Internationales Symposion
INTERPRAEVENT 2004 – RIVA / TRIENT

IMPACT OF LAND USE ON RAINFALL-RUNOFF REGIMES IN MOUNTAINOUS CATCHMENTS, CZECH REPUBLIC

CASE STUDY: THE RUSAVA CATCHMENT

EINFLUSS DER FLÄCHENNUTZUNG AUF DIE NIEDERSCHLAG-ABFLUSS-BEZIEHNG VON GEBIRGSEINZUGSGEBIETEN, TSCHECHIEN

FALLSTUDIE: RUSAVA EINZUGSGEBIET

Pavel Kovar[1], Jan Safar[1], Petra Simova[1]

ABSTRACT

This paper reports on a hydrological analysis aimed at estimating the extent to which land use and management changes on mountainous forested catchments can affect a direct runoff. For this purpose, the KINFIL model (version 2) was implemented on data from the Rusava experimental catchment. The model is distributed and physically based on a combination of Green-Ampt infiltration theory and the „kinematic wave“ direct runoff transformation. It uses physiographic, hydraulic parameters of the catchment and hydrometeorological data that can be determined from rainfall-runoff records, maps and other sources supported by GIS. The model was used to reconstruct two significant rainfall- runoff events recorded on the Rusava catchment, which is located in the middle part of the Morava river basin. The aim of the KINFIL model implementation was first to identify the catchment parameters through a reconstruction of the events. Then this model was used to simulate the scenario for the same rainfall-runoff events when 50% of the forest in the catchment has been removed. The simulated hydrograph peaks were about 10% to 15% higher than under existing (forested) conditions, which clearly shows that forest cover plays an important role even during intensive rainfall events.
The model was then implemented to simulate the effects of some of the hydraulic structures often used in torrent control to mitigate the consequences of floods.

Key words: Rainfall – runoff model, Land use changes, Scenario simulation

[1] Department of Land Use and Improvement, Forestry Faculty, Czech University of Agriculture Prague, Kamycka 129, 165 21 Prague 6 – Suchdol (Tel.: + 420 224 382 148, Fax: + 420 234 381 848, e-mail: Kovar@lf.czu.cz).

ZUSAMMENFASSUNG

Der Beitrag befasst sich mit einer hydrologischen Analyse mit dem Ziel, den Einfluss der Landnutzung und der Bewirtschaftungsweise bewaldeter Gebirgseinzugsgebiete auf die Höhe des direkten Abflusses zu ermitteln. Für diesen Zweck wurde im dem Modell KINFIL (Version 2) die Daten des Einzugsgebiets des Flusses Rusava implementiert. Das Modell beruht auf der Kombination der Green-Amptschen Infiltrationstheorie und der kinematischen Welle, das den direkten Abflusses simuliert. Es verwendet physiographische und hydraulische Parameter des Einzugsgebiets, sowie beobachtete hydrometeorologische Daten, Karten und weitere Daten zur Bearbeitung mittels GIS. Das Modell wurde für die Rekonstruktion von zwei bedeutenden Niederschlags-Abfluss-Ereignissen verwendet, die im Einzugsgebiet der Rusava beobachtet worden sind. Rusava gehört zum mittleren Teil des Einzugsgebiets des Flusses Morava. Der Verwendungszweck des Modells KINFIL war zunächst, die Parameter des Modells für die Rekonstruktion der gemessenen Ereignisse zu optimieren. Anschließend wurde das Modell zur Simulation derselben Niederschlags-Abfluss-Ereignisse verwendet, wobei jedoch im Szenario 50% des Waldes gerodet wurde. Die simulierten Abflussspitzen waren in diesen Fällen um 10% bis 15% höher als in der Wirklichkeit, was eindeutig belegt, welche wichtige Rolle der Waldbestand bei intensiven Niederschlägen spielt. Weiters wurde das Modell zur Simulation der Einflüsse einiger hydrotechnischen Bauten verwendet, die bei der Wildbachverbauung üblicherweise zur Verhinderung schädlicher Folgen von Hochwassern verwendet werden.

Schlüsselwörter: Niederschlags-Abfluss-Modell, Änderungen der Landnutzung, Szenario-Simulation

INTRODUCTION

The problem „how much“ can changes in land use influence rainfall-runoff relationships on small catchments is still urgent after suffering from recent floods in Central Europe. The use of hydrological models in GIS environment for better design hydrographs assessment is one rational way how to make a step to formulate answer. Such an answer on „how much“ will obviously never be unanimous and fully consensual. It is a well known fact that in normal daily water regime and land use plays more important role than in extreme floods when rainfall depth and intensity are the most significant variables. However, hydrological extremes floods in particular, are not isolated and their antecedent conditions as well as their physical process of runoff formation and propagation are, to certain extent, always influenced by land use. The paper tries to contribute to solve this complicated problem.

EXPERIMENTAL CATCHMENT

The Rusava catchment (area of 27.32 km2) is the part of the Morava river catchment, Czech Republic and it is a typical hilly-country with almost 77% forested area and the rest of permanent grassland. Arable land and urbanised areas are less than 4%. The catchment belongs geographically to the Hostyne Hills and their average rainfall is 795 mm, catchment slopes are very steep varying from 15% to 30%, some sites even more. Geologically, the Rusava catchment belongs to paleogennic „flyss“ rocks of the Carpatian belt with sandstones and clay-slates, locally also with limestones. Soils are shallow, non-homogenous, changing from sands to clays, soil types vary from cambisol to fluvisol. Topographical and land use maps of the Rusava catchment present figures G1 and G2.

Hydrometeorological data is collected and processed since the beginning of 1970‘. Rainfall measurement is recorded on the ombrographic station Holesov, runoff at the limnigraphic station Chomyz. Basic characteristics of the Rusava catchment are given in the Table 1.

Tab. 1: Basic characteristics of the Rusava catchment
Tab. 1: Charakteristik des Rusava-Einzugsgebietes

a. Hydrological soil groups [ha]						
Slope class	Slopes		Hydrological soil slope (U.S. SCS)			
	[%]	[°]	A	B	C	D
I.	0 – 1	0 – 1	-	2,6	3,0	7,3
II.	1 – 5	1 – 3	-	12,9	19,0	34,9
III.	5 – 10	3 – 6	0,1	33,9	34,0	66,7
IV.	10 – 20	6 – 11	3,8	175,3	155,2	345,9
V.	>20	>11	0,4	479,0	533,6	790,3

b. Land use		
	area [ha]	area [%]
1. arable land	58,5	2,2
2. meadows, permanent grassland	520,1	19,1
3. urbanised areas	46,8	1,7
4. water areas	3,9	0,1
5. forest	2088,3	76,8

c. Catchment characteristics		
Catchment area	27,18	[km^2]
Main channel length	8,2	[km]
Average channel slope	4,1	[%]
Average catchment slope	20,6	[%]
Minimum altitude	302	[m]
Maximum altitude	741	[m]
Average altitude	497	[m]
Forested area	76,8	[%]
Catchment perimeter	24,14	[km]

d. Species composition and age structure of forest			
Forest species			
Coniferous trees	%	**Decidous trees**	%
Spruce (*Picea abies* (L.) Karst)	27.6	Oak (*Quercus sp.*)	1.7
Fir (*Abies alba* (Mill.))	2.6	Beech (*Fagus silvatica* (L.))	13.6
Pine (*Pinus silvestris* (L.))	0.9	Maple (*Acer sp.*)	0.2
Larch (*Larix decidua* (Mill.))	0.7	Ashtree (*Fraxinus excelsior* (L.))	0.3
Others	0.4	Others	52.0
Together coniferous	32.2	Together decidous	67.8

Forest age structure %	
0 – 10	8.4.
11 – 20	6.7
21 – 40	10.7
71 – 60	24.1
61 – 80	18.6
81 – 100	19.5
Over 100	12.0

MODEL KINFIL AND GIS USED

The present version of KINFIL uses the Curve Number method [US SCS, 1986], but suppresses its weak physical background by substituting physically based infiltration theory for the common empirical CN approach. The correspondences between CN values and soil parameters, such as saturated hydraulic conductivity (K_S) and sorptivity (S_f), were derived through a correlation technique of these parameters with design rainfalls for the territory of the Czech Republic. These correspondences were used for a further simulation of some historical rainfall-runoff events, implementing the KINFIL model namely on typical mountainous catchments. The infiltration part of the model is based on the Morel-Seytoux equations [Morel-Seytoux, Verdin, 1981], based on the Green/Ampt concept distinguishing pre- and post-ponding infiltration from constant or variable rainfall.

The second basic component of the KINFIL model is a simulation of runoff. In the present version of the model, this process is based on a kinematic flow approximation. For the numerical solution, the explicit Lax-Wendroff finite difference scheme was implemented in the model. Three simulation components, a cascade of planes, converging or diverging segments and channel reaches were used to simulate the topography of a catchment. A more detailed model structure is described elsewhere [Kovar et al, 2002]. A recent innovation in the "geometrization" of a catchment is to respect consistently the hierarchy of sub-catchments in a flow direction. The traditional approach to the "geometrization" of topographical surfaces of a catchment cascade of planes, convergent or divergent segments, and to channel reaches, is represented by the KINFIL 1 model version. A newer and better physically-based approach which fully respects hydromorphological division into the river network (keeping flow direction as the first prerequisite) is introduced by KINFIL2. This version assumes that individual small sub-catchments are substituted by a system of serial/parallel cascades of planes arranged according to flow direction. However, this system should not go into too great topographic details, but puts emphasis on slopes and roughness conditions. This outline was confirmed by the KINFIL model sensitivity analysis [Kovar et al, 2002]. The KINFIL2 model version was only implemented on Rusava data in this paper.

The Geographic Information Systems (GIS) enable, among others, effective processing of spatial data (carrying out specialized analyses and syntheses). GIS analytic tools were used for modelling of the schematized topography of the catchment. This process is based on elevation and land-use layers. The digital Base map of the Czech Republic 1:10000 was used as primary input data. The land use layer with "forests", "grassland", "arable land", "water bodies", "urban areas" and "other areas" classes was vectorized according to entities of this map. The Digital Elevation Model was computed using contours included in the Base map and a layer of slope was derived from this model. Final result, boundaries of sub-catchments, was created by combination (by overlay and map algebra functions) of land use and slope layers. Subsequently, some geometric and hydraulic features (area, average width and slope, percentage of land use classes, etc.) were computed for each plot.

The TopoL and ArcView (with Spatial Analyst and 3D analyst extensions) softwares were used.

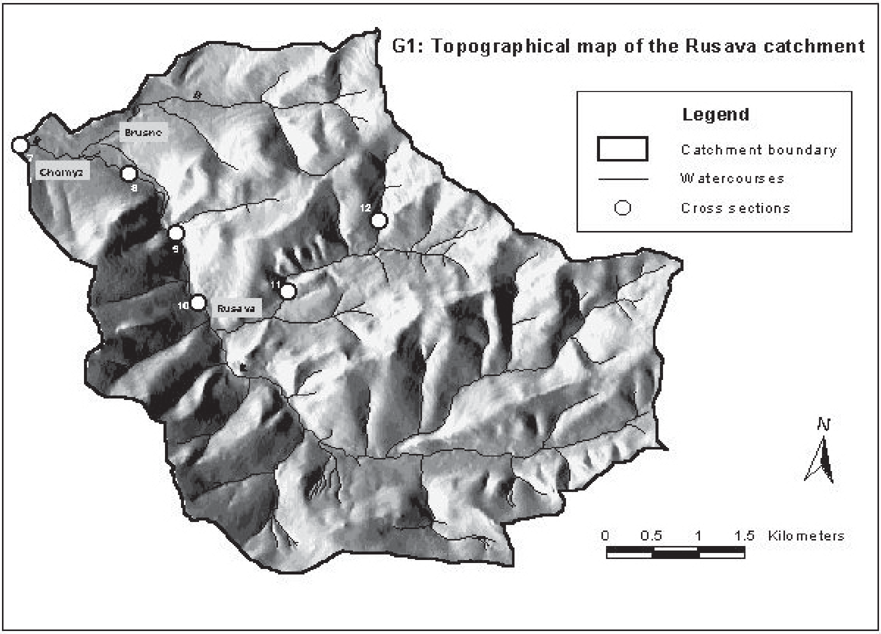

Fig1: Topografical map of the Rusava catchment **Abb. 1**: Topographische Karte des Rusava-Einzugsgebiets

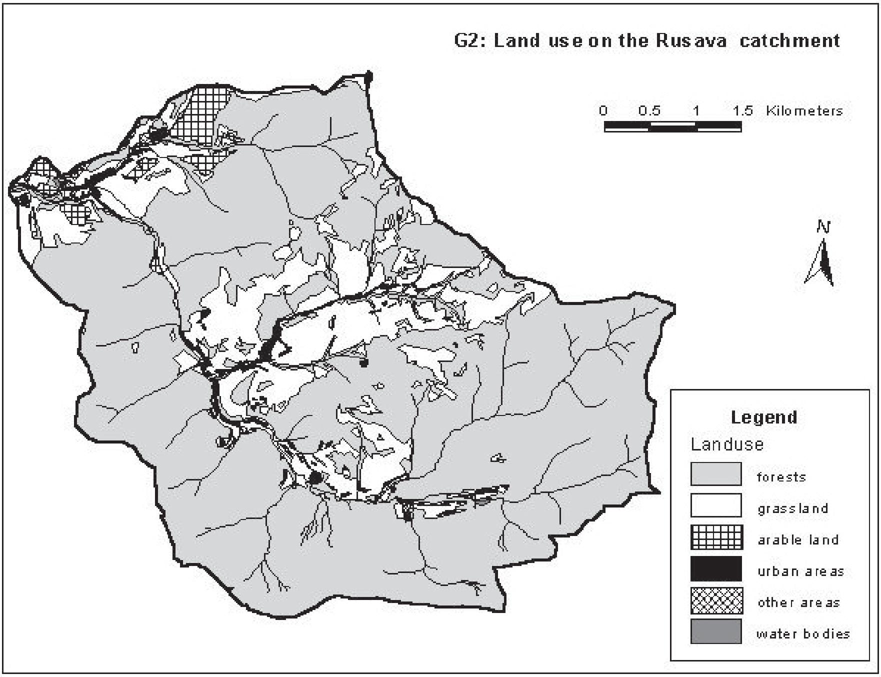

Fig2: Land use on the Rusava catchment **Abb. 2**: Landnutzung im Rusava-Einzugsgebiet

RECONSTRUCTION OF RAINFALL-RUNOFF EVENTS

The Rusava catchment was impacted by two significant torrential rainfall that both caused two flood events in June 1986 and in April 1995. Besides maps and other available materials [Kovar et al, 2002], the following data were used for the KINFIL implementation:

- Half-hourly rainfall data from the Holesov raingauge recorder
- Half-hourly runoff data from water-stage recorder at the Chomyz outlet
- Land use data, topographical and physiographical characteristics of the catchment (as shown in Table 1)
- Hydrological and soil parameters from maps and soil analysis (as shown in Table 2)
- Initial soil moisture conditions (API) were summed for five days before the causal rainfall (as shown in Table 2).

Tab. 2: Basic information on floods in June 1986 and April 1995 on Rusava catchment
Tab. 2: Grundlegende Informationen über das Hochwasser im Juni 1986 und im April 1995 im Rusava-Einzugsgebiet

Basic data	Flood wave 1	Flood wave 2
Start of causal rainfall	5.6. 1986 7,30 hr	26.4 1995 7,30hr
End of causal rainfall	5.6. 1986 18,00 hr	27.4. 1995 9,30hr
Total depth of causal rainfall	20.10 mm	31.80 mm
Total depth of effective rainfall	11.71 mm	10.95 mm
Cumulative infiltration (incl. surface retention)	8.39 mm	20.85 mm
Antecedent precipitation in previous 5 days	52.9 mm	24.5
Average coefficient satur. hydraulic conductivity K_s	1.1 mm . hr^{-1}	1.2 mm . hr^{-1}
Average storage suction factor S_f	7.1 mm	8.3 mm
Peak flow	9.64 m^3 . s^{-1}	5.815 m^3 . s

For the hydrological analysis of floods on the Rusava catchment, flood 1 (5/6 - 6/6/1986) and flood 2 (26/4 - 27/4/1995) were selected. Table 2 gives basic information about these flood events.

The KINFIL model version 2 was implemented with the GIS-elaborated schematisation given in Table 3 and Figure G3, illustrating the following approach. Borders between cascades are waterdivides. Borders within one cascade were derived from slopes respecting land use. All planes were transferred to the same area rectangulars. According to average width and real subcatchment area, the plane theoretical length was computed. All these operations were carried out using ArcView and Spatial Analyst with keeping the following principle of numbering (see Tab3 and Fig3):

1xx right part	2xx left part
x1x – x6x cascade number	xx1 – xx3 plane number in cascade (down slope)

Tab. 3: **KINFIL2**: Schematization of the Rusava catchment
Tab. 3: **KINFIL2**: Schematisierung des Rusava-Einzugsgebiets

RUSAVA (Chomyz), F = 27,177 km²											
Catch	Area	Area	Area	Av. width	Length	Slope	Landuse [%]				
No.	[km²]	No.	[km²]	[km]	[km]	[-]	Forest	Perm. grass.	Arable	Urban.	Water ar.?
DP 11	5.769	111	1.789	4.13	0.43	0.300	84	16	0	0	0
		112	2.249	4.13	0.55	0.270	96	4	0	0	0
		113	1.731	4.13	0.42	0.229	90	9	0	1	0
DP 12	6.003	121	2.348	3.84	0.61	0.296	62	38	0	0	0
		122	1.605	3.84	0.42	0.264	50	48	0	2	0
		123	2.050	3.84	0.53	0.241	38	53	0	7	1
DP 13	1.474	131	0.807	1.71	0.47	0.261	81	19	0	0	0
		132	0.667	1.71	0.39	0.272	50	44	0	6	0
DP 14	0.017	141	0.017	0.30	0.06	0.091	8	17	75	0	0
DP 15	4.144	151	2.274	3.62	0.63	0.275	87	7	6	0	0
		152	1.423	3.62	0.39	0.199	49	29	19	3	0
		153	0.447	3.62	0.12	0.155	25	59	2	14	0
DP 16	0.224	161	0.066	0.72	0.09	0.068	1	12	87	0	0
		162	0.158	0.72	0.22	0.053	20	35	25	16	3
DP 21	2.417	211	0.411	2.93	0.14	0.289	100	0	0	0	0
		212	1.293	2.93	0.44	0.275	100	0	0	0	0
		213	0.713	2.93	0.24	0.210	84	12	0	3	1
DP 22	4.022	221	1.786	2.99	0.60	0.253	100	0	0	0	0
		222	1.193	2.99	0.40	0.267	100	0	0	0	0
		223	1.043	2.99	0.35	0.203	84	12	0	4	0
DP 23	1.640	231	0.924	1.35	0.68	0.302	100	0	0	0	0
		232	0.717	1.35	0.53	0.310	93	7	0	0	0
DP 24	0.331	241	0.201	0.31	0.65	0.296	100	0	0	0	0
		242	0.130	0.31	0.42	0.397	100	0	0	0	0
DP 25	0.475	251	0.311	1.29	0.24	0.329	78	12	10	0	0
		252	0.164	1.29	0.13	0.232	77	15	7	1	0
DP 26	0.662	261	0.153	0.72	0.21	0.315	100	0	0	0	0
		262	0.205	0.72	0.28	0.207	78	22	0	0	0
		263	0.304	0.72	0.42	0.130	18	69	8	5	0

The results were given in the form of graphs including ordinates of rainfall, observed and computed (reconstructed) runoff in Figures G4 and G5. ArcView and Spatial Analyst software were used to interpolate the digital elevation model (DEM) from the altitude contour lines (map scale 1:10 000). They efficiently facilitated determination of the drainage pattern, re-arrangement of the sub-catchment into the cascade of planes, and derivation of the runoff characteristics (slopes, land use, roughness, etc.) particularly for KINFIL 2. The goodness of fit of both observed and computed discharges provides Table 4. This table shows the quality of the fit of the KINFIL 2 results expressed in the form of a statistical analysis. The pair-values of the observed and computed discharge ordinates were evaluated by the coefficient of determination RE (i.e., efficiency coefficient) and the coefficient of variation PE (WMO, 1992). For the best fit RE $\rightarrow$ 1.0 and PE $\rightarrow$ 0 (both RE and PE are dimensionless). The comparison of the peaks is expressed by the peak errors PEAK (%). Table 4 shows that implementation of the KINFIL2 model provides satisfactory results.

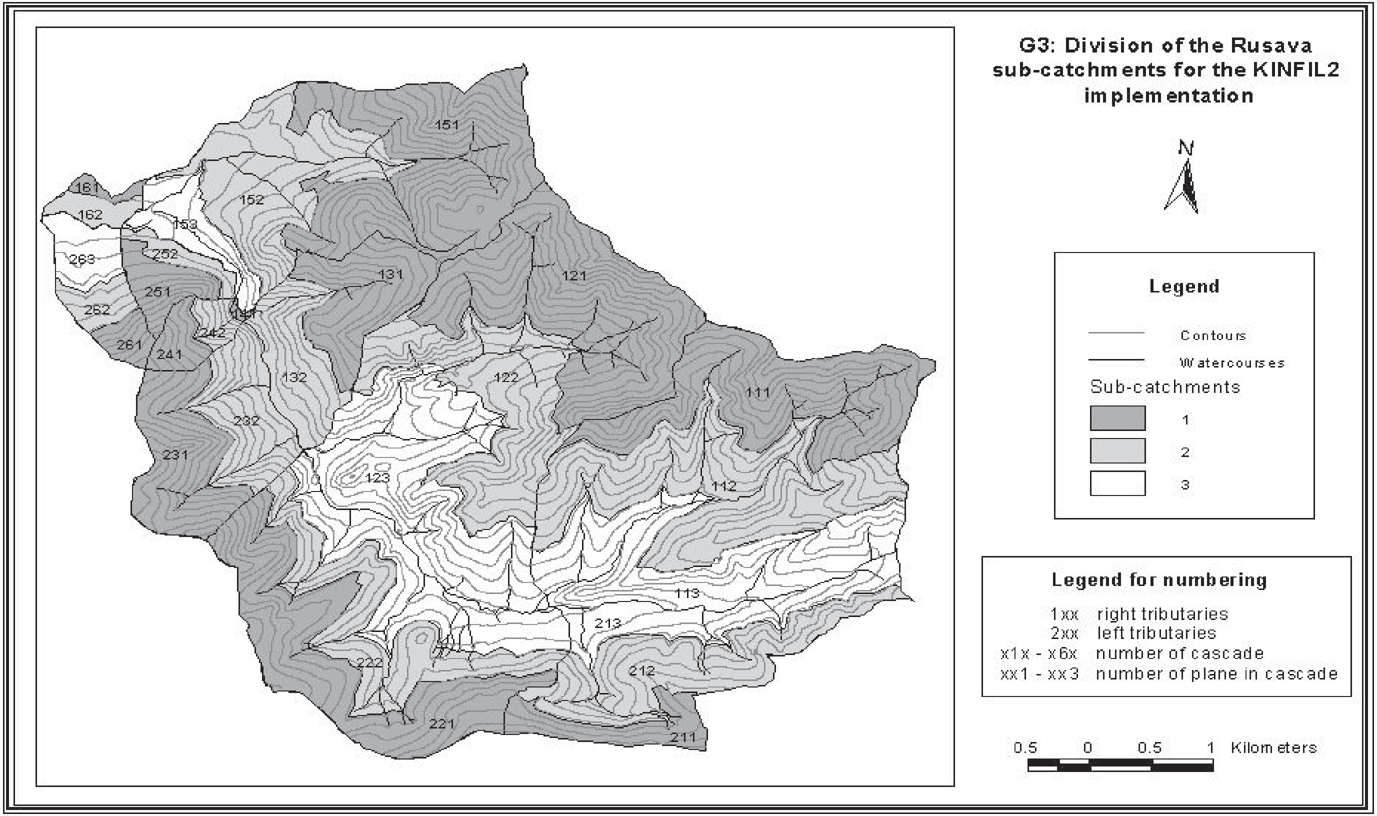

Fig3: Rusava Runoff pattern for KINFIL2 schematization

Abb3: Abflussschema des Rusava-Einzugsgebiets für das Modell KINFIL2

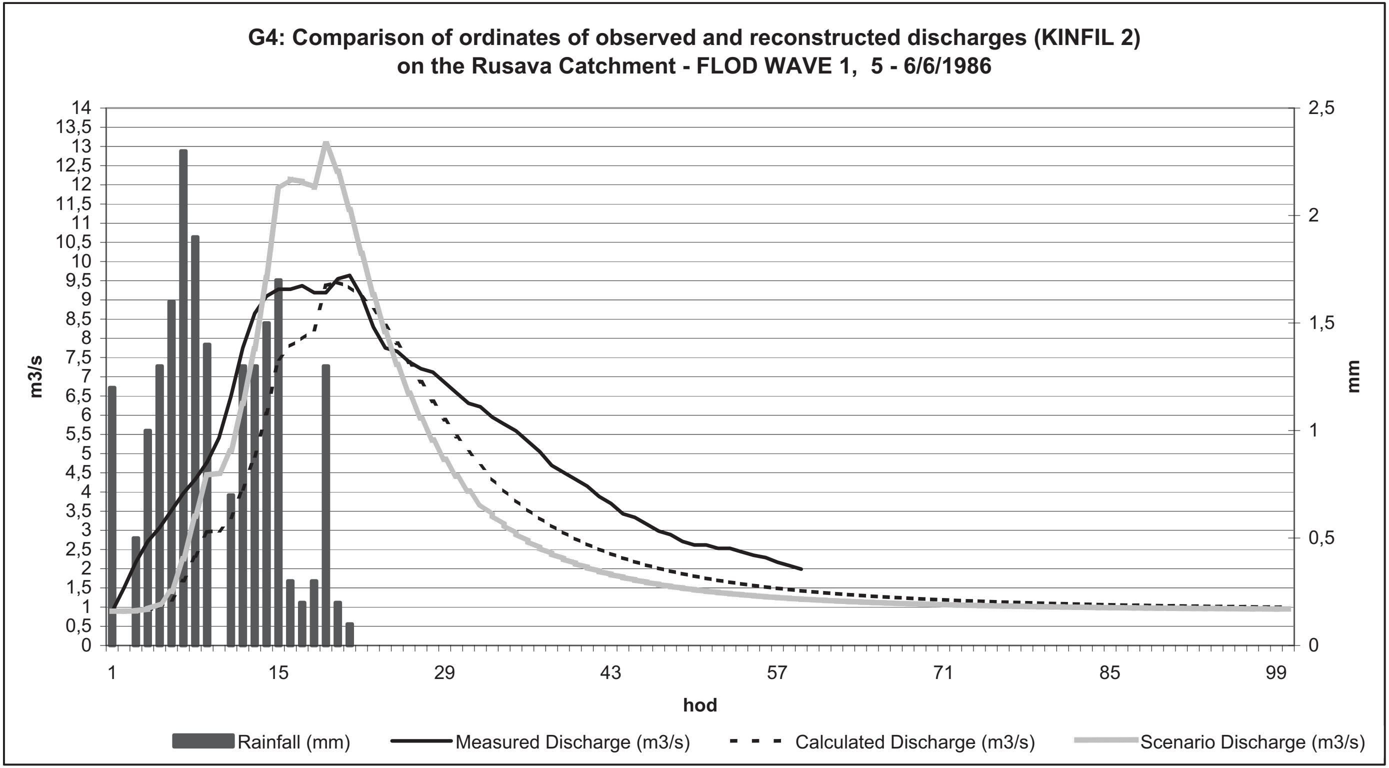

Fig4: Comparison of ordinates of observed and reconstructed discharges (KINFIL 2) on the Rusava Catchment - FLOD WAVE 1, 5 - 6/6/1986
Abb4: Vergleich der Ordinaten der beobachteten und berechneten Durchflüsse (KINFIL 2) im Rusava-Einzugsgebiet – Flutwelle 1, 5-6-/6/1986

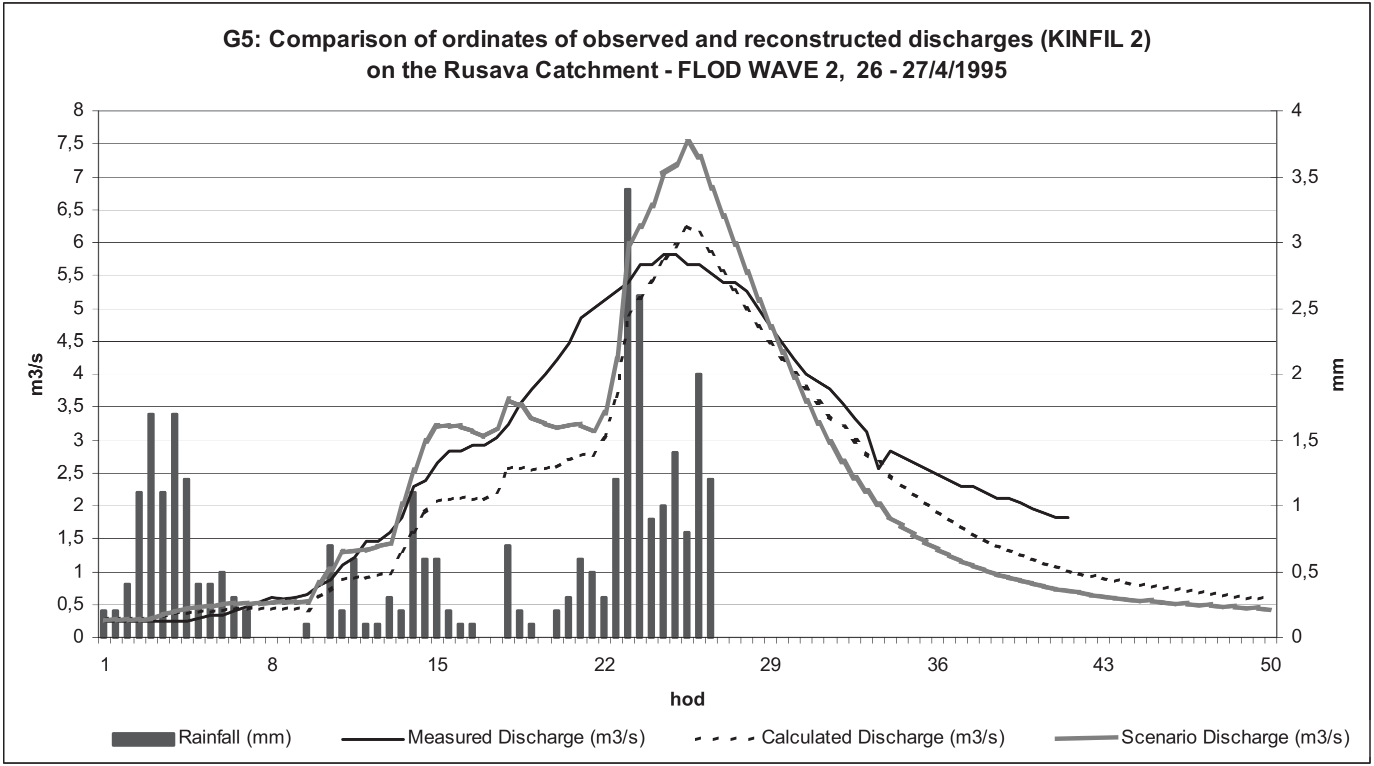

Fig5: Comparison of ordinates of observed and reconstructed discharges (KINFIL 2) on the Rusava Catchment - FLOD WAVE 2, 26 - 27/4/1995
Abb5: Vergleich der Ordinaten der beobachteten und berechneten Durchflüsse (KINFIL 2) im Rusava-Einzugsgebiet – Flutwelle 2, 26-27/4/1995

Tab. 4: Godness of fit observed and computed discharges
Tab. 4: Maß der Übereinstimmung der beobachteten und berechneten Durchflüsse

Wave No.: date	Coeficient of determination RE (-)	Coeficient of variation PE (-)	Peak error PEAK (%)
Wave 1: 5-6/6/1986	0.72	0.31	2.76
Wave 2.: 26-27/4/1995	0.84	0.26	-7.54

SCENARIO SIMULATION

After reconstruction of two historical events a simple scenario was conceived. The scenario idea was to cut of the 50% catchment area covered by forest over 60 years old mainly on slopes higher than 20%. These changes are reflected by the following model KINFIL parameter changes in Table 5. These three parameter values: Curve Number CN, Interception, limit WIC and Manning roughness n were alternated.

Tab. 5: Scenario simulation – new parameters assessment
Tab. 5: Szenario-Simulationen – Festlegung neuer Parameter

KINFIL Parameter	Calibrated parameter value	Scenario parameter value
Curve Number CN_{II}	CN = 74.0	CN = 77.0
Interception rimit WIC	WIC = 2.0 mm	WIC = 1.2 mm
Manning roughness n	n < 0.2 , 0.4 >	n < 0.2 , 0.3 >

Scenario simulations were drawn for both historical events (wave 1: 5-6/6/1986 and wave 2.: 26-27/4/1995) on figures G4 and G5. Infiltration parameters: saturated hydraulic conductivity K_s and storage suction factor S_f were derived from CN values, Manning roughness values were taken from literature [Chow et al., 1998]. Computed scenario-results clearly show the increased peak discharges. Simulated peaks are significantly higher as the consequence of deforestation of the cathment Rusava.

DISCUSSION AND CONCLUSIONS

The aim of this paper was to present the KINFIL model for reconstructing significant rainfall-runoff events and for improving the effective assistance of GIS tools in the KINFIL model for catchment parameter analysis and subsequently for process modelling. A clear visualization of the spatial parameter variability and drainage pattern can also be performed well by interconnecting the hydrological model with ARC/INFO. The quality of the fit of the observed and computed discharge pairs by the KINFIL model is not absolutely convincing, however the Holesov rain gauge lies outside the catchment and does not provide highly reliable rainfall data. Also, interconnection of the KINFIL short-term event model with the WBCM-5 water balance short-term event model is beneficial, namely concerning initial soil moisture conditions (SMD) and antecedent precipitation index values (API). This can easily be done even “on-line” regime in a daily step.

Although it was established, after summarizing experiences from the floods of 1997 and 2002 in Central Europe, that the huge depth and intensity of the rainfall were the main factors in the formation of the flood situation, change of land use can distinctly influence direct runoff [Kovar, Svitak, 1994], [Kovar, Pech, 1996]. Our scenario model analyses provide evidence of this. Good and diversified land use (with a high percentage of forest and permanent grassland) can have a positive influence on direct runoff formation to increase infiltration and thus the retention capacity of a catchment.

The KINFIL modelling technique has demonstrated good applicability and its successful use is confirmed.

LITERATURE

CHOW W. T., MAIDMENT D. R., MAYS L. W. (1998): Applied hydrology, McGraw-Hill, USA, 572 pp

KOVAR P., SVITAK M. (1994): A Possibility of Modelling Direct Runoff on Small Catchments using GIS. Zeitschrift fuer Kulturtechnik und Landentwicklung.35, pp. 374-381, Hamburg, SRN

KOVAR P., PECH P. (1996): Modelling Floods with Respect of Changes in Land Use on Small Catchments. Proceedings INTERPRAEVENT 96, Band 4, pp. 91-100, GaPa, SRN

KOVAR P., CUDLIN P., HERMAN M., ZEMEK F., KORYTAR M., (2002): Analysis of Flood Events on Small River Catchments Using the KINFIL Model. J. Hydrol. Hydromech., 50, 2002, 2, pp. 157 – 171

MOREL-SEYTOUX H. J. VERDIN, J. P. (1981): Extension of the Soil Conservation Service. Rainfall-Runoff Methodology for Ungauged Watersheds - Colorado, USA.

US SCS (1986): Urban hydrology for small watersheds. U.S. Soil Conservation. Technical Release 55 (13). Service, Washington.

WMO (1992): Simulated real-time intercomparison of hydrological models. WMO No. 779, Operational Hydrology No. 38, 1992, Geneva.