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Estimating Curve Number under changing catchment's land cover structure

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Abstract: The Curve Number method, developed in the 1950s in the United States, is commonly used to estimate runoff depth resulting from heavy rainfall. Over many years, it has been tested in various regions and for purposes beyond its original use. Despite numerous studies on this method, some issues still require consideration, i.e., a universally accepted procedure for CN determination from rainfall-runoff data. In this work, the authors attempt to estimate the CN parameter for a small, lowland catchment in central Poland. Historical data on catchment land cover and original rainfall-runoff measurements are used to determine the CN values for three periods characterized by different catchment land-cover structures. The applied approaches for CN estimation are compared and discussed. The study indicates that: i) over the period 1974-2018, a gradual increase in forested areas was observed, accompanied by a decrease in the average CN value (on average, a 1% increase in forest cover reduces CN by 0.2), ii) among approaches based on rainfall-runoff data, the least-squares calibration appears to be the most straightforward method for CN estimation; while the asymptotic approach may additionally identify a threshold rainfall beyond which the method is applicable; iii) the accepted initial abstraction ratio plays a key role in CN estimation and water-routing modelling, and further research is required to improve runoff prediction.

Introduction

Surface runoff is a fundamental process of the hydrologic cycle. It primarily results from snowmelt or rainfall and may occur at a wide range of spatial and time scales. Many studies indicate that direct human activities (e.g., land-use change and irrigation) and variations in climatic variables (temperature, evaporation, and precipitation) exert the greatest influence on hydrological cycle (Dey and Mishra 2017; Yang et al., 2021). These pressures affect both the dynamics and magnitude of runoff. Such changes become particularly problematic in small catchments, where prolonged dry periods and flooding caused by intense rainfall may occur alternately (Banasik et al., 2022; Antonkiewicz et al. 2024). Runoff processes influence economic activities, social systems, and natural ecosystems. Accurate quantification of runoff is therefore essential for effective management of water resources and sustainable development.

The Curve Number (CN) method, developed in the 1950s in the United States (Hawkins et al., 2009), is probably the most well-documented and widely recognized technique used to estimate runoff depth resulting from heavy rainfall. It is applied in scientific studies on hydrological modelling (Singh et al., 2023) as well as engineering projects related to the design of hydraulic structures (Krajewski et al., 2017; Masseroni et al., 2023). Its popularity results from its simplicity (reliance on a single parameter) and institutional acceptance, as it is endorsed by the U.S. Department of Agriculture (Chin, 2023).

The CN method has been tested in various regions and for purposes extending beyond its original application in agriculture. For instance, Sujud and Jaafar (2022) proposed an approach to quantify global-scale runoff in near-real time at a 250m resolution based on the CN method, while Mishra et al. (2006) coupled the CN method with the Universal Soil Loss Equation to estimate rainstorm-generated sediment yield. Moreover, the method was used in studies concerning urban hydrology (Banasik et. al., 2014; Yao et al., 2018), snowmelt runoff (Hejduk et al., 2015), water quality (Youn and Pandit, 2012), and rainwater harvesting and management (Al-Ghobari and Dewidar, 2021). Soulis (2022) highlights several remaining challenges associated with the method, including the need for a universally accepted procedure for CN determination from rainfall-runoff data.

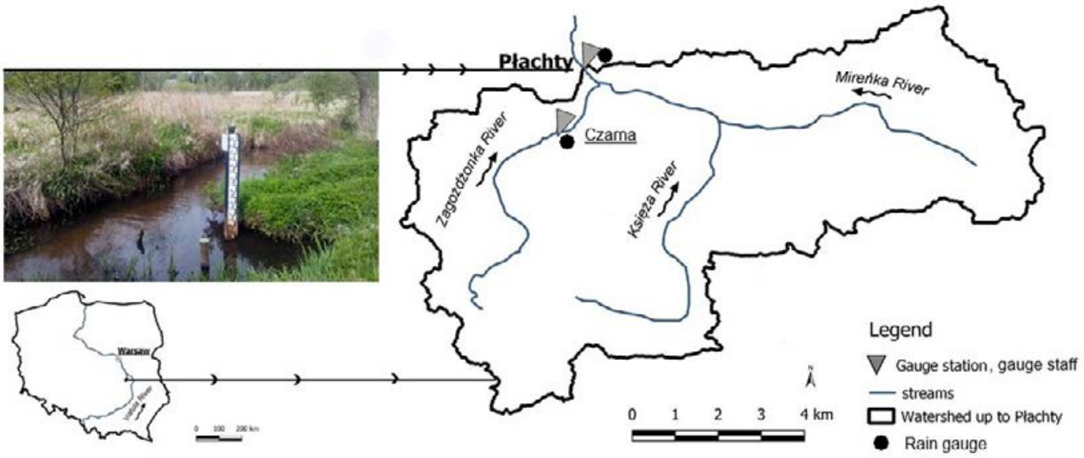


Fig. 1. Locality map of the Zagożdżonka River catchment

To address this issue, the authors of this work aim to estimate the CN parameter for a small, lowland catchment located in central Poland. The study site is representative of the Masovian Lowland, characterized by gentle slopes, agroforested land use, sandy soils, low annual rainfall, and high evaporation. Historical data on catchment land cover and original rainfall-runoff measurements are used to determine the CN values for three periods characterized by different land-cover structures. It is assumed that changes in land-cover structure, particularly afforestation, noticeably influence the rainfall-runoff process and the Curve Number value. The novelty of this work lies in tracking the coupled interactions among rainfall, runoff, and land use for over nearly 50 years within the same agricultural area, which is exceptional for small-scale studies. This study aims to apply, compare, and discuss different approaches to CN estimation in relation to land-cover variation. The results provide general guidelines for identifying the CN parameter.

Methods

Study area and data

The investigated catchment of the Zagożdżonka River (a left tributary of the Vistula River) is located in central Poland, about 100 km south of Warsaw (Figure 1). The study area upstream of the Płachty gauging station covers 82.4 km^2. Since 1962, continuous measurements of basic hydrometeorological parameters have been carried out by the Warsaw University of Life Sciences (Krajewski et al., 2021; Banasik et al., 2021; Hejduk et al., 2021). Water stages are monitored continuously at the Czarna and Płachty gauge stations, while river discharge is measured periodically, typically once a month. Precipitation is recorded using tipping-bucket rain gauges. All measurements follow the standards recommended by the Polish Institute of Meteorology and Water Management (Pasławski 1973).

The topography of the study site is typical of lowland areas, with the main watercourse exhibiting an average slope of 2-3 m per kilometre. The soils in the catchment are predominantly porous and consist mainly of light loamy sands or loamy sands. Consequently, 66.4% of the soils are classified as Hydrologic Soil Group B (moderate infiltration rates), 29.4% as group A (low runoff potential and high infiltration rates), and only 4.2% as group D (high runoff potential and very low infiltration rates). Hydrologic Soil Group C is not present in the catchment. Over time, land management in the catchment has changed. A gradual increase in forest areas has observed, accompanied by a decrease in the proportion of arable land (Krajewski et al., 2021). Portions of arable lands have been partially abandoned, leading to ecological succession characterized by the growth of trees and shrubs on former agricultural fields. The remaining land-cover types can be considered largely unchanged. Despite these long-term trends, three periods with relatively stable land-cover conditions can be distinguished (1974-1982, 1990-2000, 2006-2018); see Table 1. These periods form the basis for subsequent analyses, in which measurement data are evaluated separately for each timeframe.

	Land cover (%) in the period:		
	1) 1974-1982	2) 1990-2000	3) 2006-2018
Grains	27.8	24.6	23.4
root vegetebles	10.7	8.2	3.5
Legumes	4.3	-	-
Meadows	9.3	10.1	10.5
dense forest	41.3	44.3	49.7
scrub, sparse forests	0.2	7.7	7.8
Wetlands	2	1.4	1.4
Roads	0.6	0.6	0.6
build-up areas, farmsteads	3.8	3.1	3.1

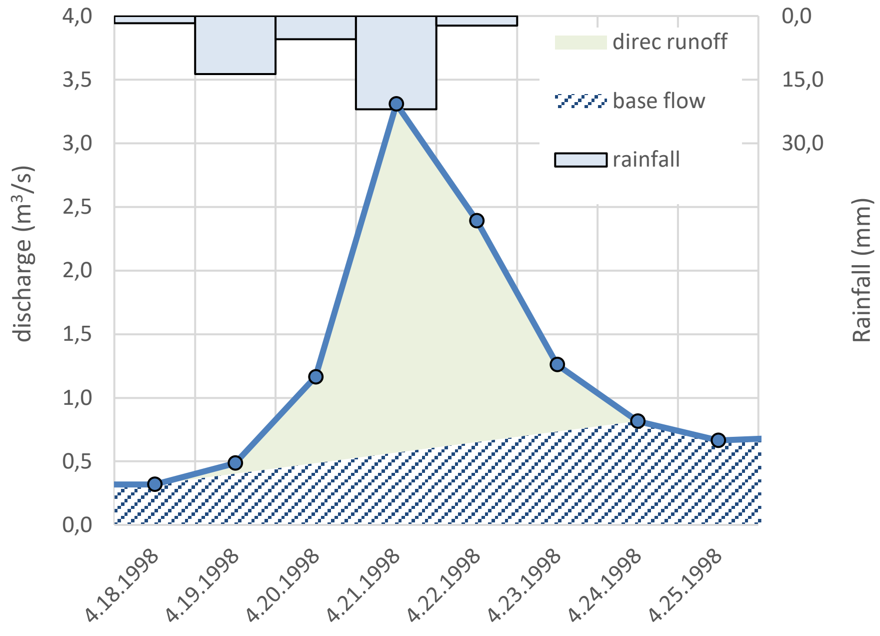


Fig. 2. An example flood event with division into direct runoff and base flow

Daily records of river discharge and catchment precipitation were used to identify flood events for analysis. Discharges values were calculated based on rating curves and water-stage data. The rating curves were established using direct, simultaneous measurements of river discharge and water stage, conducted several times per year. Runoff depth was obtained by dividing the direct runoff volume by the catchment area. For each flood event, the start and end points were identified to separate direct runoff from the total flood (Fig. 2).

From 1974 to 2018, a total of 120 rainfall-runoff events were identified: 45 in the first period, 33 in the second, and 42 in the third (Table 2). These events resulted from rainfall depths in the range of 4 to 112 mm. The average event rainfall (1974-1982: 37.6 mm, 1990-2000: 36.4 mm, 2006-2018: 38.4 mm) is slightly lower than the mean maximum daily rainfall of 39.5 mm reported for this region (Krajewski et al., 2019). Notably, the cited study indicates no long-term trend in precipitation for this area, consequently, no statistically significant variability is evident in the rainfall dataset. In contrast, the average runoff depth appears to decrease across subsequent periods. The established rainfall-runoff data pairs were subsequently used for Curve Number determination.

Curve number method

According to the method, runoff is calculated based on rainfall and catchment characteristics, i.e., soil type, antecedent moisture conditions, and land cover. These three factors are encapsulated in a dimensionless parameter, the Curve Number (CN), which ranges from 1 to 100. Accurate determination of the CN is thus essential for reliable runoff estimation, as higher CN values correspond to greater runoff depths. An incorrectly determined CN leads to either underestimation or overstatement of runoff.

The two commonly used equations for the Curve Number method are (Hawkins et al., 2009):

$$H = \begin{cases} 0 & for P - I_a \geq 0 \\ \frac{(P-I_a)^2}{P-I_a+S}, & for P - I_a > 0 \end{cases}$$

$$S = 25.4\left(\frac{1000}{CN} - 10\right) \qquad (1)(2)$$

where:
S – potential maximum catchment retention (mm),
CN – parameter (-),
H – direct runoff, or effective rainfall (mm),
P – rainfall depth (mm),
Ia – initial abstraction (mm), Ia = 0.2×S or Ia = 0.05×S.

The equations may be solved using two variants of the initial abstraction, Ia = 0.2×S or 0.05×S. The first, a long-standing ratio, is often recommended in engineering manuals (Banasik et al., 2000) but has been criticized as potentially underestimating runoff (Lim et al., 2007; Krajewski et al., 2020). The ratio of Ia =0.05×S is generally considered more appropriate for runoff estimation (Chin 2023). In this study, both variants are used to assess their potential influence on CN determination.

Curve number estimation

In this study, four independent methods were employed to determine the CN across three periods. Some methods require hydrological measurements, while others rely solely on cartographic data.

First, the average CN for the catchment was determined based on recognized soil and land-cover types. This value also served as a reference for subsequent analyses. Homogeneous areas in terms of soil and land cover were delineated, and standard CN values (for normal soil moisture conditions) were assigned to each (Table 3). The average CN was then calculated using the formula:

Table 2. Characteristic of measured rainfall-runoff events(adapted from Krajewski et al., 2021)

Characteristic	**Period**		
	1) 1974-1982	2) 1990-2000	3) 2006-2018
length of the period (years)	9	11	13
number of events	45	33	42
range of rainfall (mm)	7.3 - 94	4.1 - 105	4.8 - 112
average rainfall (mm)	37,6	36.4	38.4
range of runoff (mm)	0.11 - 17.6	0.1 - 14	0.2 - 14.6
average runoff (mm)	3.1	2.7	2.5

$$CN_{avg} = \frac{\sum_{i=1}^{n} CN_i \cdot A_i}{A} \qquad (3)$$

where:

CN_{avg} – average Curve Number for the catchment (-) estimated using land-cover and soil maps,
CN_i – CN for the homogenous plot (-),
A_i – area of the homogenous plot (km^2),
A – catchment area (km^2).

Standard values of CNs (related to 0.2×S) may be converted to 0.05×S-based CNs using the formula given by Woodward et al. (2012):

$$CN_{0.05} = \frac{100}{1.879\left(\frac{100}{CN_{0.2}} - 1\right)^{1.15} + 1} \qquad (4)$$

where:

$CN_{0.05}$ – CN related to the ratio of 0.05×S (-)
$CN_{0.2}$ – CN related to the ratio of 0.2×S, standard value of CN (-).

Rainfall-runoff data were sorted separately. After ranging the data, new rainfall-runoff pairs were generated and matched based on frequency, assuming that rainfall of a given return period (T-years) produces runoff of the same return period (Hjemfeld, 1980; Hawkins, 1993). This procedure reduces noise in the measured data. Two methods were then applied to estimate the Curve Number from the rainfall-runoff data: least-squares calibration (Moglen et al., 2022) and an asymptotic approach (Hawkins, 1993; Banasik et al., 2014).

The idea of the least-squares (LS) calibration is to determine the optimal value of the Curve Number (CN_{LS}) that minimizes the objective function Z:

$$Z = \sum_{i=1}^{n} \left(H_{obs.i} - H_i\right)^2 \qquad (5)$$

$$\min(Z) \rightarrow CN_{LS} \qquad (6)$$

where:

$H_{obs,\,i}$ – measured runoff depth (mm) for event i,
H_i –runoff depth (mm) for event i, calculated from Eqs. (1) and (2),
CN_{LS} – Curve number estimated from rainfall-runoff data using least-squares calibration.

For the asymptotic approach, the parameters S and CN are calculated separately from Equations (1) and (2) for each pair of rainfall-runoff data. The calculated CNs values are plotted against the observed in rainfall depths (P_i). There is a tendency for CN to decrease and asymptomatically approach a constant value as with rainfall increases. The data points can be approximated using a standard asymptotic function (Hawkins, 1993):

$$CN(P) = CN_{\infty} + (100 - CN_{\infty})\exp\left(-\frac{p}{k}\right) \qquad (7)$$

where:

CN_{∞} – Curve Number (-) estimated from rainfall-runoff data for rainfall approaching infinity,
P – rainfall depth (mm),
k- fitted constant (-).

Alternatively, the symmetric peak function, namely the complementary error function peak (Erfc Peak), can be applied in the form (Banasik et al., 2014; Wałęga et al., 2015):

$$CN(P) = CN_{\infty} + b \cdot erfc\left[\left(\frac{p-c}{d}\right)^2\right] \qquad (8)$$

where:

b – amplitude,
c – location parameter,
d – scaling parameter, related to full width at half-maximum of the amplitude.

Table 3. The standard value of CN assigned to homogeneous plots, average runoff condition, initial abstraction equal 0.2×S (after Banasik et. al., 2000)

Land cover	**Soil type**		
	A	B	D
grains	62	73	85
root vegetables	67	77	87
legumes	60	72	83
meadows	30	58	78
dense forest	25	55	77
scrub, sparse forests	45	66	83
wetlands	25	55	77
roads	74	84	92
build-up areas, farmsteads	59	74	86

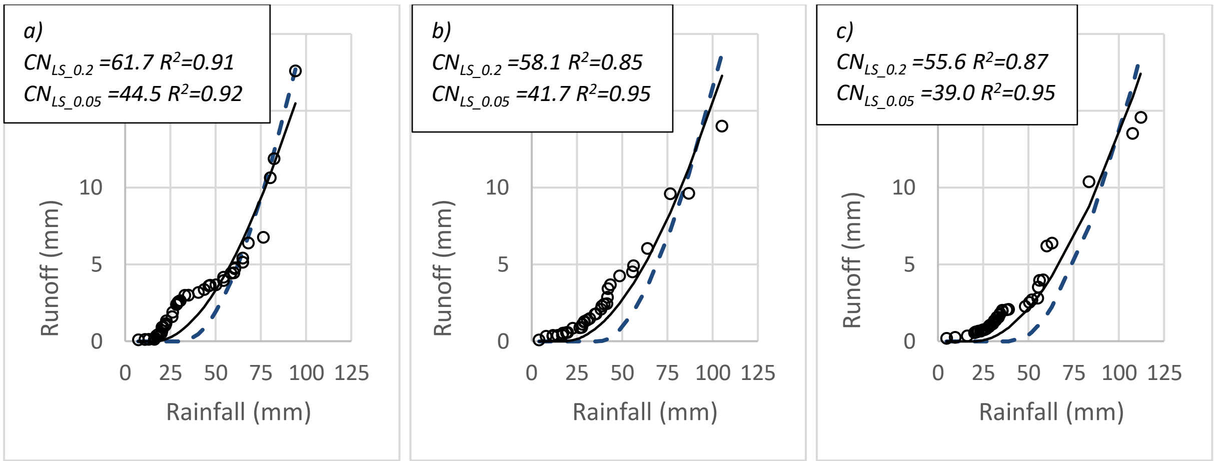


Fig. 3. Curve Numbers estimated from sorted rainfall-runoff data using least-squares calibration. Points are measured data, dashed line is calculated runoff for Ia=0.2×S, solid line is calculated runoff for Ia =0.05×S; periods: a) 1974-1982, b) 1990-2000, c) 2006-2018.

The parameters of Eqs. (7) and (8) were established using Table Curve 2D software (SYSTAT).
Note that, due to the use of two formulations of the initial abstraction ratio, two separate datasets were created, and four parameters were determined for each period. In total, 24 CN values were established.

Results

The average CN values calculated from the standard tables were 59.6, 57.5, and 54.5 for the first, second, and third periods, respectively. The corresponding parameters related to the 0.05×S ratio were lower and amounted to 45.4, 43.0, and 41.1, respectively. Table 4 summarizes all estimated Curve Number values.

Figure 3 presents the Curve Numbers estimated using the least-squares approach. The measured data are approximated using two functions, corresponding to the 0.05×S and 0.20×S ratios. Each period is characterized by a good model fit however, for lower rainfalls depths, prediction based on the 0.05×S ratio appear to be more adequate. A decreasing trend in CN can also be observed, from 61.7 or 44.5 (depending on the initial abstraction) in the first period to 55.6 or 39.0 in the last period.

The results obtained using the asymptotic Equations (7) and (8) are depicted in Figure 4. At first glance, both functions exhibit very similar behaviour, and the estimated parameters are nearly identical. The largest difference in CN_{∞} (±3.8) is observed for the period 1974-1982 (Ia = 0.2×S). However, all Curve Numbers calculated using Equation (8) are slightly higher than those estimated using Equation (7). For second period (Ia = 0.05×S), prediction obtained with Equation (8) indicate an increase in CN, which is not supported by other results or by observed land-cover changes . Reducing the initial abstraction ratio (from higher to lower values) leads to a noticeable decrease in CN of more than 10.

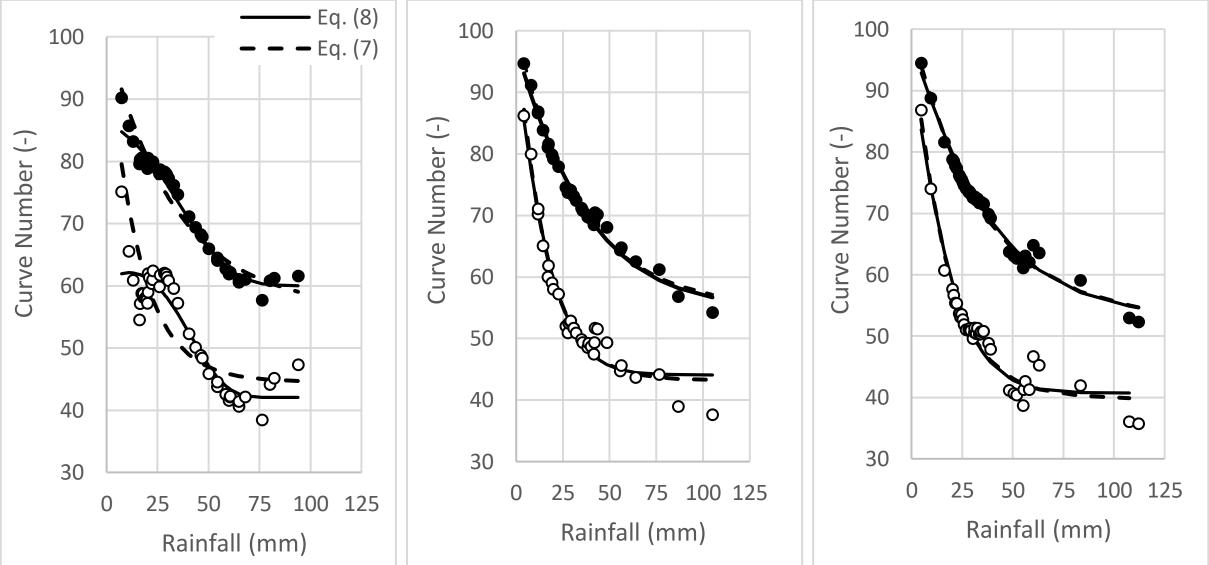
Table 4 summarizes all calculated CN values. Particular attention should be paid to parameters derived using fundamentally different methods, namely those based on homogeneous areas (CN_{avg}) and those obtained from rainfall-runoff data (CN_{LS}, CN_{∞}). Moreover, the impact of initial abstraction cannot be neglected. In general, the CN_{avg} and CN_{LS} show very close agreement. At lower initial abstraction, this agreement becomes even stronger, especially among CN_{avg}, $CN_{Ls,}$ and CN_{∞} (Eq. 7).

Discussion

Since 1980, natural afforestation has occurred in the Zagożdzonka River catchment . The total increase in forest area and scrubland amounted to 10.5% and 5.5% during the periods 1990-2000 and 2006-2018, respectively. Consequently, catchment retention increased, which was reflected in a

Table 4. Estimated Curve Number values according to applied approaches

Period	**CN_{avg}**	**CN_{LS}**	***CN_{∞} (Eq. 7)***	***CN_{∞} (Eq. 8)***
		Ia = 0.2×S		
1) 1974-1982	59.6	61.7	56.2	60.0
2) 1990-2000	57.5	58.2	55.0	55.2
3) 2006-2018	55.9	55.6	52.7	53.4
		Ia = 0.05×S		
1) 1974-1982	45.4	44.5	44.6	42.0
2) 1990-2000	43.0	41.7	43.2	44.1
3) 2006-2018	41.1	39.0	39.8	40.7



a)
Eq.(7): $CN_{\infty\_0.2}$ = 56.3 R^2=0.94
Eq.(8): $CN_{\infty\_0.2}$ = 60.0 R^2=0.97

Eq.(7): $CN_{\infty\_0.05}$ = 44.6 R^2=0.68
Eq.(8): $CN_{\infty\_0.05}$ = 42.0 R^2=0.85

b)
Eq.(7): $CN_{\infty\_0.2}$ = 55.0 R^2=0.98
Eq.(8): $CN_{\infty\_0.2}$ = 55.2 R^2=0.98

Eq.(7): $CN_{\infty\_0.05}$ = 43.2 R^2=0.96
Eq.(8): $CN_{\infty\_0.05}$ = 44.1 R^2=0.95

c)
Eq.(7): $CN_{\infty\_0.2}$ = 52.7 R^2=0.98
Eq.(8): $CN_{\infty\_0.2}$ = 53.4.0 R^2=0.98

Eq.(7): $CN_{\infty\_0.05}$ = 39.8 R^2=0.94
Eq.(8): $CN_{\infty\_0.05}$ = 40.7 R^2=0.93

Fig. 4. Curve Numbers estimated from sorted rainfall-runoff data using an asymptotic approach. Points are measured data, the upper data set corresponds to Ia=0.2×S, the lower data set corresponds to Ia=0.05×S, the dashed line is calculated CN from Eq. (7), the solid line is calculated CN from Eq. (8); a) 1974-1982, b) 1990-2000, c) 2006-2018.

reduction of the Curve Number. The average CN decreased by -2.1 (or -2.4 for Ia = 0.05×S) and -1.6 (or -1.9 Ia = 0.05×S) in the second and third periods, respectively. On average, a 1% increase in forested area reduced CN by 0.2. The land-cover changes significantly affect water routing in the Zagożdzonka catchment.

Figure 5 presents the impact of the changes in the Curve Number on runoff generated by maximum daily rainfall (39.5 mm). The influence of the initial abstraction ratio is also noticeable. Runoff occurs for CN values greater than 57 and Ia=0.2×S or for CN greater than 24 and Ia=0.05×S. Clearly, actual catchment response also depends on soil moisture conditions or vegetation development stage, which should be taken into account when modelling hydrological processes. This issue requires separate analysis. However, due to the observed decline in Curve Number, peak flows and flood risk have decreased over time. Consequently, low rainfall events are increasingly intercepted by vegetation, limiting groundwater recharge. As a result, water resources decline, median and low river flows decrease, and drought risk increases. This phenomenon is confirmed by long-term hydrometeorological monitoring at the study site (Krajewski et al., 2019; 2021; Kaznowska et al., 2024).

Because the rainfall-runoff event pairs were newly established, actual antecedent catchment conditions (soil moisture, vegetation status) were not explicitly considered. Sorting the data according to the frequency-matching concept should reduce noise and scatter, although dispersion remains noticeable, especially in Figure 3. Additional uncertainty may result from model limitations or measurement errors. Ultimately, it is assumed that the determined CN corresponds to the average value established from homogeneous land-use areas.

In the case of CN values derived from rainfall-runoff data, a decreasing trend is also observed, with only one exception. Despite methodological differences, the similarity of results confirms the reliability of both approaches. Methods based on rainfall-runoff data and those using standard CN tables can therefore be used independently and interchangeably. This flexibility is particularly useful when delineation of homogeneous areas is difficult or when measurement data is limited. At the same time, rainfall-runoff observations most accurately represent runoff formation processes and may serve to validate average CN values, confirming correct land-use classification and appropriate assignment of CN_i values.

The asymptotic approach indicates a tendency for CN to decrease and approach a constant value with increasing rainfall depth. Accordingly, Chin (2023) emphasized the need to define a rainfall threshold beyond which conventional CN values become applicable. For the Zagożdżonka catchment, this threshold appears to be approximately 40 mm, particularly when using the 0.05×S ratio.

Application of the error peak function (Eq. 8) indicates that, despite excellent datafitting, predicted CN values may deviate from expected results. Previous studies by Banasik et al. (2014) and Wałega et al. (2015) have shown that this function performs better when combined with a loss ratio of 0.2×S. Under lower initial abstraction, its performance may be less reliable. On the other hand, the standard asymptotic function (Eq. 7) produces results more consistent with CN_{avg}

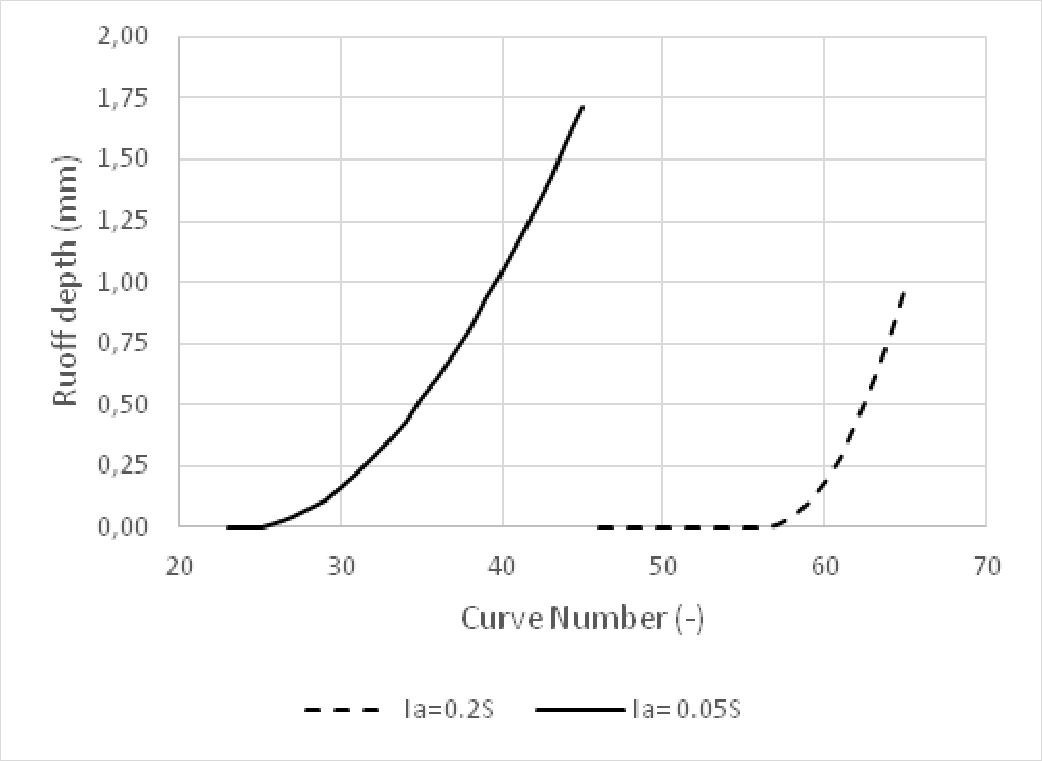


Fig. 5. The effect of Curve Number on runoff in the Zagożdżonka catchment, response to maximum daily rainfall, i.e., 39.5 mm

and CN_{LS} when combined with 0.05×S, suggesting that (Eq. 7) may be more suitable for lower abstraction ratios, whereas Eq. (8) may be preferable for standard abstraction conditions.

Overall, the similarity between CN_{LS} and CN_{∞} values, as well as their respective coefficients of determination, prevents a clear preference between these approaches. Least-squares calibration represents a simple and practical method requiring only basic spreadsheet tools, whereas the asymptotic approach additionally allows identification of rainfall thresholds for method applicability. Consequently, method selection may depend on local conditions and research objectives. Of great importance, however, is the proper determination of initial abstraction losses.

Lower initial abstraction results in lower CN values compared to standard assumption of 0.2×S. Notably, identical runoff depths for a given rainfall can be obtained using different combinations of CN and initial abstraction (Figure 5). Chin (2023) demonstrated that adopting 0.05×**S** improves runoff prediction accuracy, a finding also supported by the slightly higher R^2 values observed in Figure 3 . Therefore, the influence of actual initial losses on CN determination requires further investigation, ideally supported by high-resolution rainfall and runoff measurements (e.g., 10 minute intervals). The consistency of CN values obtained for different land-use structures and time periods confirms the validity of the adopted methodology. However, detailed runoff prediction using these parameters requires separate analysis.

Conclusions

This study focuses on the Curve Number estimation for a small lowland catchment in central Poland. Several CN determination methods were compared , and the hypothesis that land-cover changes significantly influence CN values was verified using long-term field measurements. The main conclusions are as follows:

1. In the Zagożdżonka River catchment , over the period 1974-2018, the average CN parameter dropped from 59.6 to 55.9 (at Ia = 0.2×S) and from 45.4 to 41.1 (at Ia = 0.05×**S)**. On average, a 1% increase in forested area reduced CN by 0.2.
2. Afforestation significantly affects runoff generation processes. Water availability in the region is declining and the assumed initial abstraction ratio plays a key role in modelling water routing.
3. CN values derived from land-cover analysis and rainfall-runoff data are consistent. Least-squares calibration provides a simple and robust method, while the asymptotic approach allows identification of rainfall threshold beyond which the CN method is applicable.
4. Lower initial abstraction ratios result in lower CN values, Accurate determination of initial losses is therefore essential, and further research is required, particularly in the context of runoff prediction.

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