Comparison Between Simulations of Significant Rainfall-runoff Events Generated by a SCS-CN-based Model and Measured Data in Three Subcatchments with Different Land Use

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Abstract

The purpose of this paper is to present the findings obtained by modelling rainfall-runoff processes in Kopaninský tok subcatchments using the HydroCAD hydrologic/hydraulic model. The model is based on the runoff curve method developed primarily to estimate the volume and height of the culmination wave. Numerical simulations of selected important rainfall-runoff events in three subcatchments with different land uses were performed. The inclusion criterion for events was measured daily rainfall total > 30 mm. We compared the measured and simulated flow rates and runoff volumes, and performed sensitivity analysis of selected main parameters (CN values, initial abstraction, total and intensity of rainfall) on which the runoff curve method is based. The results obtained indicate that caution is necessary when processing and interpreting results obtained by simple hydrologic tools based on the runoff curve method.

Keywords: CN method, rainfall-runoff process, land use, subcatchment

Introduction

Effects of land use and research into the relationships between ground cover vegetation and water and thermal circulation in nature become the focus of considerable interest of ecologists, particularly with an emphasis on aqueous ecosystems and biodiversity (Turner et al. 2001). A change in land use in a catchment may have a particularly significant impact on the catchment's water storage because it affects hydrological processes such as infiltration, ground water accumulation and generation of individual catchment runoff components

(Lin et al. 2007). According to Fohrer et al. (2001), a change in land use has a direct impact on hydrologic processes because of its connection with evapotranspiration on the one hand, and, on the other hand, because of the enormous influence of the degree and type of vegetation cover on surface runoff.

We decided to use the runoff curve number (CN) method (Janeček 1992; 1998) for the analysis of the rainfall-runoff patterns in the catchment. The runoff curve number – or simply CN – method used for determining direct runoff from rainfall events is a relatively well-established method in our hydrologic and landscape engineering (Janeček and Kovář 2010). The method defines catchment retention potential with respect to hydrologic properties of the soil (infiltration etc.), the initial soil saturation, type of land use, effect of vegetation cover infiltration (Hrádek and Kuřík 2004). The weakness of the model is that it does not describe spatial and temporal variability, and that its applicability is limited to the modelling of storm event losses (Janeček and Kovář 2010). Because it is used so frequently, the CN method is constantly subject to detailed research (in the Czech Republic by, e.g. Podhrázská and Toman (2002); Šercl (2007) and Malý (2010)).

The basic data input to the CN model is the rainfall total over a certain period of time, with the assumption of uniform distribution over the area. The rainfall volume is transformed to direct runoff volume using runoff curve numbers. Runoff curve numbers are tabulated according to:

- hydrological properties of soil divided into 4 groups (A, B, C, D) according to minimum properties of water infiltration into soil without any cover following long-term saturation,
- use of land, vegetative cover, type of land cultivation and soil conservation measures
- antecedent soil moisture conditions determined on the basis of total rainfall over a 5 day period preceding the storm event, or the Index of Preceding Precipitations in three degrees (Toman 1999; Hrádek and Kuřík 2004).

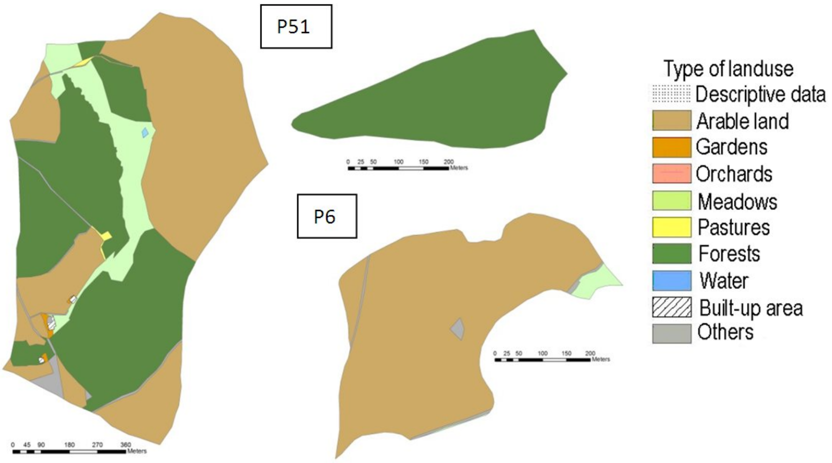
The CM-based HydroCAD model used in the present study allows for a reconstruction of important rainfall-runoff situations and, on the basis of a comparison of a generated and a measured hydrograph, to first optimize numerical simulation parameters and then to analyze runoff processes as such.

Material and Methods

Material

The experimental Kopaninský tok catchment has been monitored by the Research Institute of Soil and Water Conservation since 1985. The catchment is located in the former administrative district of Pelhřimov, and, from the geomorphological point of view, belongs to the Bohemian-Moravian Highlands area. The basic characteristics of the catchment are given in Tab. 1. The geological basement consists of paragneiss, and the dominant soil type is Cambisiol. Average annual precipitation is 715 mm, and average annual temperature is 7 °C. Of the Kopaninský tok subcatchments monitored, three subcatchments with different land use patterns (P51 – forest, P6 – arable land, P32 – mixed use) were selected (see Fig. 1). Individual subcatchments were from several hectares to several dozen hectares in size (see Tab. 1). Soil properties data were obtained from BPEJ (Land valuation System) data, forest soils data from measurements performed for the NAZV QH82095 project, and information on land use patterns from real estate cadastre maps (supplemented with data on crops cultivated in different vegetation seasons).

Fig. 1: Land use patterns in subcatchments monitored



Tab. 1: Land use patterns in subcatchments studied

Land use category	P32		P6		P51	
	Size [ha]	Size [%]	Size [ha]	Size [%]	Size [ha]	Size [%]
Arable land	36.00	46.08	15.08	95.87		
Gardens	0.16	0.21				
Meadows	7.19	9.44	0.38	2.42		
Pastures	0.19	0.25				
Forest	32.10	42.14			7.12	100.00
Water	0.04	0.05				
Built-up areas	0.13	0.17				
Others	1.27	1.67	0.27	1.72		
Total size	**76.18**	**100.00**	**15.73**	**100.00**	**7.12**	**100.00**

Methods

Input data:
Flow rate was measured continuously on Thompson's weirs fitted with ultrasonic water level sensors upstream of the spillway. The data were divided (hydrograph segmentation) into two water runoff components to determine the height and volume of the direct runoff and the base flow. The data are used to compare success of the model's simulations.

Levels of rainfall are measured at three precipitation gauge stations – at one of them continuously, and at the other two discretely (daily precipitation totals are read manually). Continuous data are the basis for time distribution of rainfall events, totals from the remaining stations serve to correct precipitation data within the catchment area. For processing, we chose important rainfall-runoff events, i.e. those with daily totals in excess of 30 mm. To prepare simulations, we used the 2004 – 2010 period where we selected 6 rainfall-runoff events. For each event, the height of total rainfall and the Antecedent Precipitation Index (API5) were determined (see Tab. 2). API5 summary is given in Tab. 3.

Tab. 2: Overview of selected rainfall-runoff events

Event	Duration(hrs)	Total (mm)	API5
1	3	73	I
2	1.75	66	I
3	2	56	I
4	17	68	I
5	25	71	II
6	26	65	I

Tab. 3: Antecedent precipitations

API group	Total rainfall in 5 days (mm)
	Vegetation season
I	< 36
II	36–53
III	> 53

Source: (Podhrázská and Toman 2002)

Numerical modelling
Peak flow rates and direct runoff volumes were calculated using HydroCAD (Computer Aided Design) software, a system for the modelling of hydrology and hydraulics of storm rain flow rates. The system is based mainly on the runoff curve method developed by the SCS/NRCS (Soil Conservation System), an agency of the US Department of Agriculture. The runoff curve model was developed to help estimate runoff patterns with the use of schematized data (CN, initial abstractions, etc.) at catchments where only minimum information about the area exist - the values were verified at a specific site and using concrete data, and optimum parameter values for the conditions given were looked for.

The model was adjusted to the situation in individual subcatchments to suit ground cover, humidity and precipitation patterns for individual rainfall-runoff events as much as possible. After the runoff pattern was selected, runoff calculation methods, methods of transformation, rainfall characteristics specifications were determined and the unit hydrograph was chosen.

Results and discussion

Using the model, peak discharge values and direct runoff volumes were calculated for individual rainfall-runoff events with the model set at recommended CN and λ (initial abstraction value – sum of infiltration, surface retention and interception) values. Both were subsequently compared with measured data. Model adjustment success is expressed by the fit between the simulated and the measured values as shown in Tabs 4 and 5. The best fit between the simulated and the measured values was in the forested catchment (P51) and the catchment with mixed use of land (P6 – API I). Even there, however, simulated values were 2 to 6 times the measured values. In the case of the catchment with predominantly arable land and that with mixed land use (P6 – API II), the model overestimated the characteristics monitored by up to an order of magnitude in certain situations, with flow rates and volumes being overestimated particularly in the case of storm rains (see events 1 to 3). Data of event 2 in catchment P6 and event 4 in catchment P51 were not included in evaluation due to complications during flow rate measurement (indicated by an “x” in the table).

Tab. 4: The ratio between simulated values of peak flow rates and direct runoff volumes to measured values in subcatchments P32 and P51 – API II

Event	**P32**		**P51**	
	Flow rate	**Volume**	**Flow rate**	**Volume**
1	10.8	3.9	5.9	5.3
2	2.4	3.9	2.0	3.3
3	24.6	5.1	3.6	3.2
4	4.1	3.7	x	x
5	1.7	4.7	1.9	1.9
6	4.1	5.0	5.3	2.6

Tab. 5: The ratio between simulated values of peak flow rates and direct runoff volumes to measured values in subcatchments P6 – API II and API I

Event	**P6 – II**		**P6 – I**	
	Flow rate	**Volume**	**Flow rate**	**Volume**
1	12.0	26.0	3.8	6.9
2	x	x	x	x
3	13.0	13.1	2.1	1.8
4	12.2	10.5	5.1	2.4
5	2.9	9.7	1.3	2.5
6	3.0	5.8	1.2	1.9

For subcatchments P32 and P51, the HydroCAD model with the API I setting simulates zero direct runoff. For that reason, the only table for that subcatchment is that with simulations of a model with an API II setting (see Tab. 6). The optimum λ values for those events in the catchment with mixed land use (P32) are in the range of 0.32 to 0.47, and 0.22 - 0.29 for the forested catchment (P51). While optimum λ values for events 1 to 3 (storm rain events) show considerable fluctuations, for long-term frontal precipitation events they are around 0.40 and 0.26 in subcatchments P32 and P51, respectively.

Tab. 6: Optimum λ values based on a comparison between simulated and measured peak flow rate values and direct runoff volumes in subcatchments P32 and P51 – API II

Event	**P32**		**P51**	
	Flow rate	**Volume**	**Flow rate**	**Volume**
1	0.47	0.40	0.29	0.29
2	0.39	0.33	0.24	0.25
3	0.32	0.36	0.22	0.22
4	0.44	0.42	x	x
5	0.37	0.40	0.27	0.24
6	0.43	0.37	0.28	0.25

For subcatchment P6 (predominantly arable land), the HydroCAD model simulates non-zero direct runoff for both API II and API I settings. Optimum λ values for those events are 0.60 to 0.83 and 0.23 – 0.31 for API II and API I, respectively (see Tab. 7).

Tab. 7: Optimum λ values based on a comparison between simulated and measured peak flow rate values and direct runoff volumes in subcatchments P6 – a comparison between values for API II and API I

Event	**P6 – II**		**P6 – I**	
	Flow rate	**Volume**	**Flow rate**	**Volume**
1	0.81	0.84	0.31	0.32
2	x	x	x	x
3	0.61	0.60	0.24	0.23
4	0.83	0.71	0.30	0.27
5	0.77	0.74	0.25	0.28
6	0.71	0.67	0.23	0.25

The threshold CN values for simulation of non-zero direct runoff for individual subcatchments and rain events were also ascertained. Ranging from 42 to 48, the values showed no major differences between events or subcatchments. They are thus above minimum CN values from the table of Average Runoff Curve Numbers – CN (Janeček 2007), where values given for permanent crops (forests, bushes, meadows, gardens) are below 40.

Table 8. Threshold CN values of selected rainfall-runoff patterns

Event	**P32 – CN**	**P6 – CN**	**P51 – CN**
1	42	42	42
2	44	x	44
3	48	48	48
4	43	43	x
5	42	42	43
6	44	44	45

Conclusions

The analysis performed leads to the following conclusions which indicate that caution is necessary when processing and interpreting results obtained using simple hydrologic tools based on the runoff curve method:

- For API5 = I conditions (less than 36 mm over the previous 5 days), which corresponds to real conditions at 5 out of 6 of the events investigated, the model for a forested catchment and for a mixed land use catchment simulated, contrary to reality, zero direct runoff.

- When recommended CN values, initial abstraction and IPS5 for design purposes were used, simulated peak flow rates and direct runoff volumes exceeded measured values 2 to 6 times (forested catchment), 2 to 25 times (catchment with mixed land use) and 3 to 26 times (arable land catchment).

- Although the recommended initial abstraction value for design purposes is $\lambda = 20$, a good fit between measured and simulated data was reached with λ in the 22 – 29 range for the forested catchment, in the 32 – 47 range for the catchment with mixed land use and in the 60 – 83 range for the arable land catchment.

- Threshold CN values for non-zero direct runoff simulations were in the 42 – 48 range and showed no major differences between individual subcatchments and rainfall events.

- The fit between measured data and simulations was better in the case of direct runoff volumes than in peak flow rate values.

- Spatial and temporal variability of rainfall data has a fundamental effect on modelling results even in catchments of small size like ours and with a dense network of precipitation gauge stations. The model can produce better flow rate simulations for long-term frontal precipitations than for storm rains events with irregular precipitation pattern – for further analysis it seems desirable to correct precipitation distributions using radar images of selected rainfall events.

The above conclusions are probably affected by the model's original purpose, i.e. to serve for the design of protective measures in the catchment. If the model is used for reconstruction purposes, some parameters such as the λ value should be adjusted (e.g. the λ value should be increased, which will in effect generate lower surface runoff compared with probably implicit "better safety" of a model, which, for that purpose, generates a proportionally higher runoff).

A better interpretation of results would require that a larger number of important rainfall-runoff events be evaluated. As of now, however, all the events with totals $>$ 30 mm that occurred in the catchments during the period investigated (i.e. 2004 – 2010) and that can be meaningfully simulated with the HydroCAD model, have already been used.

The HydroCAD model used does not offer an implicit possibility of including the effect of draining on hydrological processes during important rainfall-runoff events. As a next step in the study of the above issues, we will therefore strive at quantifying that effect and incorporating it into the CN method (and the HydroCAD model).

Acknowledgement

This contribution was supported by the Research Programme of the Ministry of Agriculture of the Czech Republic, No. MZE 0002704902 and by the Czech Ministry of Agriculture as a R&D project NAZV QH 82095.

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Srovnání významných srážko-odtokových jevů simulovaných pomocí modelu SCS-CN s daty naměřenými na třech pozemcích s různým využitím půdy

Cílem tohoto článku je představit zjištění získaná modelováním srážko-odtokových jevů na povodí Kopaninského toku pomocí hydrologicko/hydraulického modelu HydroCAD. Model je založen na metodě odtokových křivek, která slouží především k odhadu objemu a výšky kulminační vlny. Byly provedeny numerické simulace vybraných významných srážko-odtokových událostí ve třech subpovodích s různým využitím půdy. Kritériem pro zahrnutí srážkové události byl celkový denní úhrn srážek > 30 mm. Měřené a simulované průtoky a objemy odtoku byly porovnány, byla provedena citlivostní analýza vybraných hlavních parametrů (hodnoty CN, počáteční ztráta, úhrn a intenzita srážek), na jejichž základě je metoda CN založena. Získané výsledky naznačují, že je nutná obezřetnost při zpracování a interpretaci výsledků získaných pomocí jednoduchých hydrologických nástrojů založených na metodě odtokové křivky.

Klíčová slova: metoda CN, srážko-odtokové procesy, využití půdy, subpovodí

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ŽLÁBEK, P., M. KAPLICKÁ and Z. KULHAVÝ. Comparison Between Simulations of Significant Rainfall-runoff Events Generated by a SCS-CN-based Model and Measured Data in Three Subcatchments with Different Land Use. *Littera Scripta.* 2012, **5**(1), 275–284. ISSN 1802-503X.
