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On the possibilities of watershed parameterization for extreme flow estimation in ungauged basins

S. Kohnová, B. Karabová, and K. Hlavčová

Department of Land and Water Resources Management, Faculty of Civil Engineering, Slovak University of Technology in Bratislava, Bratislava, Slovakia

Correspondence to: S. Kohnová (silvia.kohnova@stuba.sk)

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Abstract. The estimation of design discharges and water levels of extreme floods is one of the most important parts of the design process for a large number of engineering projects and studies. Design flood estimates require a consideration of the hydrological, meteorological and physiographical situation, the legal requirements, and the available estimation techniques and methods. In the last decades changes in floods have been observed (Hall et al., 2014) which makes design flood estimation particularly challenging. Methods of design flood estimation can be applied either locally or regionally. A significant problem may arise in small catchments that are poorly gauged or when no recorded data exist. To obtain the design values in such cases, many countries have adopted procedures that fit the local conditions and requirements. One of these methods is the Soil Conservation Service – Curve number (SCS-CN) method which is often used in design flood estimation for ungauged sites, including those in Slovakia. Since the method was derived on the basis of the specific characteristics of selected river basins in the United States, it may lead to significant uncertainties in other countries with different hydrological conditions. The aim of this study was to test the SCN-CN method and derive regional runoff curve numbers based on rainfall and discharge measurements for selected region in Slovakia. The results show that the classical CN method gives too high estimates of event runoff depths and is not valid in the study area. To avoid the overestimation of runoff caused by extreme rainfall events, the use of the empirically derived regional runoff curves was tested and finally proposed for practical application in engineering hydrology.

1 Introduction

The Soil Conservation Service – Curve number (SCS-CN) method is a rainfall-runoff model developed in 1954 by the US Soil Conservation Service (USDA SCS, now the Natural Resources Conservation Service (NRCS)). Later, in 1985, it has been published (USDA, 1985), and since had numerous updates, (e.g., USDA, SCS 1986, 1988, 1993, 2001, 2003, and 2008). In this method the relationship between soil and land use characteristics and antecedent rainfall conditions are reflected in a Curve Number (CN) parameter. With this simple parameter a rainfall depth is transformed into a runoff depth. The tables and figures for estimating the CN parameter for the soil cover complexes of the USA are given, e.g., in the NRCS publication (USDA, 2001). Direct runoff can be computed using the tabulated CN based on the land use and surface condition, the hydrologic soil group, and the rainfall depth as follows:

$$Q = \frac{(P-\lambda S)^2}{S+(P-\lambda S)} \tag{1}$$

$$S = \frac{25400}{\mathrm{CN}} - 254 \tag{2}$$

$$I_\mathrm{a} = \lambda \cdot S \tag{3}$$

where Q is the direct runoff depth (mm), P is the storm rainfall depth (mm), S is the potential retention (mm), I_a is the initial abstraction or rainfall prior to runoff (mm), λ is the initial abstraction coefficient (according to the original methodology, it equals 0.2), and CN is a curve number parameter derived from tables (–). Equation (1) is valid for $P > I_\mathrm{a}$. For $P \le I_\mathrm{a}$, $Q = 0$.

In the original methodology, antecedent moisture conditions (AMC) is used to classify rainfall-runoff events into the

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Table 1. Characteristics of the watersheds analysed in the Upper Hron River Basin.

N.	River	Area (km^2)	Forest	Urban	Grass	Agr.	Shrub	N. of events	CN_{emp}	$CN_{tabulated}$
					%					
W1	Havraník	16.7	78.5	0.0	13.7	1.3	6.7	31	77	84
W2	Šaling	25.0	78.4	0.3	7.1	4.9	9.4	45	74	78
W3	Hron, Brôtovo	9.3	87.8	0.0	2.1	0.0	10.1	44	78	83
W4	Osrblianka	27.8	93.6	1.8	0.0	4.6	0.0	53	71	77
W5	Bystrianka	22.5	50.2	0.0	0.0	0.0	49.8	36	77	78
W6	Ramžiná	12.3	92.5	0.6	0.0	2.6	4.2	54	74	79
W7	Starohorský potok	62.6	77.4	0.6	2.0	5.6	14.3	44	70	73
W8	Hukava	10.0	86.7	0.0	2.9	4.4	6.0	27	72	77
W9	Jasenica	83.0	92.5	0.6	0.0	2.6	4.2	17	75	81

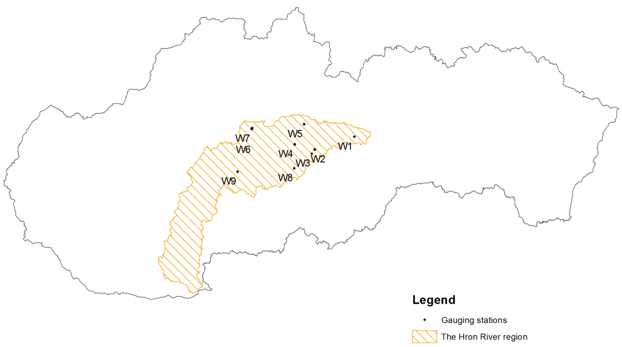

Figure 1. Location of the selected small watersheds within the Upper Hron River basin, Slovakia.

AMC I, II and III classes. These correspond to low, medium and high soil moisture conditions, depending on the total antecedent rainfall depth over the previous 5 days. The original concept of antecedent conditions has been questioned by many authors (e.g., Gray et al., 1982; Hawkins, 1983; Merz et al., 2006; Grabau, 2008; Hjelmfelt et al., 1982; Silveira et al., 2000; Banasik, 2011; Spál et al., 2011). All of these studies suggest that no apparent relationship between antecedent precipitation and curve number exists (USDA, 2004). Rallison and Cronshey (1979) state that the variability of CN may be related to infiltration, evaporation, soil moisture, lag time, rainfall intensity (Gaál et al., 2014), and temperature. The inclusion of all of these influences in the curve number procedure would lead to a physical infiltration method. To maintain the curve number format, the CN might be treated as a random variable (Hjelmfelt et al., 1982).

The availability of long discharge records has led to a review of the original initial abstraction coefficient (λ). Mockus (1972) concluded that the coefficient λ varied between 0.013 and 2.1 and that the mean value of λ (0.2) decreases the accuracy of the computed runoff. Cazier and Hawkins (1984) analyzed the data of 109 small basins and found that the most common value for the coefficient λ was 0 and that the average value was 0.0006. Baltas et al. (2007) found an average λ of 0.014 in a 15 km^2 catchment in Greece, and Hawkins and Khojeini (2000) found λ close zero in 97 small basins. Jiang (2001) found that 90 % of the λ values in 307 river basins were less than 0.2 with $\lambda = 0.05$ fitting best to the observations.

Table 2. The highest values of CN_{emp} for the three classes analysed.

Class	CN_{emp}
I	65
II	78
III	86

This review indicates that great importance needs to be given to the determination of λ. The objective of this study therefore was to further analyze the SCS – CN method, estimate the parameters CN and coefficients λ from discharge data, and derive regional runoff curve numbers based on rainfall and discharge measurements for selected regions in Slovakia.

2 Area studied and acquisition of data

A total of nine small sub-catchments that are part of the Upper Hron River basin were used (Fig. 1). The small watersheds selected were: Havraník, Šaling, Brôtovo, Osrblianka, Bystrianka, Ramžiná, Starohorský, Hukava, and Jasenica. Each of the watersheds has forest cover as its dominant land use. The Hydrologic Soil Group is B, which correspond to silt loam or loam. The watersheds were chosen based on the availability of the data needed for the study and their small catchment areas with an average of 45 km^2 (Table 1). No land use changes during the analyzed period were observed in the catchments.

Discharge data sets ($m^3\,s^{-1}$) at an hourly time step with the corresponding rainfall intensities ($mm\,h^{-1}$) for the period of 1989–2002 were used as the input data. Rainfall-runoff events from the growing season were selected based on flood

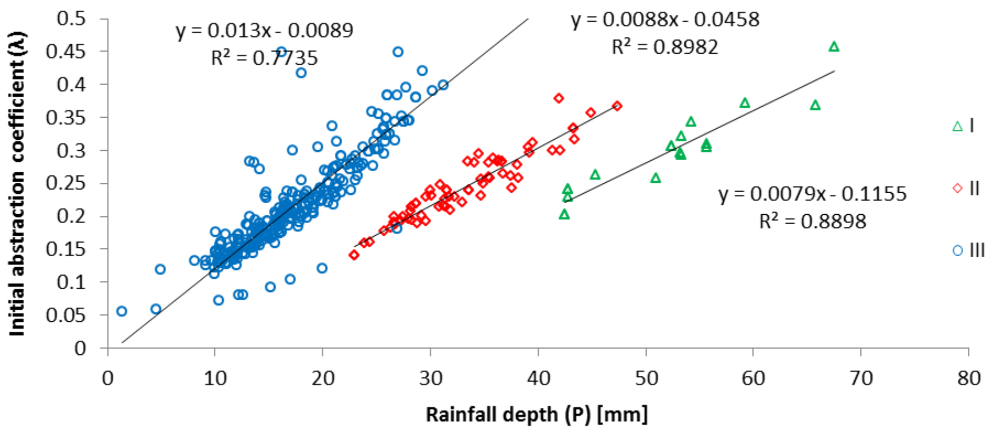

Figure 2. Relationship between initial abstraction coefficient (λ) and event rainfall (P) for the Upper Hron River basin events.

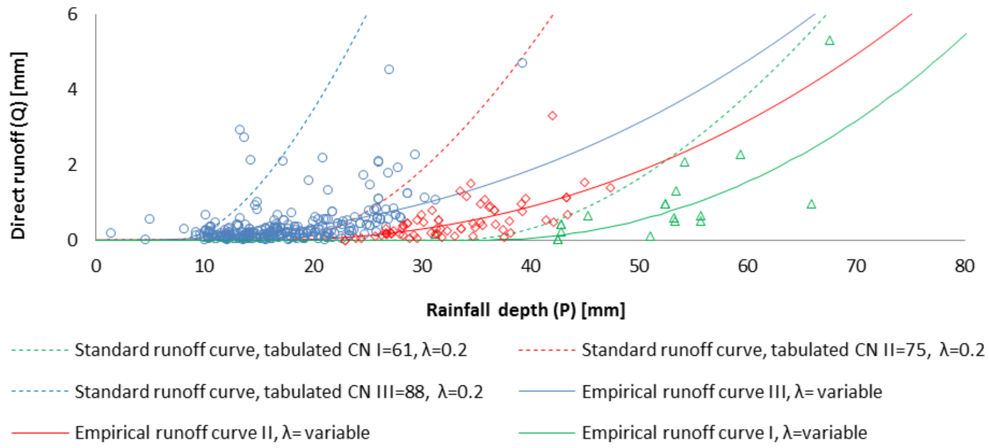

Figure 3. Regional empirical runoff curves and standard runoff curves based on tabulated curve numbers derived for the Upper Hron River basin.

hydrographs with one peak and rainfall duration of less than 24 h. Each flood hydrograph was treated individually, and the direct runoff was estimated using the base flow separation method with a constant slope. The start point of the flood wave was determined subjectively at the beginning of the rising limb, the end of the flood wave was set on the point of the maximum curvature of the recession curve. A total of 379 events were analyzed. The events of all the watersheds were pooled in order to obtain more reliable results. We used already derived pooling scheme (Kohnová et al., 2006), which was based on the similarity of the climatic and physiographic characteristic influencing the runoff formation in the Upper Hron River basin.

3 Approach and results

Using the observed runoff and rainfall data, for each storm event, $\mathrm{CN}_{\mathrm{event},i}$ was calculated by combining Eqs. (1)–(3):

$$\mathrm{CN}_{\mathrm{event},i} = \frac{25\,400}{5\left(P + 2Q - \sqrt{4Q^2 + 5PQ}\right) + 254} \tag{4}$$

where $\mathrm{CN}_{\mathrm{event},i}$ is an empirical CN for event i, and λ was set to 0.2.

For each event, the antecedent 5-day rainfall was calculated to classify the $\mathrm{CN}_{\mathrm{event},i}$ into classes according to antecedent moisture conditions as proposed by the SCS-CN methodology. The results indicate that from all events analysed, only 1 % represent the wettest class (III), 3 % belong to class II and the majority of the events represents the driest class (I). The low number of events in the II and III classes suggests that this classification is not appropriate for the present study. Many other studies (e.g. Hawkins, 1983; Hjelmfelt et al., 1982; Banasik, 2011), similarly found that no apparent relationship between antecedent precipitation and curve number exists and other factors may be more important. Consequently, another classification of $CN_{event,i}$ values was applied here, which is not based on the three antecedent conditions. The $CN_{event,i}$ values were treated as a random variable and were divided into three classes (I, II and III) with percentiles limits (0.10 and 0.90) of their distribution, following Hjelmfelt (1991). Table 2 shows the highest values of $CN_{event,i}$ for these three classes (I, II and III). Subsequently, all $CN_{event,i}$ values of each class were (arithmetically) averaged to estimate $CN_{emp(I)}$, $CN_{emp(II)}$ or $CN_{emp(III)}$.

In the next step a regional relationship was established for estimating the initial abstraction coefficient λ separately for the three CN_{emp} classes in the Upper Hron River basin. The values of λ in the literature vary from negative values to values larger than 1, suggesting that study-to-study differences in the λ values are to be expected (Schneider and McCuen, 2005). Therefore, no constant value of λ was sought in the regional estimation but λ was expressed for each event separately, with $CN_{emp(I)}$, $CN_{emp(II)}$, and $CN_{emp(III)}$ as input parameters. Figure 2 shows a regression between λ and event rainfall depth for all events in the region, separately for each of the classes (I, II, III).

To derive empirical regional runoff curves with variable λ the regression equations between the initial abstraction coefficient and event rainfall were used (Fig. 2). For comparison, standard CN curves were estimated using the tabulated CN values and $\lambda = 0.2$.

The empirical regional runoff curves together with the standard ones are presented in Fig. 3. We can observe that the empirical regional curves have smaller gradient than the standard runoff curves derived using the original SCS-CN method and standard CN curves overestimate the direct runoff caused by higher precipitation. Similar finding can be found in studies e.g. Banasik (2001) and Spál et al. (2011).

Overall, the new empirical regionally derived CN curves represent the regional rainfall-runoff conditions in the Upper Hron River basin much better than the values from the standard method.

4 Conclusions

In this paper we proposed modifications of the classical SCS-CN method in a regional context. First, a different classification of the CN_{emp} was proposed where the CN values were treated as random variables. This classification, in which CN values were derived from real rainfall-runoff events, should better represent the runoff formation and behavior of the catchments (e.g., geomorphology, geology, rainfall intensity) than the standard curves from the literature. To avoid the use of a fixed value of the initial abstraction coefficient ($\lambda = 0.2$), in the next step, a regional relationship for estimating the initial abstraction coefficient was developed for all proposed CN_{emp} classes. Finally, empirical regional runoff curves with variable λ were derived.

The results show that the standard CN method is not valid in the study area as it gives far too high estimates of event runoff depths. Using the empirical regional runoff curves the overestimation of runoff caused by extreme rainfall events, can be avoided. It can therefore be concluded, that the CN curves need to be derived from observed discharge data rather than taken from the literature.

The proposed modification of the CN method presented still has some uncertainties: nevertheless, it is a clear improvement over the standard CN method based on tabulated values for the study region. Further research in other regions in Slovakia is foreseen in the near future.

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