Comparison of Rainfall-Runoff Models for Design Discharge Assessment in a Small Ungauged Catchment

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Abstract

Vaššová D. (2013): **Comparison of rainfall-runoff models for design discharge assessment in a small ungauged catchment.** Soil & Water Res., **8**: 26–33.

Design discharges in a small experimental catchment in Žarošice (Czech Republic) were evaluated using various methods for peak discharge assessment applying 24-h storm rainfalls reduced to short duration. Rainfall-runoff models HEC-HMS based on standard Natural Resources Conservation Service hydrologic methods and KINFIL, which combines the Morel-Seytoux infiltration and kinematic wave direct runoff transformation, were used to compute runoff hydrographs. The approach of technical standard and Froehlich's method determined the peak discharges only. The aim of this study was to assess the ability of these methods to predict design peak discharge in comparison with the data obtained from the Czech Hydrometeorological Institute (CHMI), which is the authority for providing hydrological data in the Czech Republic. The results demonstrate that the peak discharges computed by Froehlich's method are mostly closest to the data provided by CHMI. For the 100-year flood, HEC-HMS based on the Curve Number method showed the best agreement.

Keywords: Curve Number; design rainfall; peak discharge

Estimation of flood magnitudes is the main task for development of management strategies that reduce the impact of flooding. In some situations, only the peak discharge from a catchment may be required, e.g. for a design of stream bank protection works. Various approaches have been used for estimation of flood peak discharges with different return periods. In stationary catchments with sufficiently long gauge records, the design discharges can be obtained from the statistical frequency analysis of streamflow data. Design discharges for ungauged or non-stationary catchments can be obtained from prediction methods based on catchment descriptors, like area, slope, land use, and other physical or climatic characteristics. For a description of catchment properties, the concept of Curve Numbers of US Natural Resources Conservation Service (NRCS) is still widely used (Bulygina *et al.* 2011; White *et al.* 2011; Buchanan *et al.* 2012; Soulis & Valiantzas 2012).

Hydrological models attempt to simulate the complex hydrological processes that lead to the transformation of rainfall into runoff, with varying degree of abstraction from these physical processes. These models have been applied to simulate a rainfall-runoff process in gauged catchments successfully for over 40 years, but the representation of flow in ungauged catchments remains a

challenge. To overcome the difficulties, physically based models are used, in which catchment physical properties can be used as model parameters. In the case of small catchments, we can assume that the amount of data needed for reliable simulation of physical processes is not the limitation factor for the application of physically based models such as MIKE SHE (Refsgaard & Storm 1995), CASC2D (Rojas *et al.* 2003), Kineros2 (AlQurashi *et al.* 2008) or SHETRAN (Ewen *et al.* 2000) like in the large catchments (Beven 1989). Using this type of models, design rainfalls of different return period are input to a model. The peak discharge of the obtained hydrograph is assumed to be design discharge with the same return period as its corresponding input design rainfall (Froehlich 2012).

The aim of this study is to carry out a comparative study of design peak discharges assessed for small catchments by different methods. In this paper data obtained by four different approaches are compared with peak discharges provided officially by the Czech Hydrometeorological Institute (CHMI).

MATERIAL AND METHODS

Design rainfalls. In this study, the design-storm approach is used. It is assumed that *N*-year rainfall causes *N*-year flood wave (Hrádek 1988; Guo 2001; Guo & Markus 2011). Design rainfalls with *N*-year return period and various durations *t* were computed using the DES_RAIN program (Vaššová & Kovář 2011) for maximal one-day rainfalls derived from long-term observations by the relationship in Eq. (1) (Hrádek & Kovář 1994; Kovář *et al.* 2011):

$$P_{t,N} = P_{1d,N} \times k \times t^{1-c} \quad (1)$$

where:

$P_{t,N}$ – design rainfall depth (mm) with return period N and duration t

$P_{1d,N}$ – maximal one-day rainfall depth (mm)

k, c – regional parameters

For the study rainfalls with return period N = 2, 5, 10, 20, 50 and 100 years and duration from 10 up to 120 min were applied. Design rainfalls for the study catchment (Figure 1) were derived from observed rainfalls at Kyjov rain gauge (Šamaj *et al.* 1983), which is about 13 km SE of the study catchment.

Methods for peak discharge assessment. Results of two rainfall-runoff models were compared. The first one is HEC-HMS (USACE 2000), in which NRCS Curve Number (CN) method (NRCS 1986) was chosen as an infiltration part of the model and direct runoff was transformed by US SCS unit hydrograph (UH), due to low data requirement. Excess precipitation P_e is described in this study as the function in Eq. (2) (NRCS 2004a):

$$P_e = \frac{(P - 0.2R)^2}{P + 0.8R} \quad (2)$$

where:

P_e – accumulated excess rainfall (mm) at time t

P – accumulated precipitation depth (mm) at time t

R – potential maximum retention (mm)

R is related to CN (NRCS 2004a) as indicated in Eq. (3):

$$R = \frac{25400 - 254 \times \mathrm{CN}}{\mathrm{CN}} \quad (3)$$

NRCS unit hydrograph is a dimensionless single-peak hydrograph. Discharge is expressed as a ratio to UH peak discharge U_p for any time t, a fraction

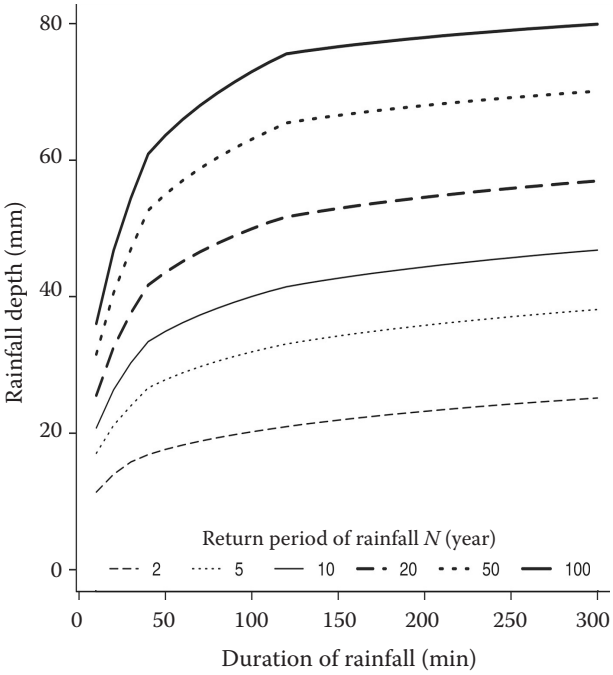

Figure 1. Design rainfall depths calculated using the DES_RAIN program (Vaššová & Kovář 2011) for Kyjov rain gauge station (13 km SE of the Žarošice catchment)

of time to peak. Peak discharge U_p is computed from Eq. (4) (USACE 2000; NRCS 2007):

$$U_p = 2.08 \frac{F}{\frac{\Delta t}{2} + 0.6 \times t_c} \quad (4)$$

where:
F – catchment area
Δt – excess precipitation duration
t_c – time of concentration of the catchment

Further description of the model can be found in NRCS (1986, 2004a, 2007) or USACE (2000). Time of concentration was assessed by the velocity method (NRSC 2010). The time of concentration is the sum of travel times for segments along the hydraulically most distant flow path. The segments used in the velocity method may be of three types: sheet flow, shallow concentrated flow, and open channel flow. The velocity method uses Manning's kinematic solution and it is considered to be the best method for calculating time of concentration if hydraulic changes to the watercourse are being considered.

The second model, KINFIL (Kovář *et al.* 2011, 2012), is physically based, using saturated hydraulic conductivity and Green and Ampt sorptivity as parameters. These parameters can be assessed either from field measurement (Kovář *et al.* 2011) or from relationships of CN with hydraulic conductivity and sorptivity at field capacity, CN = $f(K_s, So)$, derived for conditions of the Czech Republic (Kovář 2000, 2006).

In this model, infiltration is computed by formulas of ponding time t_p (Eq. (5)) (Mein & Larson 1973) and cumulative infiltration V (Eq. (6)) (Morel-Seytoux & Verdin 1981):

$$t_p = \frac{So^2 / 2K_s}{i \times (i / K_s - 1)} \quad (5)$$

$$V = V_p + K_s(t - t_p) + So \times \frac{i/K_s}{i/K_s - 1} \times \left(\sqrt{t - t_p + 0.5 t_p \left(\frac{i/K_s}{i/K_s - 1} \right)^3} - \sqrt{0.5 t_p \left(\frac{i/K_s}{i/K_s - 1} \right)^3} \right) \quad (6)$$

where:
So – sorptivity at field capacity (m/s$^{1/2}$)
K_s – hydraulic conductivity (m/s)
i – excess rainfall intensity (m/s)
V_p – cumulative infiltration (m) at ponding time t_p
t – time (s)

Direct runoff is transformed using the kinematic wave equation (Eq. (7)) (Woolhiser & Liggett 1967; Kovář 2000):

$$\frac{\partial y}{\partial t} + \alpha m y^{m-1} \frac{\partial y}{\partial x} = i(t) \quad (7)$$

where:
y – depth of flow (m)
t, x – time (s) and space (m) ordinates, respectively
i – excess rainfall intensity (m/s)
α, m – hydraulic parameters of kinematic wave, $\alpha = \sqrt{J}/n$
J – slope (–)
n – Manning's overland flow roughness (–)

This equation is solved numerically by the Lax-Wendroff explicit scheme (Singh 1996; Woolhiser *et al.* 1970).

The third approach to design peak discharge assessment employs the technical standard "Design discharges for very small catchments" (Hrádek 1988). Excess rainfall computation in this model is based on the CN method (Eqs (2) and (3)). Time of concentration of the catchment, t_c, is solved by modified accounting of design rainfall height (Eq. (1)) from Eq. (8):

$$\frac{(P_{1d,100} \times k \times t_c^{1-c} - 0.2R)^2}{P_{1d,100} \times k \times t_c^{1-c} + 0.8R} = \left(\frac{L}{a} \right)^{\frac{1}{b-1}} \times t_c^{\frac{1}{1-b}} \quad (8)$$

where:
k, c – regional parameters of design rainfall
t_c – time of concentration (min)
R – potential maximum retention (mm) calculated from Eq. (3)
L – length of drainage path (m)
a, b – hydraulic parameters of flow, $a = 87\sqrt{J}/\gamma$, $b = 2$
J – slope (–)
γ – Bazin's roughness coefficient

Peak discharge with the return period of 100 years is then obtained from Eq. (9):

$$Q_{100} = 16.67 \times \frac{a}{L \times t_c} \times F \quad (9)$$

where:
Q_{100} – peak discharge with the return period of 100 years (m^3/s)
a – hydraulic parameter
L – length of drainage path (m)

t_c – time of concentration (min)
F – catchment area (km^2)

Peak discharges with different return periods are calculated by multiplying Q_{100} by reduction coefficients (Table 1).

The fourth approach to catchment peak discharge evaluation used in this study is the method developed by Froehlich (2012). This method is based on the NRCS rainfall-runoff relations (2007) and it uses dimensionless normalized peak runoff rate q_{p*} calculated from Eq. (10):

$$q_{p*} = aR_*^3 + bR_*^2 + cR_* + d \quad (10)$$

where:
a, b, c, d – coefficients that depend on the particular NRSC storm type (NRCS 1986) and time of concentration t_c
R_* = $R/P_{1d,N}$ is normalized maximum storage depth
R – potential maximum retention from Eq. (3)
$P_{1d,N}$ – maximal one-day rainfall depth

The peak discharge is then computed from Eq. (11):

$$q_p = 16.67 \times q_{p*} \frac{P_{1d,N} \times F}{t_c} \quad (11)$$

where:
q_p – peak discharge (m^3/s)
$P_{1d,N}$ – maximal one-day rainfall depth (mm)
F – catchment area (km^2)
t_c – time of concentration (min)

The method is developed for four storm types prepared for geographic regions of the United States. Types I and IA represent the Pacific maritime climate with wet winters and dry summers. Type III represents the Gulf of Mexico and Atlantic coastal areas where tropical storms bring large 24-hour rainfall amounts. Type II represents the rest of the country (NRCS 1986). Storm type II was considered in this study, because it may be the most similar to high-intensity rainfalls in central Europe.

Experimental catchment. The study catchment is located north-west of the village of Žarošice in southern Moravia, Czech Republic. This area has an annual average temperature of 9°C and annual average precipitation of 560 mm. The catchment area is 0.18 km^2. There is a dry retention reservoir in the outlet of the catchment. Drainage network is not developed in the catchment. Altitude ranges from 226 m to 277 m a.s.l. Average slope of the catchment is 8.6%. The bedrock is formed of loess and loess loam, covered with Chernozem. Arable land and orchard cover 76.6% and 18.7% of the catchment area, respectively. Other areas and dry retention reservoir cover less than 5% (Table 2, Figure 2).

Soils in the catchment are classified in group B according to the comprehensive soil survey of the Czech Republic. The curve number for the catchment is CN = 73.3 (Table 2) and the time of concentration established by velocity method (NRCS 2010) t_c = 20 min. This value was used for the calculation by the HEC-HMS as well as Froehlich's method. The field measurements of hydraulic conductivity and sorptivity at field capacity estimate the values of K_s = 0.16 mm/min and So = 1.37 mm/min$^{1/2}$. Manning's roughness coefficients were set up according to tabular values (NRCS 2010; USACE 2000) n = 0.4 for permanent grassland in a dry retention reservoir, n = 0.24 for unmaintained orchard and n = 0.17 for arable land. The technical standard uses Bazin's roughness coefficients (Hrádek 1988) γ = 3 for arable land and γ = 9 for permanent grassland and orchard.

For the KINFIL model, the catchment was schematized in a cascade of rectangular planes

Table 1. Reduction coefficients for derivation of design discharges with return period N ($Q_N = a_N \times Q_{100}$)

Slope (%)	Afforestation	Return period N (year)					
		1	2	5	10	20	50
≤ 2	no forest	0.14	0.22	0.34	0.45	0.54	0.76
	partly forested	0.18	0.29	0.44	0.55	0.67	0.84
2–5	no forest	0.10	0.14	0.23	0.33	0.47	0.73
	partly forested	0.14	0.21	0.33	0.45	0.60	0.81
> 15	no forest	0.06	0.08	0.13	0.21	0.34	0.62
	partly forested	0.10	0.15	0.23	0.33	0.47	0.70

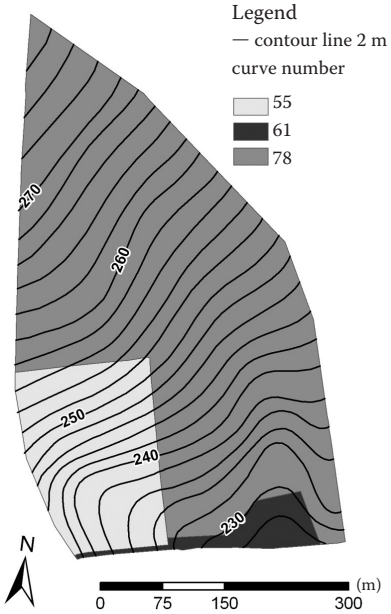

Figure 2. Catchment map depicting topography and hydrologic properties (Curve Number – CN)

Table 2. The runoff Curve Number (CN) (NRSC 2004b) estimated for the Žarošice catchment (F_i is the area subject to the given land use); weighted mean CN = 73.3; soil group B

Land use	F_i (ha)	F_i (%)	CN
Arable land	14.14	77.3	78
Orchard (unmaintained)	0.84	4.5	61
Retention reservoir	3.43	18.7	55

to describe the shape of the hillside. This simplified geometric configuration of the catchment is described in Table 3. In the HEC-HMS model and Froehlich's method, characteristics of a slope are projected in the time of concentration.

RESULTS

Rainfall-runoff models were not validated because there is no discharge gauge in the catchment. Kovář (2000) showed in his study on various catchments that the KINFIL model provides good agreement between simulated and observed discharges when CN values are determined according to NRSC methodology (NRSC 2004b). Hjelmfelt (1991) tested the NRCS runoff equation for several watersheds with good results. Therefore it is assumed that the HEC-HMS may provide acceptable results of discharges without calibration.

Design flood hydrographs from design rainfalls with corresponding return period were simulated for different rainfall durations by the HEC-HMS and the KINFIL model. The KINFIL model was applied both with the CN value (KINFIL-CN), which was the same as in the HEC-HMS model, and with measured parameters (KINFIL-field). Only the peak discharges were calculated on the basis of the technical standard and method of Froehlich (2012).

The highest peak discharges for every return period N and both HEC-HMS and KINFIL were chosen, see Table 4. In the case of the HEC-HMS model, the most dangerous rainfall duration was decreasing with increasing return period. On the other hand, the KINFIL model showed rainfalls with duration of 40 min as the most crucial.

Peak discharges of flood hydrographs obtained from HEC-HMS and KINFIL models, from the technical standard and from Froehlich's method were compared with peak discharges provided by the CHMI (Table 4). The HEC-HMS model and the technical standard method evinced underestimation of peak discharges compared to data from CHMI. Only slight underestimation was revealed in the case of return period N = 50 and

Table 3. Schematic geometric representation of the Žarošice catchment for the KINFIL model

Plane	Area (ha)	Length (m)	Width (m)	Slope (%)	Land use (% of catchment area)			
					arable land	other areas	dry retention reservoir	orchard
SC1	1.41	112	127	5.5	7.6	–	–	–
SC2	3.59	121	297	8.2	19.4	0.06	–	–
SC3	4.48	135	332	7.4	18.8	0.3	–	5.2
SC4	4.21	117	361	8.8	14.5	0.3	0.07	7.9
SC5	4.04	139	291	7.3	15.7	–	0.7	5.5
SC6	0.68	68	100	5.1	0.5	–	3.1	–

Table 4. Design peak discharges for the Žarošice catchment estimated using different methods of calculation

Return period N (years)	Peak discharge (m^3/s)					
	CHMI	HEC-HMS	KINFIL-CN	KINFIL-field	Technical standard	Froehlich's method
2	0.14	0.03	0.08	0.05	0.14	0.04
5	0.30	0.17	0.36	0.20	0.23	0.27
10	0.49	0.34	0.67	0.43	0.33	0.50
20	0.75	0.65	1.16	0.83	0.47	0.78
50	1.20	1.17	1.95	1.51	0.73	1.17
100	1.70	1.61	2.60	2.17	1.00	1.51

CHMI – Czech Hydrometeorological Institute

100 years (2.5% and 5.3%, respectively), which is the estimation closest to the CHMI data. Peak discharges computed by the technical standard method with return periods shorter than 100 years are computed from the 100-year value by reduction coefficients, so a potential mistake in the estimate of Q_{100} affects the other peak values.

Using the KINFIL model with parameters derived from CN underestimated peak discharge with return period N = 2 years, the other peak discharges were overestimated in the range from 20% to 62%. The same model with parameters measured in the field shows underestimation of peak discharges of events with shorter return period (2 to 10 years) and overestimation in longer return periods. The difference between KINFIL-CN and KINFIL-field values can be caused by inaccuracy of soil hydraulic parameters computed from regional relationships CN = $f(K_s, So)$ and also by measurement error in the field determination of these parameters. The hydraulic conductivity and sorptivity at field capacity computed from the CN value are also lumped parameters for the entire Žarošice catchment and need not correspond to the values measured locally (Kovář 2000).

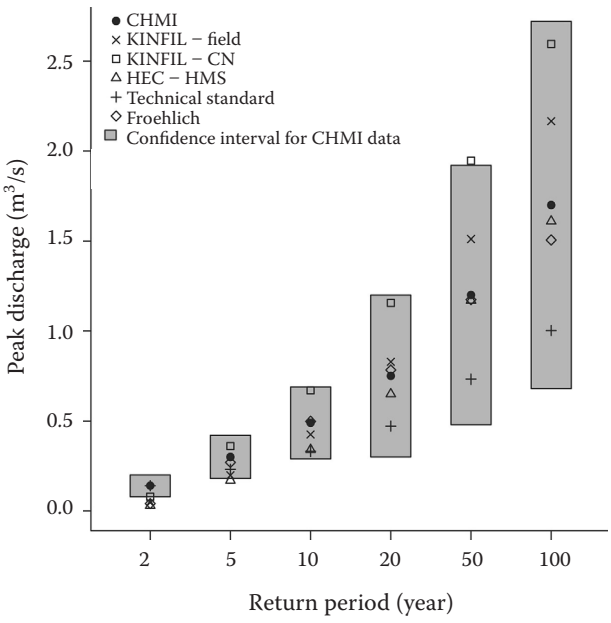

Figure 3. Comparison of design peak discharges with various return periods for the Žarošice catchment estimated using different methods of calculation within confidence interval given by data of Czech Hydrometeorological Institute (CHMI)

Peak discharges obtained by Froehlich's method were closest to data provided by CHMI with deviation up to 11%, except the 2-year discharge (Figure 3). Peak discharges calculated from HEC-HMS and Froehlich's method are quite similar. The reason is probably that these approaches are built on the same background of the CN method.

The data provided by CHMI are from the fourth group of accuracy, which means that the standard error of the mean is 40% for N = 1 to 10 years and 60% for N = 20 to 100 years (Figure 3). Most of the peak discharges with return period from 5 to 100 years assessed by the above-described methods fall into these spans, except peak discharges calculated by the KINFIL-CN model for N = 50 years and by HEC-HMS for N = 5 years. For the return period of N = 2 years, only the technical standard was able to assess the peak discharge within the confidence interval of the CHMI data.

DISCUSSION

In this study various methods of peak discharge assessment are presented. Various uncertainties

are related with the results. The assumption about the equality of return period of rainfall and corresponding runoff, which was used, is not proved to always be acceptable because of various uncertainties (Adams & Howard 1986). For example assuming even identical antecedent conditions in the catchment, two different hyetographs could have produced runoff hydrographs with the same peak discharge but with different hydrograph shapes and volumes and peaks occurring at different times from the beginning of the storm. Neither would the catchment under different antecedent conditions response identically to the same hyetograph. Moreover, design storms are typically associated with summer convective storms and do not reflect the conditions of snowmelt (Adams & Howard 1986). Nevertheless, some studies (e.g. Packman & Kidd 1980; Guo 2001) showed that the design storm approach can produce peak discharges of desired return periods with the acceptable level of accuracy (about 40 to 50%) if used properly and these peak discharge are comparable to those obtained by continuous simulation approach or analytical probabilistic approach (Guo 2001). Another uncertainty arises from the fact that the rainfall gauge is not located in the experimental catchment. Therefore the design storm data are burdened with inaccuracy due to geographic distance.

Although Froehlich's method provides very good results, it is necessary to point out that storm type II was assumed to be the most appropriate pattern for design rainfalls in the study catchment. The duration-frequency data for the Czech Republic were not compared with the data from the United States, which brings an uncertainty to the results of this method.

All above-mentioned hydrological models conceptualize complex spatially distributed processes in the catchment using relatively simple mathematic equations with parameters that do not often represent directly measurable entities. This leads to uncertain parameter estimates and consequently to uncertain forecasts (Vrugt *et al.* 2005). Also the models are lumped and the average parameters may not reproduce well the spatial heterogeneities in the catchment (Beven 1989).

The absence of calibration and validation of models applied in this study includes another uncertainty in results. However, Hjelmfelt (1991) and Kovář (2000) proved that KINFIL and HEC-HMS models can perform satisfactorily even with parameters obtained directly from catchment characteristics.

The study evinces that there are approaches for design discharge calculation in the Žarošice small catchment giving acceptable agreement with data provided by the CHMI. Especially Froehlich's method could be used as an alternative for design discharge calculation, but further research on its applicability in conditions of the Czech Republic is necessary. Also the comparison of the above-mentioned methods on a higher number of catchments seems to be appropriate.

Acknowledgements. The study was supported by Ministry of Education, Youth and Sports of the Czech Republic, Project No. MSMT 2B06101 – Optimization of Agricultural and River Landscape.

References

Adams B.J., Howard C.D.D. (1986): Design storm pathology. Canadian Water Resources Journal, **11**: 49–55.

Al-Qurashi A., McIntyre N., Wheater H., Unkrich C. (2008): Application of the Kineros2 rainfall-runoff model to an arid catchment in Oman. Journal of Hydrology, **355**: 91–105.

Beven K.J. (1989): Changing ideas in hydrology: the case of physically-based models. Journal of Hydrology, **105**: 157–172.

Buchanan B., Easton Z.M., Schneider R., Walter M.T. (2012): Incorporation variable source area hydrology into a spatially distributed direct runoff model. Journal of the American Water Resources Association, **48**: 43–60.

Bulygina N., McIntyre N., Wheater H. (2011): Bayesian conditioning of rainfall-runoff model for predicting flows in ungauged catchments and under land use changes. Water Resources Research, **47**: W02503.

Ewen J., Parkin G., O'Connell P.E. (2000): SHETRAN: Distributed river basin flow and transport modeling system. Journal of Hydrologic Engineering, **5**: 250–258.

Froehlich D.C. (2012): Graphical calculation of small catchment peak discharge. Journal of Irrigation and Drainage Engineering, **138**: 245–256.

Guo Y. (2001): Hydrologic design of urban flood control detention ponds. Journal of Hydrologic Engineering, **6**: 472–479.

Guo Y., Markus M. (2011): Analytical probabilistic approach for estimating design flood peaks of small watersheds. Journal of Hydrologic Engineering, **16**: 847–857.

Hjelmfelt A.T. (1991): Investigation of curve number procedure. Journal of Hydrologic Engineering, **117**: 725–737.

Hrádek F. (1988): Design Discharges for Very Small Catchments. Technical Standard. Hydroprojekt, Prague. (in Czech)

Hrádek F., Kovář P. (1994): Computation of substitute storm rainfall intensities. Vodní Hospodářství, **11**: 49–53. (in Czech)

Kovář P. (2000): Hydrologic Models Application For Maximum Discharge Assessment On Small Catchments. CULS, Prague. (in Czech)

Kovář P. (2006): The extent of land use impact on water regime. Plant, Soil and Environment, **52**: 239–244.

Kovář P., Vaššová D., Hrabalíková M. (2011): Mitigation of surface runoff and erosion impacts on catchment by stone hedgerows. Soil and Water Research, **6**: 153–164.

Kovář P., Vaššová D., Janeček M. (2012): Surface runoff simulation to mitigate the impact of soil erosion, case study of Třebsín (Czech Republic). Soil and Water Research, **7**: 85–96.

Mein R.G., Larson C.L. (1973): Modeling infiltration during a steady rain. Water Resources Research, **9**: 384–394.

Morel-Seytoux H.J., Verdin J.P. (1981): Extension of the SCS Rainfall Runoff Methodology for Ungaged Watersheds. [Report FHWA/RD-81/060.] U.S. National Technical Information Service, Springfield.

NRCS (1986): Urban Hydrology for Small Watersheds. Technical Release 55 (13), U.S. Department of Agriculture, Washington D.C.

NRCS (2004a): Chapter 10 Estimation of Direct Runoff from Storm Rainfall. National Engineering Handbook, Part 630 Hydrology. U.S. Department of Agriculture, Washington D.C.

NRCS (2004b): Chapter 9 Hydrologic Soil-Cover Complexes. National Engineering Handbook, Part 630 Hydrology. U.S. Department of Agriculture, Washington D.C.

NRCS (2007): Chapter 16 Hydrographs. National Engineering Handbook, Part 630 Hydrology. U.S. Department of Agriculture, Washington D.C.

NRCS (2010): Chapter 15 Time of Concentration. National Engineering Handbook, Part 630 Hydrology. U.S. Department of Agriculture, Washington D.C.

Packman J.C., Kidd C.H.R. (1980): A logical approach to the design storm concept. Water Resources Research, **16**: 994–1000.

Refsgaard J.C., Storm B. (1995): MIKE SHE. In: Singh V.P. (ed.): Computer Models of Watershed Hydrology. Highlands Ranch, Colorado, USA: Water Resources Publications.

Rojas R., Julien P., Johnson B. (2003): CASC2D-SED v. 1.0 – Reference Manual. A 2Dimensional Rainfall-Runoff and Sediment Model. Colorado State University, Fort Collins.

Singh V.P. (1996): Kinematic Wave Modeling in Water Resources: Surface-Water Hydrology. John Wiley & Sons, Inc., New York.

Soulis K.X., Valiantzas J.D. (2012): SCS–CN parameter determination using rainfall-runoff data in heterogeneous watersheds – the two-CN system approach. Hydrology and Earth System Sciences, **16**: 1001–1015.

Šamaj F., Brázdil R., Valovič J. (1983): Daily rainfall heights with extraordinary intensities in Czechoslovakia in the period 1901–1980. In. Proc. SHMI. Alfa, Bratislava. (in Slovak)

USACE (2000): Hydrologic Modeling System HEC-HMS – Technical Reference Manual. Hydrologic Engineering Center – US Army Corps of Engineers, Davis.

Vaššová D., Kovář P. (2011): DES_RAIN. Program for Design Rainfall Computation. CULS, Prague. (in Czech)

Vrugt J.A., Diks C.G. H., Gupta H.V., Bouten W., Verstraten J.M. (2005): Improved treatment of uncertainty in hydrologic modeling: Combining the strengths of global optimization and data assimilation. Water Resources Research, **41**: 1–17.

White E.D., Easton Z.M., Fuka D.R., Collick A.S., Adgo E., McCartney M., Awulachew S.B., Selassie Y.G., Steenhuis T.S. (2011): Development and application of a physically based landscape water balance in the SWAT model. Hydrological Processes, **25**: 915–925.

Woolhiser D.A, Liggett J.A. (1967): Unsteady, one-dimensional flow over a plane – the rising hydrograph. Water Resources Research, **3**: 753–771.

Woolhiser D.A., Hanson C.L., Kuhlman A.R. (1970): Overland flow on rangeland watersheds. Journal of Hydrology, **9**: 336–356.

Received for publication July 20, 2012
Accepted after corrections November 1, 2012

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