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CURVE NUMBER ESTIMATION FOR A SMALL URBAN CATCHMENT FROM RECORDED RAINFALL-RUNOFF EVENTS

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Abstract: Runoff estimation is a key component in various hydrological considerations. Estimation of storm runoff is especially important for the effective design of hydraulic and road structures, for the flood flow management, as well as for the analysis of land use changes, i.e. urbanization or low impact development of urban areas. The curve number (CN) method, developed by Soil Conservation Service (SCS) of the U.S. Department of Agriculture for predicting the flood runoff depth from ungauged catchments, has been in continuous use for ca. 60 years. This method has not been extensively tested in Poland, especially in small urban catchments, because of lack of data. In this study, 39 rainfall-runoff events, collected during four years (2009–2012) in a small (A=28.7 km^2), urban catchment of Służew Creek in southwest part of Warsaw were used, with the aim of determining the CNs and to check its applicability to ungauged urban areas. The parameters CN, estimated empirically, vary from 65.1 to 95.0, decreasing with rainfall size and, when sorted rainfall and runoff separately, reaching the value from 67 to 74 for large rainfall events.

INTRODUCTION

Estimation of direct runoff, which is also called the effective rainfall, as response to heavy rainfall is often required for both: agricultural and urban catchment flood management [2, 10, 11]. Among many ways of its estimation for ungauged catchments a great reputation enjoys a curve number method proposed in the 1950s by the USDA Soil Conservation Service – USDA-SCS [23, 27, 37]. The Natural Resources Conservation Service curve number (NRCS-CN) method, earlier called the SCS-CN method, represents an event-based lumped conceptual approach and is often used due to its simplicity and practical design. Utilizations of the method for small catchments in Poland have been carried on for more than 30 years [6, 19, 20, 25]. Nevertheless, a number of studies, which consider recorded rainfall-runoff events from gauged catchments, is still very limited [6, 8, 9]. In this work, 39 rainfall-runoff events, collected during four years (2009–2012) in a small (A=28.7 km^2) urban catchment of Służew Creek, located in southwest part of Warsaw, were used with the aim of determining the CNs and comparing them with the CN-table value.

RESEARCH METHODOLOGY

Description of the NRCS-CN method

The original equation for runoff estimation was developed applying the basic water budget for rainfall event, i.e. on the assumption that rainfall (P) is distributed for two components, i.e. runoff (H) and losses (L), all in depth units [16]. Then maximum potential retention of the catchment (S) was defined as upper limit of losses (L), when rainfall (P) is reaching infinity, and finally equality between H/P and L/S was assumed. As a result, after substituting the losses (L) by difference of rainfall and runoff (P-H), the following equation for storm runoff was found:

$$H = \frac{P^2}{P + S} \tag{1}$$

where H is runoff (mm), P is rainfall (mm) and S is maximum potential retention of the catchment (mm).

After introducing initial abstraction and assuming its amount as 0.2S, the commonly used equation was presented in the form:

$$H = \begin{cases} \dfrac{(P - 0.2S)^2}{(P + 0.8S)} & for \quad P > 0.2S \\ 0 & for \quad P \leq 0.2S \end{cases} \tag{2}$$

The maximum potential retention (S) has been arbitrary related to the catchment curve number (CN) [16], which in metric units, forms the equation:

$$S = 25.4\left(\frac{1000}{CN} - 10\right) \tag{3}$$

where CN is curve number, i.e. nondimensional quantity varying in the range (0,100>, and for ungauged catchment it is estimated on the basis of land use and soil type as constant factors, and of land moisture and hydrological conditions as variable ones.

Tables and charts for CN as a function of land use and soil types were given in NEH-4 for agricultural areas and in TR-55 for urban catchments. The NRCS-CN method has gained general acceptance in engineering practice due to its simplicity in estimating storm water runoff depth from rainfall depth [7, 11, 12, 16, 18, 21, 31, 40]. For design, the CN value is selected for ungauged catchments representing an acceptable level of risk. Historically, the method for determining the design CN value has been used to select it from tabulated values in published handbooks such as the SCS National Engineering Handbook Section 4: Hydrology (NEH-4) or Technical Release 55 (TR-55) based on watershed characteristics including the hydrologic soil group (HSG), land use, surface condition, and antecedent runoff condition (ARC) [4, 36–38].

Estimation of the CN from rainfall-runoff data

Solving Eq. (2) for S as a function of rainfall depth (P) and runoff depth (H) [15] gives:

$$S = 5\left(P + 2H - \sqrt{\left(4H^2 + 5P \cdot H\right)}\right) \tag{4}$$

where S is maximum potential retention of the catchment, P is the storm rainfall depth and H is the storm runoff depth, all in mm.

The curve number for each event can be calculated from the converted Eq. (3) to the form:

$$CN = \frac{25\,400}{S + 254} \tag{5}$$

When equations 4 and 5 are used to calculate values of CN from observed rainfall depth and runoff depth, a strong secondary relationship between CN and P often develops. The CN method is often used as a transformation of design rainfall depth to design runoff depth for a given return period. Frequency matching or rank ordering rainfall and runoff data separately to approximate the same frequency (ordered pairs) is a useful approach for determining a CN value from data [15, 17]. Such approach, i.e. estimating the CNs for pairs of rainfall and runoff depths, ordered separately in descending way, used in some earlier researches [9, 26, 32, 34, 35], has been also applied in the presented investigation for small urban catchment located in Warsaw.

Study area and data used

The catchment of Służew Creek, located in the southwest part of Warsaw, is a research area of the Department of Water Engineering, in which rainfall-runoff and water quality issues have been investigated for over 25 years [1, 5, 22, 29, 30]. The stream passes through the following districts of Warsaw: Włochy, Okęcie, Grabów, Ursynów and Wilanów. The investigation, conducted for the upper part of the catchment, upstream of the gauge at Wyścigi Pond, is shown in Fig. 1.

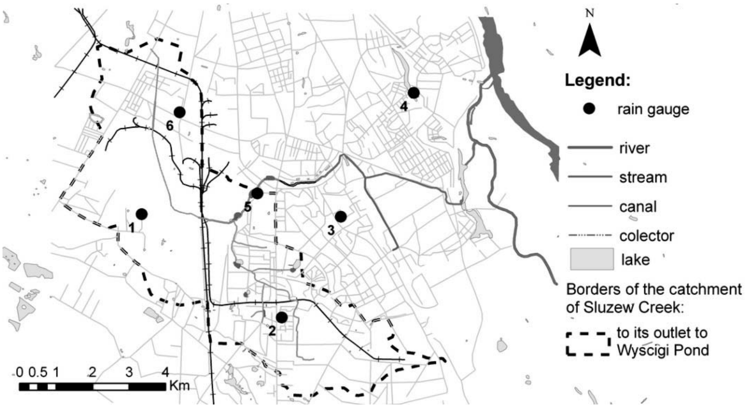


Fig. 1. Służew Creek catchment upstream of the Wyścigi gauge

Its area is 28.7 km^2 and the impervious factor of the catchment is about 22% [3, 13, 28]. The catchment is heterogeneous in terms of land development. The northern part can be characterized by stronger urbanization, as it is encircled by housing estates and the Okęcie airport. Further south, there are single-family houses, fields, wastelands and woodlands. From this area, the water reaches the Służew Creek flowing through a network of artificial canals, and the watercourses pass through several small detention ponds.

The catchment area is flat, there are no hills or depressions. The land slopes are inconsiderable. The analyzed catchment, upstream of Wyścigi Pond, is located on moraine upland. It is composed mostly of boulder clay and fluvioglacial sands. Undeveloped areas are covered with vegetation typical for such urban green areas, e.g. weeds, ruderal species accompanying allotments [14]. The average annual precipitation for that part of Warsaw is estimated for 510–530 mm [13, 24]. The table curve number value for the catchment, treated as ungauged one, was estimated as CN_{tabl}=75.8 [13, 28], based on topographic and soil maps.

The rainfall data, for this study, was derived from six rain gauges located within the area, and outside the catchment (Fig. 1). Five of them were installed and operated by the Division of River Engineering of Warsaw University of Life Sciences – SGGW, and one of them, marked as 1 in Fig 1, was operated by Okęcie Airport. The rainfall depth was recorded in 10-minute intervals. The average areal rainfall for the analyzed part of catchment was determined by means of the Thiessen polygon method. Water level at Wyścigi gauge, which is located just upstream of the Wyścigi Pond, was recorded with use of a digital limnigraph, also in 10-minute intervals. Water level records were verified by staff gauge readings, which were conducted two or three times a week. Based on the rating curve, estimated with use of hydrometric measurements and hydraulic relationship, the water levels were converted to stream flow. Monitoring of the precipitation and stream flow was carried out from May 2009 to November 2012. For further analysis, we selected events for which the peak flow was at least four times greater than the average long period discharge. Winter floods, i.e. caused by snowmelt, were excluded from the investigations. The characteristic of 39 rainfall-runoff events selected for the analysis, with the computed CNs according the Eqs 4 and 5, are presented in Table 1.

Table 1. Characteristics of the 39 recorded rainfall – runoff events

Category	Unit	Value for the events	
		average	range
1	2	3	4
Rainfall depth – P (avg. in the catchment)	mm	24.3	8.0–56.9
Rainfall depth – P (at Okęcie gauge)	mm	20.8	5.8–75.2
Runoff depth – H	mm	2.49	0.6–17.8
Peak discharge – Q_{max}	m^3/s	1.76	0.89–5.74
Curve Number	–	82.2	65.1–95.0

RESULTS AND DISCUSSION

The purpose of this study was: (i) to estimate the values of CN_{emp} (empirical) for each of the recorded rainfall-runoff events, (ii) to estimate the catchment (design) CN_{design}, which can be assumed as representative for computing design runoff from design rainfall, (iii) to compare the last one (CN_{design}) with the table CN, i.e. with CN_{tabl}, estimated in the earlier analysis, as $CN_{tabl} = 75.8$ [3, 13, 28], from the land use and soil maps.

The CNs were computed from recorded rainfall depths H, and runoff depths P, according to Eqs 4 and 5 for each of the 39 events, and the relationship H vs. P are shown in Figure 2 (as dots), with the relationship H vs P estimated for $CN_{tabl}=75.8$, from equation 2 and 3 (shown as line). In Figure 3 the empirical CN values, which range from 65.1 to 95.0, are related to rainfall depth of the events. The distribution of the dots in Figure 3 indicates a strong secondary relationship between curve number vs. rainfall depth, i.e. the CNs are decreasing with the increase of rainfall depths. Hawkins [15] proposed to use asymptotic functions for approximation of the relationship CN vs. P values, after applying a sorting technique to the measured data.

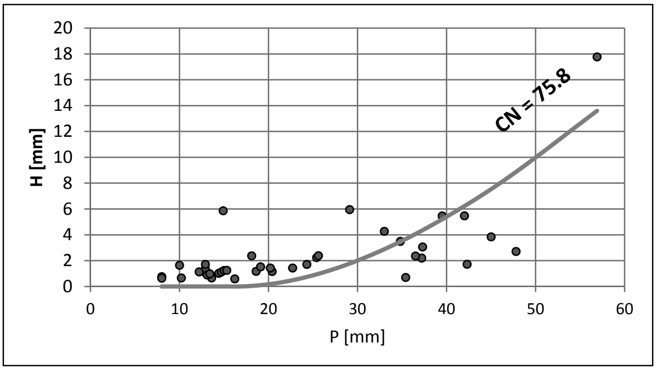


Fig. 2. Relationship of runoff depth (H) vs. rainfall depth (P) for the 39 recorded events (dots) and for the $CN_{tabl}=75.8$ (line)

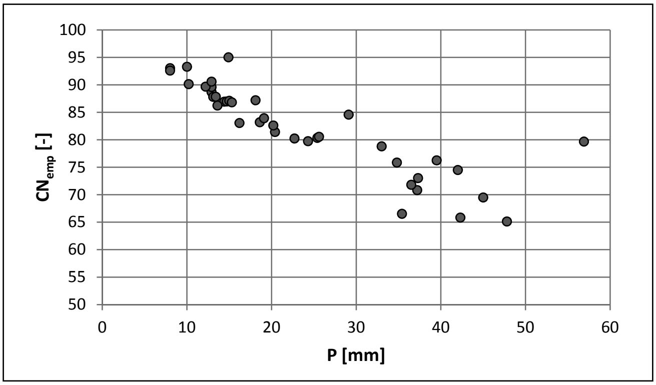


Fig. 3. Curve Number of recorded events versus rainfall depth

This technique is based on the frequency matching concept, i.e. the rainfall depths and runoff depths are sorted separately, and then realigned on the rank-order basis to form P:H pairs of equal return periods. As Hawkins indicated [15], CNs calculated from the recorded data for the matched pairs, according to equation 4 and 5, approach a constant value with increasing rainfall. A standard asymptote occurs if there is a tendency for CN to decline and then approach a constant value with increasing P according to formula:

$$\mathrm{CN(P)} = \mathrm{CN}_{\infty} + (100 - \mathrm{CN}_{\infty})\exp\left(-\frac{\mathrm{P}}{\mathrm{b}}\right) \tag{6}$$

where CN_{∞} is a constant approached as $P \to \infty$; and ***b*** is a fitted constant.

The 39 pairs P vs CN are plotted in Fig. 4. Table Curve 2D software [33], "Automated curve fitting and equation discovery" of SYSTAT has been used to find parameters of the formula 5. The flowing relationship was found:

$$\mathrm{CN(P)} = 67.3 + 32.7\exp\left(-\frac{\mathrm{P}}{27.3}\right) \tag{7}$$

with r^2 (coefficient of determination) = 0.925 and SE (standard error of estimation) of CN = 1.78. Relatively high coefficient of determination of the equation 6, confirms the standard behavior of the catchment, i.e. declining of CN with increasing storm size and then approaching a near constant value with increasingly larger storms, what happens in about 70% of all watersheds evaluated [15, 39]. However, the $\mathrm{CN}_{\infty} = 67.3$ seems to be significantly lower than the tabulated $\mathrm{CN}_{\mathrm{tabl}} = 75.8$ estimated on the basis of land use and soil types. So, using $\mathrm{CN}_{\infty} = 67.3$ as design value for estimating response of the catchment to 100-year rainfall would led to significant underestimation of design flood. Also computing CN(P) according equation 7 for P=70 mm and 80 mm, what accounts for rainstorm of 100-year return period of duration 8 and 20 hours [3], one receives CN=69.8 and CN-69.0, what still seems to be too big difference with comparison to $\mathrm{CN}_{\mathrm{tabl}}$.

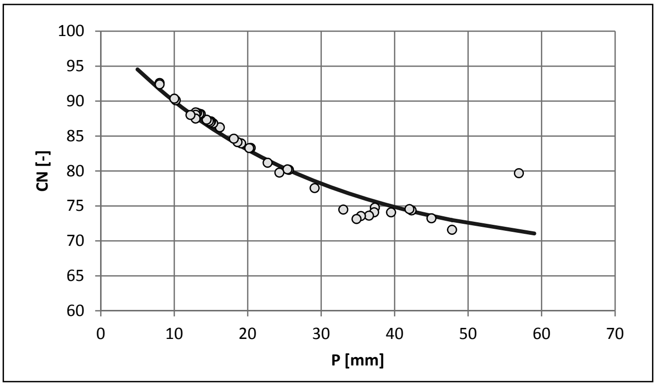


Fig. 4. CNs estimated on the based on rainfall and runoff data ranged separately (dots), with approximation relationship 6 (CN vs. P)

As the CNs, computed for 39 pairs of P-H, earlier ordered separately, indicate systematic decrease with P (Figure 4), in search for better agreement the CN of large rainfall depth with the CN_{tabl}, two other relationships of CN versus rainfall depth are presented, one from a group of kinetic functions and the other from a group of peak functions. To estimate the parameters of the set of functions of two groups of functions, the above mentioned TableCurve 2D software [33] was used. The following functions were selected as the best approximations:

- from the set of kinetic equations, the variable order decay function (DecayN):

$$\mathrm{CN(P)} = \mathrm{CN_L} + [b^{1-d} + cP(d-1)]^{1/(1-d)} \tag{8}$$

where: $\mathrm{CN_L}$ is curve number for large P, b is amplitude, c and d – are fitted constants,

- from the set of symmetric peak functions the best approximation was reached for complementary error function peak (Erfc Peak) in the form:

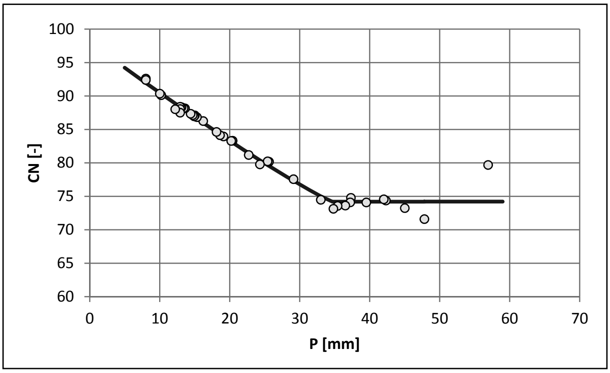
$$\mathrm{CN(P)} = \mathrm{CN}_\infty + \mathrm{b\ erfc}\left[\left(\frac{P-c}{d}\right)^2\right] \tag{9}$$

where CN_∞ is a constant approached as P→∞; b is amplitude, c – location parameter (mode), d – scaling parameter, i.e. parameter related to full width at half-maximum of amplitude (FWHM is 1.381d). The values of the constants of equations 8 and 9, as well as measure of approximation functions 7–9, i.e. determination coefficients and standard errors of estimation, are presented in Table 2. The relationships 8 and 9 are also presented in the Figure 5.

Table 2. Characteristics of the various statistical relationships of CN vs. rainfall depth

Relationship	Equation number	Values of parameters	Determination coefficient – r^2	Standard error of estimation
1	2	3	4	5
Standard asymptotic function	7	$\mathrm{CN}_\infty = 67.3$ b = 27.3	0.925	1.78
Variable order decay function (DecayN)	8	$\mathrm{CN_L} = 74.2$ b = 23.8 c = 0.552 d = 0.103	0.972	1.13
Complementary error function peak (Erfc Peak)	9	$\mathrm{CN}_\infty = 74.1$ b = 20.3 c = -3.31 d = 31.8	0.966	1.24

CN_∞, $\mathrm{CN_L}$, *b*, *c*, *d* – estimated parameters of the Eqs (7)–(9)



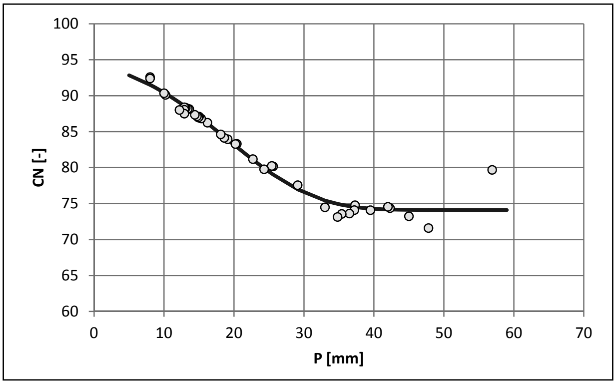


Fig. 5. CNs estimated on the based on rainfall and runoff data ranged separately (dots), with approximation relationship 8 (upper graph) and 9 (lower graph)

The value CN(P) = CN_L in equation 8 is reached when the value of the expression in brackets is not larger than zero, which after rearranging assumes the form:

$$P \geq \frac{b^{1-d}}{c(1-d)} \tag{10}$$

where b, c and d are fitted constants of eq. 8. After inserting the constants as given in Table 2, one receives P≥34.7 mm, for which CN(P) = CN_L = 74.2.

Analyzing the equation 9 with the fitted parameters as in Table 2, one can find out that for P≥45 mm the values of erfc(x^2) is close to zero, so one can replace CN_∞ by CN_L, and consequently would receive CN(P) = $CN_L \approx 74.1$.

In both cases the values CN_L equal to 74.2 and 74.1 are relatively close to the table value CN_{tabl} = 75.8, which should be assumed as confirmation of the curve number method as reliable procedure for estimating runoff depth as urban catchment response to design rainfall. The table CN_{tabl} is 1.7 and 1.6 above that of CN_L, estimated on the basis of empirical data according to the equations 8 and 9. This will cause also slight difference in flood prediction, i.e. overestimation when using CN_{tabl} in comparison with the application of CN_L. As the difference in CN is quite small, and application of FFA (flood frequency analysis) for verification is not possible, as continuous land use changes take place in the catchment, the recommendation for further study are:

- in respect of this catchment;
    - to carry out a similar investigation, however with splitting the investigating area for two sub-catchments to be able to consider the differences in land use between them and for estimating more reliable rainfall, assumed as lumped values, of the events,
    - to collect additional set of rainfall-runoff data to confirm these findings,
- in respect of other natural or agricultural small catchments, with long rainfall--runoff records, where land use changes are insignificant – to compare results of presented procedure with the results of flood frequency analysis.

CONCLUSIONS

The following conclusions can be drown from the investigation:

- the values of curve number estimated from the recorded rainfall-runoff events characterize large variation, since 65.1 to 95.0 with the mean value equals 82.2. As there is tendency for CN decreasing with increase of rainfall depth, application of mean CN for design flood estimation is not allowed. Table CN, estimated for the investigated catchment as for ungauged are, on the basis of land use and soil types was $CN_{tabl} = 75.8$.
- applying the frequency matching concept, i.e. after sorted the rainfall depths and runoff depths separately, and estimating CNs for rank-order P:H pairs of equal return periods, we confirmed that standard asymptotic relation occurs, with a tendency for CN to decline and then approach a constant value with increasing P, as suggested in many contributions of Hawkins and others. However the approached constant, as well as CN(P) for design P, were significantly lower than CN_{tabl}, what would produce underestimation in flood runoff when applied for designing.
- the value of CNs, estimated with the frequency matching concept, are well approximated with rainfall depths by the following equations: (i) the variable order decay function (DecayN), and (ii) complementary error function peak (Erfc Peak). In both cases CN_L for large rainfall (i.e. for $P \geq 34.7$ mm, and $P \geq 45$ mm, for the first and the other case) was 74.2 and 74.1, for the first and the other function, respectively. Good agreement, i.e. very small differences between the CN_L and CN_{tabl}, allow to accept the curve number procedure for applying it in designing flood runoff from urban catchments,
- further investigations would be specially required in natural or agricultural small catchments, with long rainfall-runoff records, where land use changes are insignificant – to compare results of application of the curve number procedure with results of flood frequency analysis.

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WYZNACZENIE PARAMETRU ODPŁYWU CN MAŁEJ ZLEWNI ZURBANIZOWANEJ NA PODSTAWIE ZAREJESTROWANYCH ZDARZEŃ OPAD-ODPŁYW

Wyznaczenia odpływu jest jednym z kluczowym zagadnień badań hydrologicznych. Określenie warstwy odpływu z opadów burzowych jest potrzebne zarówno do prac projektowych, tj. do wymiarowani obiektów hydrotechnicznych (jazy, zapory) i komunikacyjnych (mosty, przepusty), jak i do analiz skutków zmian środowiskowych jak; użytkowania terenu, urbanizacji czy zwiększania retencyjności w terenach miejskich. Jedną z najbardziej rozpowszechnionych w praktyce inżynierskiej metod, do wyznaczania odpływu w zlewniach nieobserwowanych, jest opracowana w latach 50-tych ubiegłego wieku, przez Departament Rolnictwa USA, metoda – SCS-CN (Soil Conservation Service – Curve Number). Celem pracy jest sprawdzenie stosowalności metody w przykładowej małej zlewni zurbanizowanej (A=28.7 km^2) w Warszawie, poprzez wyznaczenie parametru metody (CN), na podstawie zarejestrowanych 39 zdarzeń opad-odpływ w latach 2009–2012, i porównanie jej z wartością tablicową (wyznaczoną na podstawie rodzaju gleb i pokrycia terenu zlewni). Analiza zarejestrowanych zdarzeń opad-odpływ wykazała zmienność parametru CN, określonego dla każdego ze zdarzeń, w zakresie od 65 do 95, z tym że wartości te maleją wraz ze wzrostem warstwy opadu. Wyznaczając CN dla par, niezależnie uszeregowanych warstw, opadu i odpływu stwierdzono, że dla dużych opadów (przekraczających 35 mm) parametr CN dąży do wartości 67–74, w zależności od rodzaju przyjętej funkcji aproksymacji, i jest zbliżony do wartości ustalonej z map glebowych i użytkowania zlewni.