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The L-moment based regional approach to curve numbers for Slovak and Polish Carpathian catchments

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Abstract: The main objective of the paper was to propose and evaluate the performance of a regional approach to estimate *CN* values and to test the impact of different initial abstraction ratios. The curve number (*CN*) was analyzed for five Slovak and five Polish catchments situated in the Carpathian Mountains. The L-moment based method of Hosking and Wallis and the ANOVA test were combined to delineate the area in two homogenous regions of catchments with similar *CN* values. The optimization condition enabled the choice of the initial abstraction ratio, which provided the smallest discrepancy between the tabulated and estimated *CN*s and the antecedent runoff conditions. The homogeneity in the *CN* within the regions of four Slovak and four Polish catchments was revealed. Finally, the regional *CN* was proposed to be at the 50% quantile of the regional theoretical distribution function estimated from all the *CN*s in the region.

The approach is applied in a group of Slovak and Polish catchments with physiographic conditions representative for the Carpathian region. The main benefit of introducing a common regional *CN* is the opportunity to apply this procedure in catchments of similar soil-physiographic characteristics and to verify the existing tabulated *CN*. The paper could give rise to an alternative way of estimating the *CN* values in forested catchments and catchments with a lack of data or without observations.

Keywords: Catchment curve number; Homogeneity; Regional frequency analysis.

INTRODUCTION

The SCS-CN method is a rainfall-runoff model developed for the United States by the USDA Soil Conservation Service (SCS) (now the Natural Resources Conservation Service (NRCS)) in 1956. In this method the relationship between a watershed´s characteristics and antecedent rainfall is represented by the Curve Number parameter. With this simple parameter, the depth of a rainfall is transformed to the depth of direct runoff. The tables and figures for estimating the *CN* parameter for soil cover groups of the USA are given, e.g., in the publications of NRCS (USDA, 2004). Despite the fact that the *CN* method was developed based on the empirical data of the USA, the method is used in many countries all over the world. The *CN* method is said to be the most often used model for rainfall-runoff (Ajmal et al., 2015), and the main reasons for its use are i) the efficiency of the calculation; ii) the land cover and land use, soil class, and management practices data are easily obtainable; and iii) it generates suitable runoff estimates for agricultural and urban catchments (Yuan et al., 2014). Furthermore, this model provides three important values: (1) it calculates the return period of direct runoff from the same return period of the rainfall depth; (2) it explains the rainfall-runoff for individual events; and (3) it infers the infiltration processes and soil moisture-*CN* relations.

Originally, the *CN* was assumed to be a function of the physiographic-soil properties that are constant in each catchment or in a part of it. This tabulated value is determined using the Hydrologic Soil Groups (USDA, 2004). Soils are placed into groups A, B, C and D, with A being the least runoff-prone and D the most runoff-prone in this system. In practice, however, the parameter changes as a result of variable air conditions, the soil, and storm or catchments morphology. Therefore, some improvements in the method have been introduced according to the seasonal and spatial variability (Geetha et al., 2007; Soulis and Valiantzas, 2012) and sediment yield (Mishra et al., 2006). A great deal of work on the *CN* was conducted by Hawkins (e.g., 1973, 1979) and Hawkins et al. (1985). Hawkins proposed the antecedent moisture conditions (AMC), later converted to antecedent runoff conditions (ARC), introduced an asymptotic approach (Hawkins, 1993), and developed the *CN* infiltration rate equation. Currently, the antecedent runoff conditions (ARC I, ARC III) are recommended (Hawkins et al., 2009) in cases of wet or dry conditions in a catchment, through the formulas of Hawkins or the method of Hjelmfelt (1983). At present, the model is a part of several water management systems, i.e., GLEAMS (Leonard, 1987), SWAT (Arnold et al., 1995), and AnnAGNPS (Bingner and Theurer, 2005). Various modifications of the SCS-CN method are also used (e.g., Sahu et al., 2010; Wałęga et al., 2017).

The original initial abstraction ratio λ equal to 0.20 in the SCS-CN method has also been questioned by many authors. New methods and availability of data with longer observation periods have led to a review of the original value because the mean value of λ is approximate and can have a negative effect on the accuracy of the computed runoff. Mockus (1972) concluded that the coefficient λ varied in the interval $\lambda_{min} = 0.013$, $\lambda_{max} = 2.1$. Cazier and Hawkins (1984) analyzed the data of 109 small catchments and determined that the most common value for the parameter λ was 0, Baltas et al. (2007) analyzed the relationship $\lambda = \frac{I_a}{S}$ in a catchment in Greece; the average coefficient λ was 0.014, and the design value was determined to be 0.037. Hawkins and Khojeini (2000) analyzed data for 97 small catchments, and the coefficient λ ranged from 0 to 0.0966. Jiang (2001) used two methods to evaluate the coefficient λ which corresponded to empirical data from 307 river basins and proposed $\lambda = 0.05$. Lower values, e.g., 0.15, 0.10 or 0.05, are recommended by the American Society of Civil Engineers (Hawkins et al., 2009). Also, studies of Slovak forested catchments revealed that estimated coefficients of λ were below 0.2 (Karabová and Marková, 2013). Among the other authors who observed uncertainties and re-evaluated the λ values and proposed their modification, we can mention, e.g., Elhakeem and Papanicolaou (2009), Shi et al. (2009), Woodward et al. (2003); Yuan et al. (2014) and Durán-Barroso et al. (2017).

Statistical studies have also been undertaken because of the variability of the *CN*. Bondelid et al. (1982) investigated the sensitivity of the SCS-CN model, Banasik and Ignar (1983) and Banasik and Woodward (2010) performed a comprehensive analysis of the empirical *CN*; Hjelmfelt (1983, 1991) introduced a probabilistic approach based on the assumption that *CN* is a random variable and proposed error bands as ARC. McCuen (2002) considered the confidence intervals of the 100-*CN*. The other authors who considered the variability of the CN are Tedela et al. (2008), Hitchcock et al. (2013), Banasik et al. (2014, 1997) and Rutkowska et al. (2015).

The proper calibration of the CN and λ is crucial for a correct assessment of direct runoff volumes for the design of flood control devices such as dams, reservoirs, floodwalls, levees, and channels. Statistical methods can often be helpful in the calibration process of rainfall-runoff data, but they often face the problem of small samples. Therefore, to reduce the uncertainty of the quantile estimates, regional methods are an alternative when several small samples are put together in a large homogeneous sample.

The main objective of the paper was to propose and evaluate the performance of a regional approach to estimate *CN* values and to test the impact of different initial abstraction ratios on 0.20, 0.15, and 0.10. The approach is applied in a group of Slovak and Polish catchments with physiographic conditions representative for the Carpathian region, so the results can be compared to existing tabulated *CN* values and applied to similar ungauged catchments in the region.

METHODS

The SCS-CN method delineates the relationships among the Curve Number [–], the maximum soil potential retention *S* [mm], the rainfall depth *P* [mm], the direct runoff depth *H* [mm], and the initial abstraction ratio λ, namely

$$H = \frac{(P - \lambda S)^2}{P + (1-\lambda) S} \quad \text{for} \quad P > \lambda S \quad \text{and} \quad H = 0 \quad \text{otherwise;} \quad (1)$$

$$CN = \frac{25400}{S + 254} \,. \quad (2)$$

Empirical CNs

The sample *CN* values were computed using Eq. (1) and (2) from rainfall depth *P* and direct runoff *H* values, registered during independent rainfall-runoff events. Three abstraction ratios λ were considered, namely $\lambda = 0.20, \lambda = 0.15, \lambda = 0.10$. The empirical values of *S* were calculated first using solutions of Eq. (1) for various λ values:

$$S = \begin{cases} 5\left(P + 2H - \sqrt{4H^2 + 5PH}\right) & \text{if } \lambda = 0.20 \\ \frac{10}{9}\left(6P + 17H - \sqrt{289H^2 + 240PH}\right) & \text{if } \lambda = 0.15 \\ 5\left(2P + 9H - \sqrt{81H^2 + 40PH}\right) & \text{if } \lambda = 0.10 \end{cases} \quad (3)$$

The empirical *CN*s were calculated next from Eq. (2). Finally, three samples of *CN*s were obtained for every catchment.

The Hosking and Wallis method

The basic equation of the Hosking and Wallis (1997) (HW) method calculates the relationship between $CN_i(F)$, the at-site quantile of order *F*, where $0 < F < 1$, the mean value μ_i, and the regional, dimensionless quantile $q(F)$,

$$CN_i(F) = \mu_i q(F) \quad \text{for } i = 1, \ldots, N \,, \quad (4)$$

where *i* is the catchment number, and *N* is the number of elements in a homogeneous region (pooling group). Homogeneity in the distribution function of all catchments in a region is represented by the quantile *q* (growth factor), common for all the catchments. Eq. (4) was proposed by Dalrymple (1960) and is known as the "index flood equation".

The regions were delineated using Eq. (3). The homogeneity in the growth factor was tested using the L-moments based method of Hosking and Wallis and the similarity in μ using a variance analysis (a one-way ANOVA). The choice of the optimal λ was conducted according to the mean absolute relative error.

In this paper, the initial delineation of the group of catchments was based on the comparison of the values of *CN*. Afterwards, the Hosking and Wallis method was used to verify the regions.

Comparison of the values of CN

The ANOVA test (Scheffé 1959) allows the comparison between mean values. The analysis was carried out for every λ. The two assumptions of the test, namely normality and equality of variances, were tested first using the Shapiro-Wilk test (Shapiro and Wilk, 1965) and the Levene's test (Levene et al., 1960), respectively. The Levene's test is known to be powerful (Gastwirth et al., 2009) and robust for small violations from normality. If the null hypothesis was rejected then the Scheffe's post-hoc test (Scheffé, 1959) was used to identify the pairs of catchments with different mean values and to establish groups of catchments with similar CN. If the strong assumptions of the ANOVA are not perfectly fulfilled, the non-parametric Kruskal-Wallis test (Kruskal and Wallis, 1952) can be used to verify the groups. The two methods were used in this paper.

L-moments

In the present paper a regionalization based on L-moments was used for estimating the CN. The research made use of the methodology of Hosking and Wallis (1997), which has been successfully applied for regional flood frequency analysis (RFFA). Its effectiveness in flood frequency analysis has resulted in its broad applicability around the world (e.g., Adamowski, 2000; Burn and Goel, 2000; Kohnová et al., 2006; Yang et al., 2010; Kochanek et al., 2012; Rutkowska et al., 2010; to name but a few). In this method, a homogeneous region (pooling group) is interpreted as a group of catchments for which the quantile functions of design flood discharges are identical, apart from site-specific scaling factor, the index flood. Using the L-moments method, the regional frequency distribution is estimated and the theoretical at-site quantiles are derived. The method of L-moments yields more accurate and efficient parameter estimates than the maximum likelihood method when the sample sizes are small to moderate (Ulrych et al., 2000; Wang, 1996). In the literature, the Hosking and Wallis methodology was applied by Mishra et al. (2009) to delineate the territory of Nepal into homogenous regions. Jeon et al. (2014) found regionalized CN parameter to apply in L-THIA model using methods like soil group area weighted average, spatial nearest neighbour, inverse distance weighted average, global calibration and others.

The L-moment of order r is a linear combination of the expected values of the order statistics $X_{r:n}$, $1 \le r \le n$ (Hosking and Wallis, 1997; Węglarczyk, 2010),

$$L_r = r^{-1} \sum_{k=0}^{r-1} (-1)^k \binom{r-1}{k} E(X_{r-k:r}). \tag{5}$$

Usually, the dimensionless coefficient of L-variation LCV, k and the L-moment ratios τ_r are used for $r \ge 3$, namely

$$LCV = \frac{L_2}{L_1}, \qquad \tau_r = \frac{L_r}{L_2}. \tag{6}$$

Specifically, τ_3, τ_4 are the L-skewness and L-kurtosis, respectively.

The estimators of the L-moments are the sample L-moments, l_r. In an analogous way, they are linear combinations of the sample order statistics $x_{1:n} \le x_{2:n} \le \ldots \le x_{n:n}$,

$$\begin{aligned} &l_1 = b_0, \qquad l_2 = 2b_0 - b_1, \qquad l_3 = 6b_2 - 6b_1 + b_0, \\ &l_4 = 20b_3 - 30b_2 + 12b_1 - b_0, \end{aligned} \tag{7}$$

where

$$b_r = \frac{1}{n} \sum_{j=r+1}^{n} \frac{(j-1)(j-2)\ldots(j-r)}{(n-1)(n-2)\ldots(n-r)} x_{j:n}. \tag{8}$$

The sample LCV, L-skewness and L-kurtosis are given by $t = \frac{l_2}{l_1}$, $t_3 = \frac{l_3}{l_2}$, $t_4 = \frac{l_4}{l_2}$, respectively. Note that l_1 is the sample mean value. The sample L-moments are asymptotically unbiased and robust to outliers.

Homogeneity in the distribution function

The tests (Hosking and Wallis, 1997) are based on simulations of equivalent pooling groups. The HW heterogeneity measures are

$$H_j = \frac{V_j - \mu_{V_j}}{\sigma_{V_j}}, \; j = 1,2,3, \tag{9}$$

where V_j are the weighted standard deviations of t (for $j=1$), t_3 (for $j=2$) and t_4 (for $j=3$) of the rescaled data $CN / \overline{CN}$, where μ_{V_j}, σ_{V_j} are the means and standard deviations of V – the statistics derived from the simulated data. The numbers $j = 1,2,3$ represent the tests for heterogeneity in the LCV, L-skewness and L-kurtosis, respectively.

If $H_j < 1$, then the pooling group is considered to be homogeneous; if $1 \le H_j < 2$, then possibly heterogeneous; and if $H_j \ge 2$, then heterogeneous. In flood frequency analysis, the statistic H_1 plays a crucial role (Hosking and Wallis, 1997).

It should be stressed that in practice, no ideal except an approximate agreement of q is required. The spatial proximity is not needed for a group of catchments to be homogeneous. The groups should be as numerous as possible to obtain more benefits from regionalization. In flood frequency analysis the minimum number of station-year data (the sum of all the data in a region) is recommended to be 5T (Castellarin et al., 2001; Merz and Blöschl, 2005) or 3T (Gaál et al., 2013), where T is the target return period of the quantile Q that is to be estimated; $T(Q) = \frac{1}{P(X \ge Q)}$ where X is the flood discharge. Using the criterion 3T in the current paper, the minimum number of *CN*s in a homogeneous group should be 30 for the estimation of the 90%th quantile. Out of the symmetry, the same number was required for the estimation of the 10%th quantile.

Choice of the regional distribution function

If a group of catchments was homogeneous, the regional distribution function (RD) was selected among the Generalized Logistic (GLO), Generalized Extreme Value (GEV), lognormal (LN3), Generalized Pareto (GP), and Pearson III (P3) distributions. The parameters of each distribution were estimated using the L-moments method. The final decision was based on the statistics (Hosking and Wallis, 1997):

$$z^{dist} = \frac{\tau_4^{dist} - t_4 + B_4}{\sigma_4}, \tag{10}$$

where τ_4^{dist}, t_4 are the theoretical and sample L-kurtosis, and B_4, σ_4 are the simulated bias and standard deviation of the regional L-kurtosis. The value z^{dist} closest to 0 pointed at the best fit, assuming that $\left| z^{dist} \right| < 1.64$.

Antecedent runoff conditions of Hawkins and of Hjelmfelt

In the Hawkins method, the tabulated *CN*, denoted here as $CN(II)$, is transformed to $CN(I)$ and to $CN(III)$ using the formulas (ASCE, 2009):

$$CN(I) = \frac{CN(II)}{2.281 - 0.01381 \cdot CN(II)}, \tag{11}$$

$$CN(III) = \frac{CN(II)}{0.427 + 0.00573 \cdot CN(II)} . \qquad (12)$$

In the Hjelmfelt method, the moderate value of the CN is the 50%th quantile. It is denoted by $CN(II)_{Hje}$ in the current paper. The 10%th and 90%th quantiles are the ARC I and ARC III, denoted $CN(I)_{Hje}, CN(III)_{Hje}$. These three quantiles were estimated for each catchment from a region using Eq (4), where μ_i and $q(F)$ were the empirical mean values of the CN and the theoretical dimensionless quantiles in the $i-$th catchment, respectively, and where $F = 0.1, 0.5$ or 0.9.

Choice of the optimal λ

The $CN(I)$, $CN(II)$ and $CN(III)$ values were compared to the $CN(I)_{Hje}, CN(II)_{Hje}$ and $CN(III)_{Hje}$ for every λ For every catchment in a group, the mean absolute relative error was derived for every λ ,

$$MARE(\lambda) = \frac{1}{3}\left(\begin{array}{c} \dfrac{\left|CN(I) - CN(I)_{Hje}\right|}{CN(I)} + \\ \dfrac{\left|CN(II) - CN(II)_{Hje}\right|}{CN(II)} + \\ \dfrac{\left|CN(III) - CN(III)_{Hje}\right|}{CN(III)} \end{array} \right), \qquad (13)$$

and the regional MARE was

$$MARE_R(\lambda) = \frac{1}{N}\sum_{i=1}^{N} MARE_i(\lambda) \qquad (14)$$

where N was the number of catchments in the region. The final choice of λ was based on the minimum value of $MARE_R$ over all λ values, $\min_{\lambda \in \Lambda} MARE_R(\lambda)$, to guarantee the minimum discrepancy between the tabulated and estimated CN values.

The regional CN and antecedent runoff conditions of Hjelmfelt

If the mean values μ_i were not significantly different and the region was homogenous, the regional distribution was fitted to all empirical CNs in a region using the method of L-moments. The regional CN was proposed as the theoretical 50%th quantile estimated from all the empirical CNs in the region. The ARC I and III were the 10%th and the 90%th quantiles,

$$CN_R(I) = CN_{10\%},\ CN_R(II) = CN_{50\%},\ CN_R(III) = CN_{90\%} \qquad (15)$$

All the calculations were carried out in the R software environment (Hosking, 2019; R Core Team, 2018; Viglione, 2018). All tests were conducted at the significance level 0.05.

Study region and data

Ten small catchments in Slovakia and Poland were selected for the analysis. Figure 1 presents the location of the study areas in Slovakia and Poland. The Slovak catchments of Stupavský, Račiansky, Gidra, Vištucký, and Petrinovec creeks (denoted by A in Fig. 1) are located in the Inner Western Carpathians in Slovakia. The Stupavský creek rises on the eastern slope of the Little Carpathians. Although the stream is dry most days, it derives storm water from forests and vineyards. The length of the stream to the gauging station equals 16.7 km. The Račiansky creek rises in the southern part of the Little Carpathians on a western slope and flows through woods. The length of the creek to the gauging station is 7.1 km. The Gidra creek flows through forests and various recreational areas. The stream flows through vineyards, where it is aligned and has a straight route. The flow length is approximately 5.4 km. The Vištucký (Vištuk) creek, with a length of 5.9 km, has an oak forest, which covers most of the catchment. The Petrinovec creek is

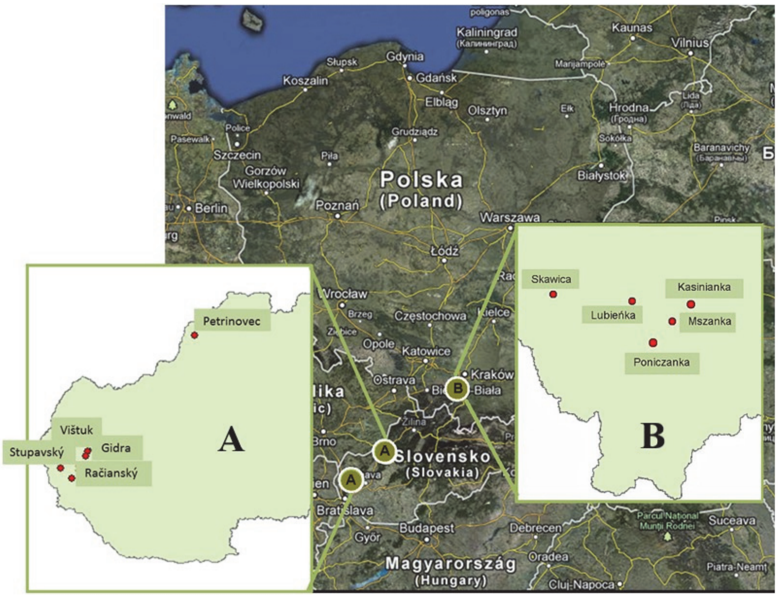

Fig. 1. Location of the study area. Slovak (A) and Polish (B) catchments.

located apart from the four catchments at Stredné Považie in the district of Púchov and rises in the Javorníky Mountains.

Its length is approximately 5.9 km to the gauging station, and it is the steepest catchment among all the catchments analysed. The mean elevation of the Slovak catchments ranges from 126 m a.s.l. at Račiansky to 1472 m a.s.l. at Petrinovec. All the catchments, apart from the Račiansky, have a typically forested character. Only small parts are croplands, urbanized areas, woodland shrubs, and tall grass. The soil type is B (silt loam or loam) in all the Slovak catchments. Therefore, their capability to produce direct runoff is not high. Most of the Slovak catchments have a typically forested character because the forest ratio can reach 0.90 there.

The Polish catchments of Poniczanka, Mszanka, Kasinianka, Lubieńka and Skawica (denoted B in Fig. 1) are located in the Central Carpathian Mountains (Fig. 1). The mean elevation of these catchments ranges from 570 m a.s.l. at Kasinianka to 900 m a.s.l. at Skawica. Skawica is the steepest catchment among the Polish ones. The catchments are mainly covered by forests, croplands, grasslands and pastures. Spruce, birch, fir, pine and oak trees dominate in the forests. Twenty percent of the arable lands are root crops (potatoes, beetroots, onions); 55% are corn (oats, wheat and rye), and 25% are legumes (clover, alfalfa, peas, beans). The thickness of the soil is low, and the two main soil types are C (over 90%, skeletal and loamy soils) and D (less than 10%, alluvial soils).

The capability to produce direct runoff is higher in the Polish catchments than in the Slovak catchments, which is reflected in the lower retention parameters and higher CNs. The average annual rainfall depth varies from 880 mm at Mszanka to 1200 mm at the Skawica catchments.

More detailed information about the creeks, catchments and sample lengths is given in Table 1. The tabulated values of the *CN*, which were determined from the soil and topography properties, are placed in the second column. They range from 62–72 for the Slovak catchments; similarly, the four Polish catchments of Poniczanka, Mszanka, Kasinianka and Lubieńka possess tabulated *CN*s of about 79. This observation was the main impulse for investigating as to whether each region was homogenous in *CN*.

Table 1. Summary of the selected catchment characteristics.

Creek	CN weighted tabulated values	Catchment area [km^2]	Forest ratio [–]	Number of events
Stupavský	65	33.0	0.89	28
Račiansky	72	21.0	0.35	23
Gidra	62	33.0	0.90	14
Vištucký	67	9.8	0.89	18
Petrinovec	65	6.0	0.86	28
Poniczanka	79.5	33.1	0.42	12
Mszanka	79.9	51.0	0.38	12
Kasinianka	79.7	32.0	0.44	13
Lubieńka	80.2	48.7	0.35	16
Skawica	75.3	48.6	0.78	11

The Slovak data from the selected catchments are provided by the Slovak Hydrometeorological Institute and the Department of Land and Water Resources Management, Slovak University of Technology, Bratislava, Slovakia. The Polish data were collected by the Department of Hydraulic Structures, University of Agriculture, Cracow, Poland.

To obtain the rainfall-runoff data (*P*, *H*), the discharge data for a 60 min time step were initially collected from all the stations analyzed. The 1-day heavy rainfall totals from the summer season, which were of a convectional rainfall origin, were recorded at the climatological gauging stations. Only the rain-gauge stations representative of the Vištucký and Gidra catchments have a one-hour resolution of rainfall. The lengths of the rainfall-runoff data observations range from 11 (Skawica station) to 28 (Petrinovec station) events, and the observation period ranges between the years 1988–2013. Secondly, clearly defined, single, extreme rainfall-runoff events were selected. The rainfall-runoff events had to be independent of other events and visibly distinguishable in the runoff data records. Additionally, the hyetographs that caused the runoff were approximately uniform. Subsequently, the hydrograph was analyzed for each event, and the direct runoff was separated by drawing a line from the point of the hydrograph rise to the beginning point of a fitted part of the recession curve matched to the recession segment, see Fig. 2 for an example.

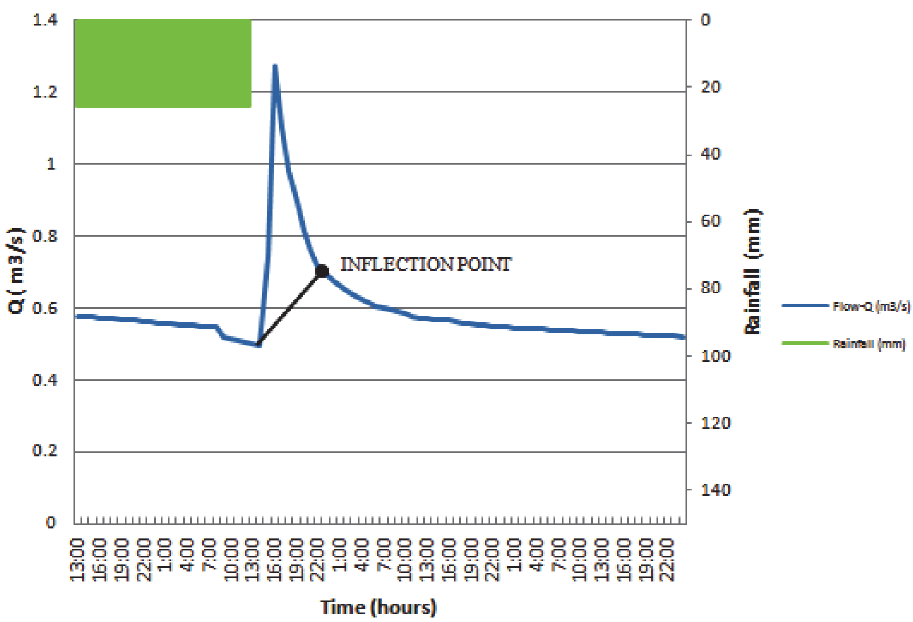

Fig. 2. An example of a hydrograph separation and a hyetograph for the Gidra River catchment.

RESULTS

The Hosking and Wallis regionalization method enables the verification of tabulated CN values based on rainfall-runoff data measurements. Specifically, it makes use of merging small samples into a large sample where the distribution fitting may lead to more reliable CN values than for each small sample separately.

The sample L-moments, l_1, t, t_3 and t_4 are collected in Table 2.

The mean values l_1 decrease with the decreasing λ, because the lower values of λ result in a lower CN, which can be concluded from Eq. (4). The characteristic t slightly grows with decreasing λ. The sample skewness t_3 is negative, apart from the Vištucký, and increases with decreasing λ. Hence, for a low λ, the empirical distribution function tends to be more symmetrical. This tendency can be also observed in the sample kurtosis t_4, which decreases with decreasing λ and is close to the kurtosis of the normal distribution, i.e. 0.12 for certain catchments.

The Slovak catchments have lower mean values and slightly higher variations in comparison to the Polish catchments. The Slovak catchments have a lower range of t_3 and t_4 than the Polish catchments. Among the Polish catchments, B2 has the highest skewness in its absolute value and the highest kurtosis for all λ.

The normality assumption for the ANOVA test was fulfilled in all catchments and for all λ, apart from the Gidra catchment for $\lambda = 0.2$ with p-value $= 0.01$ and for $\lambda = 0.1$ with p-value $= 0.04$. However, because of robustness of ANOVA to small deviations from normality, all the catchments were designated for further analysis. The Levene's test resulted in high p-values, from 0.39 to 0.76 for both groups of catchments and all λ, apart from the Slovak group for $\lambda = 0.2$ with p-value = 0.02.

The ANOVA and Scheffe's tests revealed that in the group of the Slovak catchments, the Petrinovec differed from the others in the mean value of the CN of every λ. No differences in the mean values were identified in the group of Polish catchments for $\lambda = 0.20$. However, for $\lambda = 0.15$ and $\lambda = 0.10$, the Poniczanka catchment had higher mean value than the others. The results were confirmed by the Kruskal-Wallis test and by its post-hoc versions which has been applied due to some violations from normality. This means that there are no significant differences in CN between catchments within every group. The following groups were established:

SL_λ = {Stupavský, Račiansky, Gidra, Vištucký} for $\lambda = 0.20, 0.15, 0.10$,

$PL_{0.20}$ = {Poniczanka, Mszanka, Kasinianka, Lubieńka, Skawica}

PL_λ = {Mszanka, Kasinianka, Lubieńka, Skawica} for $\lambda = 0.15$ and $\lambda = 0.10$.

The results of the HW tests are presented in Table 3. All H_1 values were less than 1 within the groups SL_λ and PL_λ, which proved the homogeneity in L-CV within every group. Similarly, SL_λ and $PL_{0.20}$ were homogeneous in L-skewness and L-kurtosis; however, H_2 and H_3 were greater than 1 for $PL_{0.15}$ and $PL_{0.10}$, which suggested heterogeneity in these two parameters. The Generalized Logistic (GLO) was designated to the regional distribution function, apart from $SL_{0.10}$ where the Pearson 3 distribution (P3) gave a better fit.

Table 2. Sample L-characteristics of *CN* the Slovak and Polish catchments for various initial abstraction ratios λ .

	Stupavský	Račiansky	Gidra	Vištucký	Petrinovec	Poniczanka	Mszanka	Kasinianka	Lubieńka	Skawica
	$\lambda = 0.20$									
l_1	65.74	65.64	67.02	66.90	73.30	88.34	82.55	79.68	80.67	80.79
t	0.05	0.05	0.05	0.05	0.07	0.04	0.05	0.06	0.05	0.03
t_3	–0.10	–0.15	–0.72	–0.25	–0.19	–0.23	–0.63	–0.06	–0.13	–0.28
t_4	0.14	0.16	0.66	0.14	0.19	0.29	0.44	0.00	0.09	0.27
	$\lambda = 0.15$									
l_1	64.04	60.44	66.54	63.29	71.48	87.78	80.67	76.50	77.64	78.60
t	0.06	0.06	0.07	0.06	0.09	0.04	0.05	0.07	0.06	0.04
t_3	–0.10	–0.12	–0.41	–0.08	–0.10	–0.19	–0.67	–0.04	–0.10	–0.29
t_4	0.06	0.14	0.65	0.19	0.22	0.21	0.50	0.02	0.08	0.25
	$\lambda = 0.10$									
l_1	58.30	53.12	64.82	57.00	68.98	85.64	76.64	71.92	73.28	76.08
t	0.09	0.07	0.08	0.08	0.10	0.05	0.05	0.08	0.08	0.06
t_3	–0.03	–0.06	–0.25	0.02	–0.11	–0.16	–0.64	–0.02	–0.07	–0.07
t_4	0.10	0.10	0.18	0.21	0.20	0.17	0.52	0.04	0.07	0.39

Table 3. Measures of the heterogeneity test in the groups of Slovak (SL) and Polish (PL) catchments for various initial abstraction ratios λ, the measure z^{dist}, and the regional distribution (RD).

	$SL_{0.2}$	$SL_{0.15}$	$SL_{0.1}$	$PL_{0.2}$	$PL_{0.15}$	$PL_{0.1}$
H_1	–1.36	–1.52	–1.41	–0.82	–0.42	–0.34
H_2	0.21	–0.78	–0.35	0.11	1.52	1.49
H_3	0.00	0.10	–0.70	0.25	1.31	1.97
z^{dist} / RD	–0.18 / GLO	0.08 / GLO	–0.29 / P3	0.15 / GLO	0.20 / GLO	–1.13 / GLO

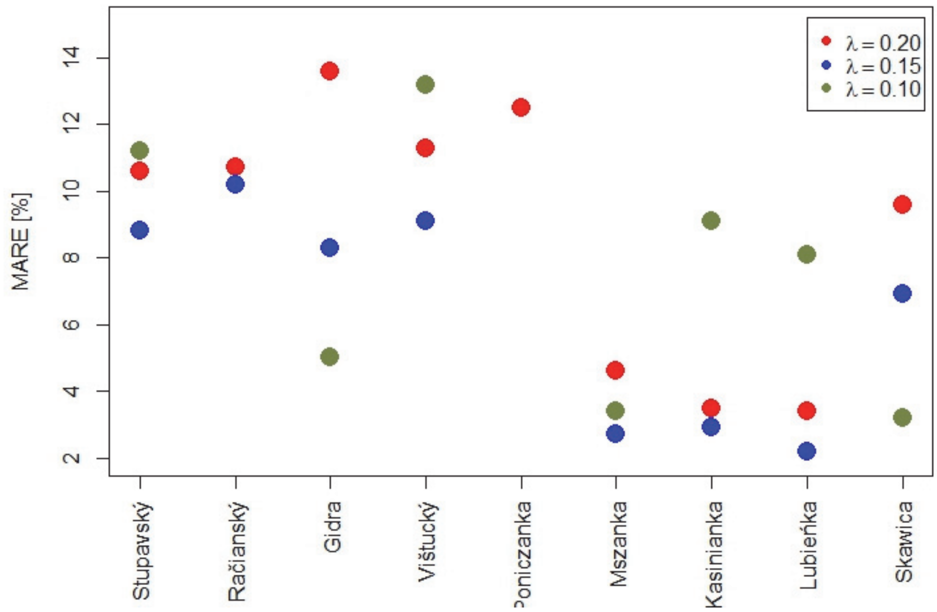

Fig. 3. The error $MARE(\lambda)$ (Eq. (13)) (in %).

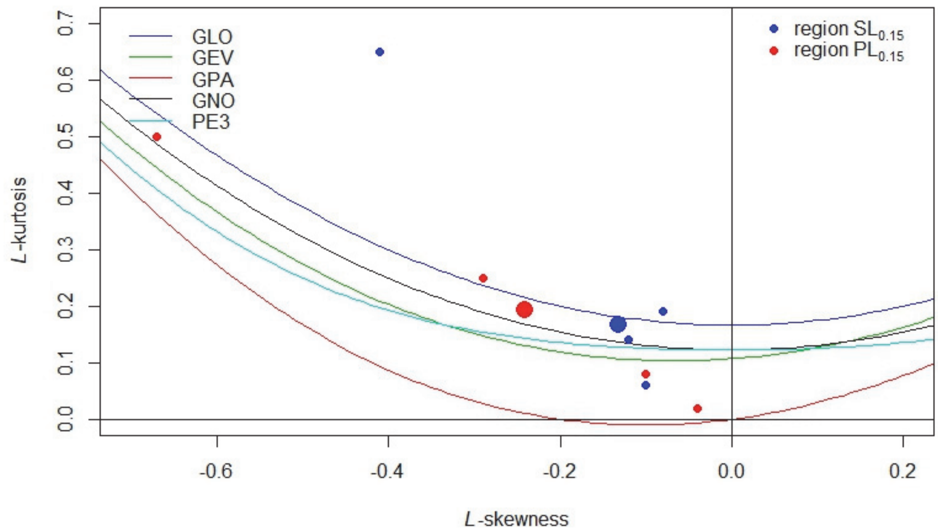

Fig. 4. The L-moment ratio diagram for the Slovak and Polish regions with abstraction ratios λ = 0.15 ($SL_{0.15}$ and $PL_{0.15}$). The small bullet points depict the catchment characteristics and the thick bullet points depict the regional characteristics.

For the choice of the optimal abstraction ratios λ, the $MARE(\lambda)$ error (Eq. (13)) was derived for every catchment from groups SL_λ and PL_λ. The results are presented in Fig 3.

The lowest regional $MARE_R(\lambda)$ (Eq. (14)) equal to 9.1% was achieved for λ = 0.15 in the group $SL_{0.15}$ and equal to 3.6% in the group $PL_{0.15}$.

Finally, the following homogenous regions were delineated: $SL_{0.15}$ = {Stupavský, Račiansky, Gidra, Vištucký} and $PL_{0.15}$ = {Mszanka, Kasinianka, Lubieńka, Skawica}.

The L-moment ratio diagram for the regions $SL_{0.15}$ and $PL_{0.15}$ was plotted in Fig. 4. The catchment's and regional L-skewness and L-kurtosis are depicted there. The closeness of the GLO line to the regional points confirms the final choice of the regional distribution.

For those groups the regional CN s were obtained from Eq. (15), namely

$$CN_{SL_{0.15}}(I) = 54.50 \qquad CN_{SL_{0.15}}(II) = 64.28$$
$$CN_{SL_{0.15}}(III) = 72.20$$
$$CN_{PL_{0.15}}(I) = 68.15 \qquad CN_{PL_{0.15}}(II) = 79.43$$
$$CN_{PL_{0.15}}(III) = 87.01$$

Observe that $CN_{SL_{0.15}}(II)$ slightly differed from the tabulated values with a mean value of about 66 in the Slovak catchments and of about 75.3 in the Skawica catchment. These findings permit the conclusion that, for practical purposes, the tabulated *CN*s should be corrected in those catchments, because they seem to be too high in the Račiansky and Vištucký and too low in the Skawica catchments.

Apart from the main subject of the study, the heterogeneity in q was tested in all ten catchments. Surprisingly, all the H_js were less than one, which proved similarity in the distribution of the rescaled *CN* for all the Carpathian catchments investigated.

DISCUSSION AND CONCLUSION

The paper focuses on an estimation of the regional *CN* values for a group of ten small Slovak and Polish catchments. The Slovak catchments are located in the Inner Western Carpathians in Slovakia; the areas of the catchments are in a range of 6 – 33 km^2. Most of the Slovak catchments have a typically forested character, achieving a forest ratio of 0.90. The tabulated values of the *CN*, which were determined from soil and topography properties range from 62 to 72. The Polish catchments with areas in a range from 33.1 to 51 km^2, are located in the Central Carpathian Mountains. The four Polish catchments of Poniczanka, Mszanka, Kasinianka, and Lubieńka possess tabulated *CN*s of about 79, the Skawica catchment has a lower *CN* about 75.

For estimating empirical *CN*s, the individual rainfall-runoff events were collected for all the catchments from the summer season of 1988-2013; the number of events analyzed ranged from 11 to 28. The discharge data were collected in a 60 min time step, and the direct runoff was separated from all the selected hydrographs by a graphic separation method. Rainfall data were collected in a 1-day time step; only the rain-gauge stations representative of the Vištucký and Gidra catchments have a one-hour resolution of rainfall.

The L-moment based method of Hosking and Wallis and the ANOVA test were combined to delineate the area in two homogenous regions of catchments with similar *CN* values. The combination of these methods revealed homogeneity in *CN* within the regions of the four Slovak and four Polish catchments. They possessed similar mean *CN* values and were similarly distributed.

For the choice of the optimal λ, the $MARE(\lambda)$ error was derived for every catchment from groups SL_λ and PL_λ. The lowest $MARE_R(\lambda)$ was achieved for $\lambda = 0.15$,which is equal to 9.1 % for the group $SL_{0.15}$ and 3.6% for the group $PL_{0.15}$.

The optimization condition allowed for the choice of $\lambda = 0.15$ in every region. This is in accordance with other studies in forested catchments in Slovakia, e.g., Karabová and Marková (2013), revealed the estimated coefficients λ below 0.2.

The regional *CN* was proposed as the 50%th quantile of the theoretical distribution function estimated from all the *CN*s in the region. These estimations of the *CN*, which are more representative of catchment heterogeneities, slightly differed from the tabulated *CN*s. The ARC of Hjelmfelt were estimated as the 10%th and 90%th quantiles. In the future, further catchments can also be added to the study to broaden the groups with similar *CN*s.

In relation to the problem of forming regions, it is worth remembering that the HW tests were designed to flood frequency where the distributions of annual maxima flows are skewed while the ANOVA test assumes normality to enable the comparison between mean values. The procedure presented in this paper can therefore be applied when the violations from normality are not large and the variances are not far different. The use of the Kruskall-Wallis test enabled the verification and potential re-delineation of groups if the assumptions of ANOVA were not fulfilled. On the other side, in general, the strong ANOVA assumptions may not always be fulfilled in groups of catchments with similar *CN* values. The expert knowledge about the study area is sometimes needed to verify the regions. Summarizing, the procedure presented in this paper is useful when the distributions of CNs are not very far from symmetrical and the differences between variances are not large. Another method of regionalization should be used instead.

Due to its basic empirical character, the SCS-CN method has several limitations and drawbacks, and it is restricted to certain geographic regions and land use types. It works well for small agricultural catchments but has significant shortcomings for other types of catchments, specifically forested catchments (Barlett et al., 2016, 2017). The *CN* values determined from look-up tables as a dimensionless catchment index are usually considered as a fixed parameter. However, they are random variables that change with regional rainfall-runoff processes, hydrological soil groups, land-use conditions, antecedent rainfall and soil moisture, and vary across different sources of spatio-temporal variability. Besides, the tabulated *CN* values are appropriate for slopes of around 5% because these reference values were identified from small agricultural catchments where slope does not play a significant role (Verma et al., 2017).

To move beyond some of these limitations and extend the applicability of the SCS-CN method for forested catchments in the Carpathian Mountains, the *CN* values for individual catchments treated were determined from observed rainfall-runoff events. A statistical framework that provides a quantitative basis for regional estimates of the *CN* values together with the optimization of the initial abstraction of λ was developed. Accordingly, the paper brings a novel approach to the estimation of *CN* value based on regional *CN* that may better represent geographic regions and site types that the traditional SCS-CN method and can give rise to verify this approach in other regions of the world. The additional benefit of introducing a common regional *CN* is the opportunity to apply in catchments with a lack of data or without observations, and with similar soil-physiographic characteristics. Accuracy of estimated empirical CNs strongly depends on a number of analyzed rainfall-runoff events. Therefore, regional methods for estimating empirical CN are helpful where several small samples are put together in a large homogeneous sample and where the distribution fitting may lead to more reliable *CN* values than for each small sample separately.

The methodology still has issues requiring further improvement, which can also be achieved by estimating λ as a regional parameter.

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