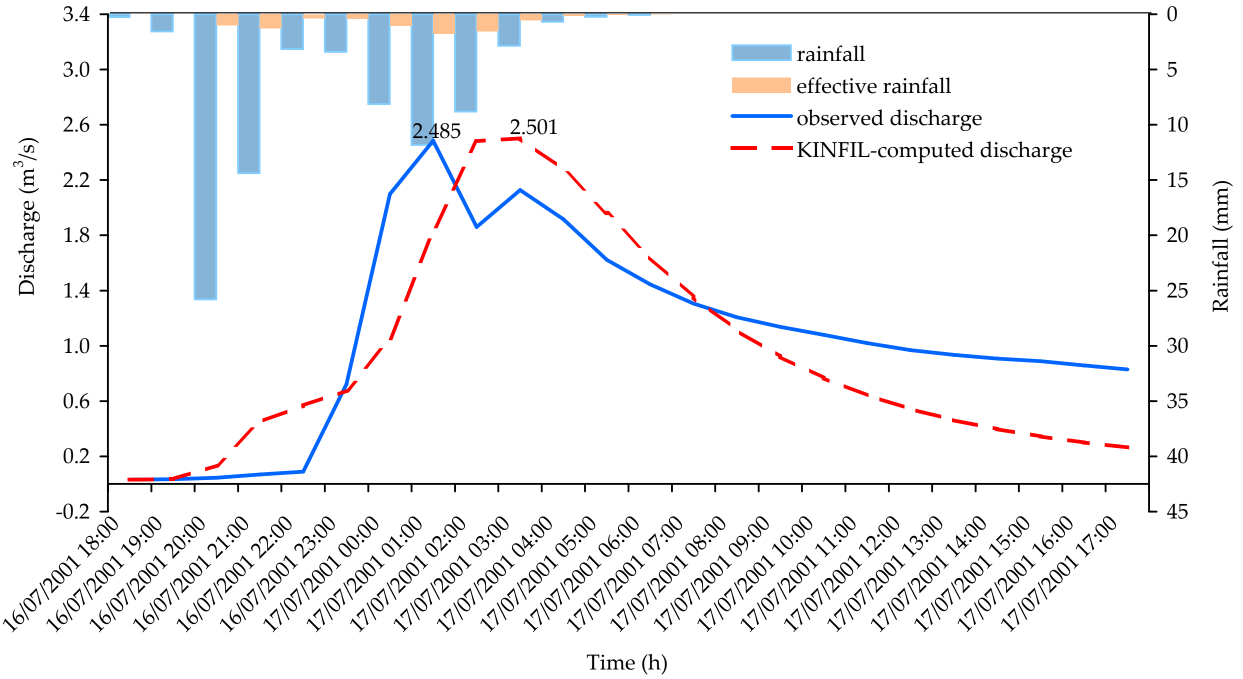

Figure 2. Measured and computed discharges of the KINFIL model, Hukava catchment, Wave 1, date of event: 16. 07. 2001

scenarios of the flood runoff from *N*-year design rainfall exceedence probability and return period p = 0.01 (N = 100 years).

The design rainfalls of various duration and exceedence probability were assessed through the method of reduction of daily maxima precipitation according to the Gumbel statistics of extremes (Šamaj *et al.* 1983). The Hriňová-Snohy precipitation measuring station in the Hukava catchment was chosen for the design rainfall computation. From the maxima daily precipitation ($P_{24,N}$), the individual rainfall depths for various duration and various return periods time precipitation ($P_{t,N}$) and the replacement equivalent of rainfall intensi-

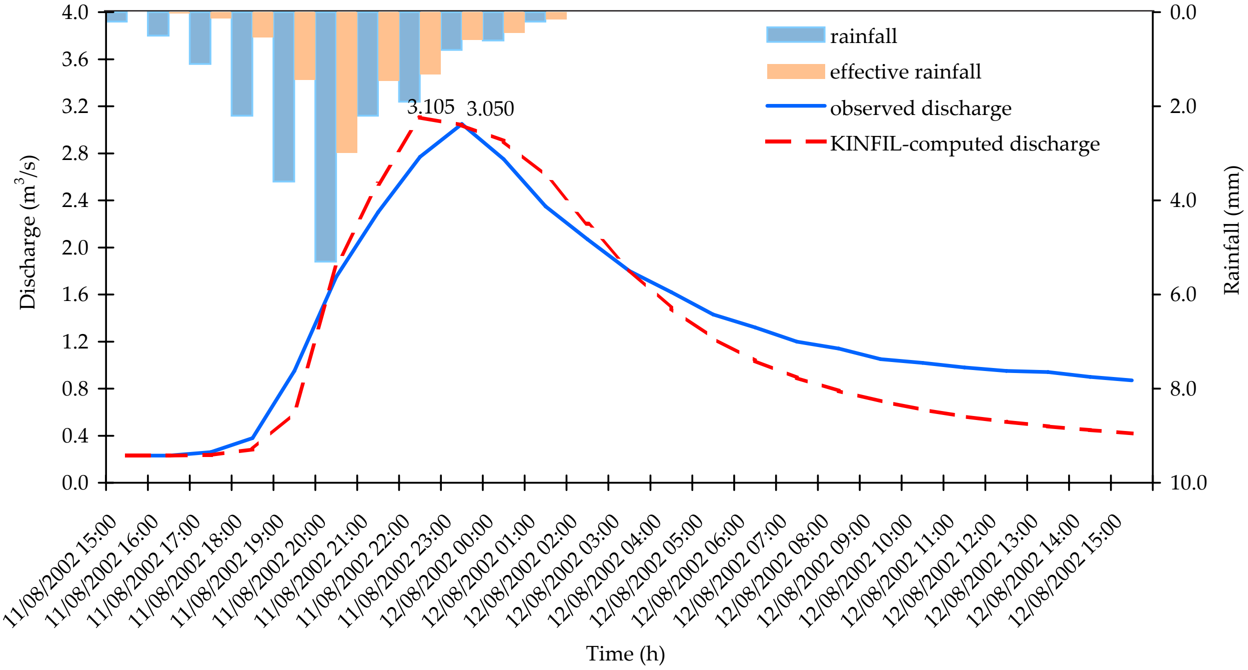

Figure 3. Measured and computed discharges of the KINFIL model, Hukava atchment, Wave 2, date of event: 11. 08. 2002

Table 5. Statistical evaluation of the correlation of measured and computed discharges

Wave No.	Coefficient of determination RE (–)	Coefficient of variation PE (–)	Error peak (%)	Error volume (%)
16. 07. 2001	0.59	0.41	–0.64	28.44
11. 08. 2002	0.87	0.21	–1.80	15.40

ties ($i_{t,N}$) were calculated according to the time-reduction method (Hrádek & Kovář 1994):

$$P_{t,N} = P_{24} \times a \times t_d^{1-c} \qquad (1)$$

$$i_{t,N} = P_{24} \times a \times t_d^{-c} \qquad (2)$$

where:

a and c – reduction coefficients of storm rainfalls and

t_d – duration of rainfall in minutes

Table 6 gives the values of the design rainfall depths $P_{t,N}$ and design intensities $i_{t,N}$ at the Hriňová-Snohy rainfall station.

Scenario simulations in an area with the modified land use

After the calibration of the model parameters, a simple scenario to change the land use was chosen. The forested areas, which cover almost 90% of the catchment area, were replaced with permanent grass, which means the reduction of the forested area to 50% and 10%, respectively. The change in the land use was simulated graphically using GIS.

During the simulation of the hypothetical land use changes, we presumed a catchment highly saturated by previous precipitation which cor-

Table 6. Design rainfall depths ($P_{t,N}$) and intensities ($i_{t,N}$) for the Hriňová-Snohy station

Hriňová-Snohy			t (min)				
N (years)	$P_{24,N}$ (mm)		30	60	90	120	300
100	100.5	$P_{t,N}$ (mm)	62.25	75.42	81.70	86.40	91.37
		$i_{t,N}$ (mm/min)	2.07	1.26	0.91	0.72	0.30

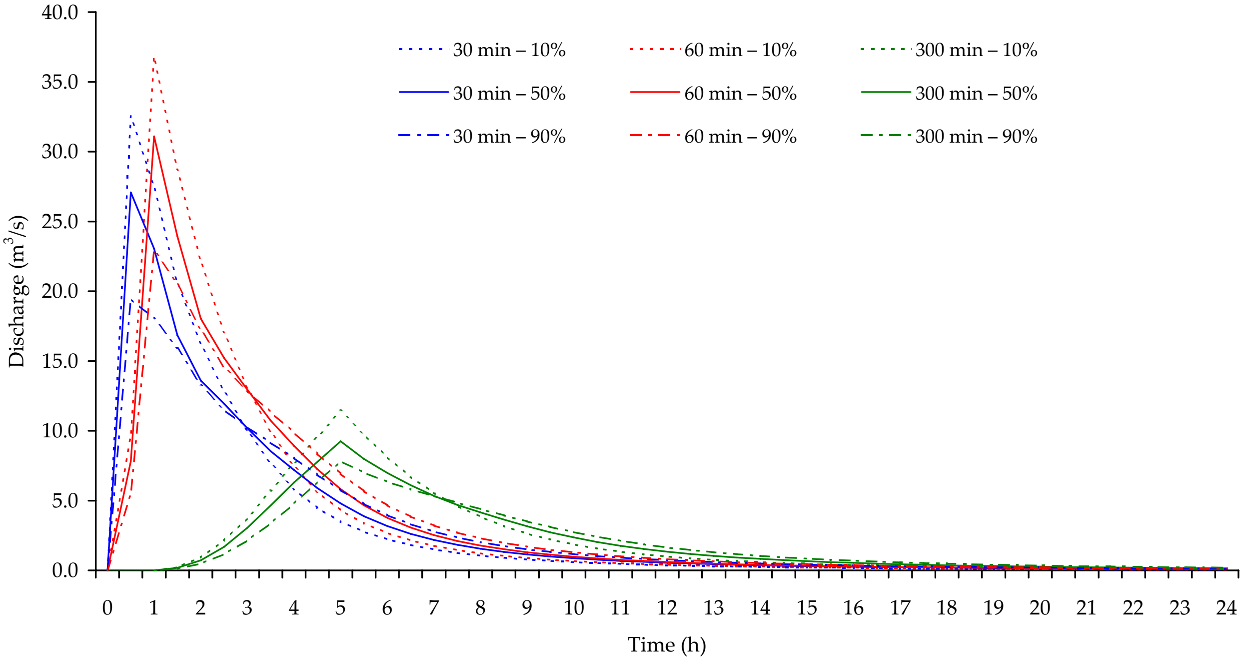

Figure 4. Scenario simulation of the land use change for design rainfall $N = 100$, $t_d = 30, 60, 300$ min

Table 7. Design discharges (m^3/s) with an event duration of t_d = 30, 60, 300 min, return period of 100 years and scenario changes of forestation

KINFIL	Design discharges (m^3/s) in the Hukava catchment, return period of 100 years (100.5 mm)		
	Rain duration (min)		
Forestation (%)	30	60	300
10	32.529	36.781	11.446
50	27.087	31.103	9.254
90	19.438	22.930	7.820

responded to the antecedent moisture condition AMC III situation, on a saturation level. The earlier computed average value of CN 55.64 (AMC II, through the traditional method U.S. SCS 1986) changed to 74.64 and, consequently, we also had the values for the situations with reduced forestation, i.e. 75.42 for the 50% forestation and 76.09 for the 10% forestation, both according to the U.S. SCS method. The results are summarised in Table 7 and Figure 4.

The changes in the land use (i.e. reduction of forestation by increase of permanent grass land) have caused an increase in the peak discharge of 26.3% (50% forestation) and 37.7% (10% forestation) for the rainfall duration of 60 min. From the results, it was further concluded that the most dangerous rainfall duration in the return period N = 100 years was about 60 min.

The advantageous way of solving infiltration by the Morel-Seytoux equations provides much more detailed catchment structuring in the infiltration and runoff areas (i.e. subcatchments). Instead of the CN-parameter(s) as an exclusive value, the KINFIL model uses the infiltration parameters K_s and S_f, geometric shape of subcatchments WID (width), LEN (length), ROUG (Manning roughness), and OBST (flow obstacles). The most sensitive parameter is undoubtedly the roughness that is usually one-order higher on the forested slopes than in the river bed.

CONCLUSION

The rainfall-runoff modelling methods enable not only the simulation of real hydrological events, but they also provide the possibilities of predicting an approximate behaviour of catchments during various extreme flood situations.

The KINFIL model, which is a physically based distributed deterministic model, is well proven for the simulation scenarios as well as for design purposes. In the connection with GIS technology, which also respects the heterogeneity of the catchment, it represents a relatively ingenious apparatus for the flood analysis. The scenario simulations of N-year discharges (in the case of the land use changes and various storm time durations) offer an appropriate tool to predict the possible flood waves – their shape, peak, and duration.

The most difficult case is usually the simulation of the design runoff from the forested areas when the microrelief can be very non-homogenous. In particular, a clear-cut surface may be also affected by the runoff paths on the steep slopes when logging. Future experience of this kind of model simulation will show whether we are going in the right direction.

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