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Estimating the curve number for conventional and soil conservation technologies using a rainfall simulator

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Abstract: The aim of the article was to verify the curve number (CN) values given in the National Engineering Handbook (NEH) methodology, whether they really correspond to all wide-row crops. The tested crops were maize, hops and potatoes grown using conventional and soil conservation technologies. All these crops are classified as wide-row crops, but they are very different in terms of the cultivation process. The basis for the calculation of our CN values were field measurements carried out using a rainfall simulator within the time span from 2014 to 2020 on the soil corresponding to hydrological group B in two repetitions: naturally dry soil corresponding to an ARC II curve and saturated soil corresponding to an ARC III curve. The results show that our calculated CN values for the conventional cultivation of wide-row crops are, in principle, the same as the CN values given in the NEH methodology. On the contrary, a certain difference was recorded in the soil conservation technologies with plant residues on the surface, in the case of naturally dry soil. Lower CN values are clearly seen in the technologies of no-till maize, strip-till maize and hops with catch crops, which was confirmed by the statistical tests, probably due to the interception and surface roughness.

Keywords: cover; row crops; soil degradation; surface runoff; residue tillage practice

Mathematical models (Amutha & Porchelvan 2009) are usually used to evaluate the amount of surface runoff. Some of the models are based on the curve number method, which is currently one of the most often used methods (Hawkins et al. 2009). Some examples of these models include SWAT (Soil and Water Assessment Tool) (Gassman et al. 2014), EPIC (Environmental Policy Integrated Climate) (Williams 1990), SWIM (Soil and Water Integrated Model) (Krysanova et al. 2000), AGNPS (AGricultural NonPoint Source) (Young 1989), etc. The curve number (CN) method is a procedure for estimating the streamflow volume generated by large rain storms, which was developed in the 1950s by the Soil Conservation Service in the USA (Cronshey 1986). The method is widely accepted because of its simplicity for surface runoff prediction all over the world (Ponce & Hawkins 1996), with the Czech Republic being no exception, as this methodology was implemented by Janeček et al. (2002). Basically, only two parameters are required for the surface runoff prediction (Ponce & Hawkins 1996), i.e., the initial abstraction coefficient (λ) and the potential maximum retention (S) expressed in terms of the curve number. Of course, the curve number includes the soil type, antecedent runoff condition, land use and cover (Hawkins et al.

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2009). At first glance, the methodology often combines relatively different technologies for establishing agricultural crops. Under one group of crops and the method of "treatment" (thus, also the CN number), permanent crops with a width of inter-rows of up to 3 m, crops grown in variously modified ridges shapes, as well as classic wide-row crops which are commonly grown are included. For this reason, we wondered whether one CN number for all crops was really reflective for all these crops. At the same time, a further discrepancy may occur when crops are combined with soil conservation technologies. It is common knowledge that these technologies reduce the surface runoff and erosion (Wischmeier & Smith 1965; Vanmaercke et al. 2011). However, is this method of treatment with crop residue for a mulching technology on the land, the establishment of crops with the catch crop and various other soil shaping technologies really telling in the methodology? The aim of this article was to verify the reported CN values in the National Engineering Handbook Hydrology (NEH) methodology part 630 Hydrology (NRCS 2004), whether they correspond to our determined values from measurements for individual wide-row crops. Simultaneously, another objective was to statistically verify whether the specified CN values for conventional and soil protective technologies are demonstrably different.

MATERIAL AND METHODS

The research dealing with the curve number values for various crops was carried out between 2014 and 2020. In total, three typical crops (maize, hops, potatoes) were verified in the Czech Republic. We have chosen hops for the maximum width of the inter-row spacing of 2.7 m, potatoes for their cultivation in ridges and maize due to the fact that it is the most frequently cultivated crop from the wide-row crops. Locations that are typical for the crop due to their soil-climatic conditions were selected for the verification. The locations of the experimental plots are shown in Figure 1 and their basic soil characteristics are in Table 1.

The experimental areas: (1) Víska u Jevíčka (maize) – the study area is located in Moravia. The summer climate is warm, dry to slightly dry with an average annual temperature of 8.4 °C and an annual precipitation of 650–750 mm. The average altitude is 360 m a.s.l.; (2) Solopysky (hops) – the study area is located in Central Bohemia. The typical summer climate is slightly warm and dry. The mean annual rainfall is 450–550 mm and has a temperature of 7–8.5 °C. The average altitude is 300 m a.s.l.; (3) Věž (potatoes) – the study area is located in Vysočina (i.e., the Highlands). The summer climate is mild to slightly cold, slightly dry with an average annual temperature of 7.2 °C and an annual precipitation of 600–750 mm. The average altitude is 547 m a.s.l. The basic soil characteristics are listed in Table 1.

The verified technologies were:
(a) Maize conventional cultivation
(b) Maize strip tillage
(c) Maize no tillage
(d) Hops conventional cultivation
(e) Hops with catch crops

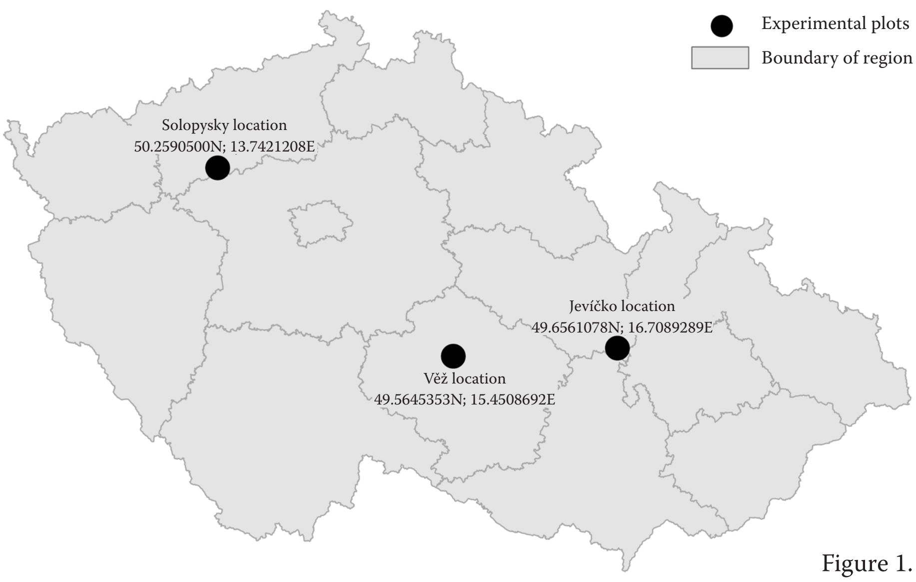

Figure 1. Map of the experimental areas

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Table 1. Basic soil characteristics of the experimental areas

Location	Agricultural crop	Soil classification	Soil texture	Division of soil texture (%)				Slope of the experimental plot (%)	Hydrologic soil group	Oxidisable carbon	Humus	Total nitrogen	Oxidisable carbon/total nitrogen
				< 0.002 mm	< 0.01 mm	< 0.05 mm	< 0.1 mm			(%)			
Jevíčko	maize	Haplic Luvisols	silt loam	22.7	34.8	75.6	89.1	11	B	1.25	2.2	0.15	8.3
Solopysky	hops	Luvic Cambisols	silt loam	23.8	36.5	66.7	84.4	17	B	1.53	2.6	0.18	8.3
Věž	potatoes	Haplic Cambisols	silt	11.1	22.6	41.8	50.3	8	B	1.05	1.8	0.12	8.8

(f) Potatoes conventional
(g) Potatoes aerated during vegetation

A rainfall simulator was used to measure the surface runoff rates. A rainfall simulator is a device which has been increasingly used to study soil erosion processes, and the use of simulators is widely accepted (Vahabi & Nikkami 2008; Kovář et al. 2012, etc.). The rainfall simulator has been used a couple of times in the past in several foreign studies to determine runoff curves (Auerswald & Haider 1996; Elhakeem & Papanicolaou 2012). However, we have not encountered a study that would comprehensively evaluate multiple wide-row crops and treatment establishing technologies at the same time. The principle of measuring by a rainfall simulator is based on the water spraying on a clearly defined and experimental plot of 21 m^2. The water spraying mode lasts for 30 min during the first rainfall simulation, then there is a 15-min technological break, after which the second rainfall simulation lasting 15 min follows. The spraying intensity is about 1.0 mm/min. Due to the fact that the rainfall simulator detects the course and volume of the surface runoff, it is possible to determine how much water runs off from the rainfall simulation area during a particular time-span. The subsurface runoff was not included in the calculation due to the relatively small size of the experimental area.

The measurement of the selected crops and technologies was carried out in three developmental stages on growing dates defined in the Prediction Rainfall Erosion Losses from Cropland East of the Rocky Mountains: A Guide for Selection of Practices for Soil and Water Conservation (Wischmeier & Smith 1965).

(I) – date of measurement (second growth period) – period from plot preparation to sowing up to one month after sowing or planting.
(II) – date of measurement (third growth period) – period to the end of second month from the spring or summer sowing.
(III) – date of measurement (fourth growth period) – from the end of the third period up to harvest.

Determination of runoff curve numbers from runoff data and statistical analysis. The basic material for the evaluation of the CN curves numbers from the measured data is the NEH methodology. The first step was to determine the potential maximum retention (S) from the simulated events. Its algebraic calculation is based on the knowledge of the achieved precipitation P and runoff Q on the experimental area. In this approach, the scatter in

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the S data is assumed to be described by a log normal distribution around the median. The value of the initial abstraction ratio for most of our measurements ranged from 0.04 to 0.06. For this reason, we decided to use the equation according to Woodward et al. (2003) to calculate the potential maximum retention (S) containing lambda 0.05. Hawkins et al. (2009) identified $\lambda = 0.05$ which would be more appropriate to use in runoff calculations for various parts of the world, as this value produced a greater coefficient of determination and a standard error smaller than 0.2.

$$S_{0.05} - 10\,[(2P + 19Q) - \sqrt{361Q^2 + 80PQ}]$$

The next step was to calculate the decimal logarithm of the potential maximum retention for each rainfall-runoff event and to determine its mean and standard deviation. The last step was to calculate the median value of the curve number and its boundary. The following equation adapted to a metric system was used to calculate the median curve number:

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

The curve numbers for 10% and 90% of the extremes correspond with the 1.282 percentiles of the normal distribution. Descriptive statistics were firstly performed for each dataset. This included the determination of the arithmetic mean, standard deviation and sample size. Each dataset (CN values) was also examined for a normal distribution using the Shapiro-Wilk test with a significance level of $\alpha = 0.05$. As some datasets showed that the CN values did not have a normal distribution, we decided to demonstrate the difference between the soil-conservation technologies and conventional cultivation using the non-parametric Mann-Whitney U test. The test checks the continuous or ordinal data for a significant difference between two independent groups. Basically, the significance of a difference of the location (value) of the medians of two groups is tested. The level of significance was chosen at 0.05 with the right-tailed variant test.

RESULTS AND DISCUSSION

To calculate the runoff of the row crops, this method distinguishes the technologies according to the orientation method of the crop rows on the slope, the presence of terraces on a plot, the presence of plant residue on the surface or a combination of these conditions. At the same time, the hydrological conditions related to the factors influencing the infiltration and runoff are further specified. These are the density and canopy of the vegetative areas, the amount of the year-round cover, the amount of grass or close-seeded legumes, the percent residue cover on the land surface, and the degree of the surface toughness. In addition to the already mentioned properties, the Antecedent Runoff Conditions (ARC) are also reflected in the resulting CN value. These indicators include the rainfall intensity and duration, total rainfall, soil moisture conditions, cover density, stage of growth and temperature. ARC is divided into three classes: II for average conditions, I for dry conditions, and III for wetter conditions. In our measurements, the second simulation carried out on wet soil is associated with the ARC III curve, where this connection corresponds to the original classification according to AMC (Antecedent Moisture Condition criteria) and its sum of the total precipitation within the previous 5 days. The first simulation carried out on naturally dry soil then corresponded to the conditions for the ARC II curve for most of the performed simulations.

In our research, we also dealt with and addressed the question of the extent to which the CN values were affected by neglecting the subsurface runoff. We found the answer in the study of Mazur (2018), who, on the soil of a haplic luvisol and a slope of 11% (similar conditions to the locality Jevíčko) derived the ratio between the rainfall and the rate of the subsurface runoff. In our case, it is approximately 1% of the subsurface runoff from the simulated rainfall. Therefore, we believe that the non-inclusion of the subsurface runoff in the calculation did not fundamentally affect the overall resulting value.

Results of CN values for conventional technologies of cultivating row crops. According to the information from NEH, for a row crop with straight rows cultivated on soil with hydrological group B, the values are in the range of 90–92 are stated for ARC III. In our case, in the second simulation carried out on the saturated soil, CN values in the range of 93–94 were found for the monitored row crops. As for ARC II, the methodology states that the CN values are in the range of 78–81. This result would correspond to the set value of 81 in maize. A similar result for the conventional technology of growing maize was obtained by Elhakeem and Papanicolaou (2009), when they determined a CN value of 82 in the Cass locality in the summer. This measurement was also carried out using a rainfall simulator on

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Table 2. Comparison of the curve number (CN) values according to National Engineering Handbook (NEH) with simulated rainfall for conventionally cultivated row crops

Antecedent runoff condition	NEH row crops – straight row hydrologic soil group B hydrologic condition		Moisture condition	Conventional tillage		
	good	poor		maize	hops	potatoes
ARC III	90	92	saturated soil – second simulation	94	94	93
ARC II	78	81	natural moisture – first simulation	81	83	86
ARC I	60	64				

the soil with hydrological group B/D and under moisture conditions corresponding to ARC II. In the conventional technology of hop and potatoes cultivation, however, the resulting values were set slightly higher, i.e., 83 and 86. The results comparison is shown in Table 2. Furthermore, a chart (Figure 2) of the resulting CN values for the first measurement, based on ARC III for the saturated measurement technology, was created. ARC III was chosen because it represents the most uniform conditions, which can be substantiated by the relatively low standard deviations of the second simulation.

Results of CN values for soil conservation technologies of cultivating row crops. The soil conservation technologies of the selected row crops were compared with the technology according to the information from NEH, which considers straight rows down the slope with plant residue on the surface (crop residue cover). The assessment was carried out again on a soil with hydrological group B, where the CN values for ARC III are reported in the range of 88–91. Virtually the same values for the CN curves were found in the assessed crops (Table 3). The lowest values were found for the soil conservation technologies in maize and the highest values were found in potatoes. The first simulation corresponding to the conditions for ARC II had disproportionately lower results for the CN curves for the soil conservation technologies, having some exceptions compared to the methodology (Figure 3). It states that the CN values for ARC II are in the range of 75–80. The measurements showed the lowest value for the strip-tillage technology, where the CN value only reached 56. Another technology significantly below the stated range was the technology for cultivating no-till maize with a value of 67.

In terms of the resulting CN value for maize cultivated by the no-till technology, our results also differ slightly from the study by Elhakeem and Papanicolaou (2009), which states that the summer CN value at the Cass 77 site (hydrological soil group B/D) and at the Pocahontas 75 site (hydrological soil group B and B/C) Slightly lower compared to the NEH methodology was also the technology for cultivating hops with catch crop, where CN reached 72. The only exception was the technology of potatoes aerated during the growing season. Although this technology is generally considered to be a soil conservation method, it had a slightly higher CN value which reached a value of 82. This clearly showed the positive effect of the plant residue or the effect of the whole plants in the interrows, which have a significant role in reducing the

Table 3. Comparison of the curve number (CN) values according to National Engineering Handbook (NEH) with simulated rainfall for the soil conservation technologies cultivated row crops

Antecedent runoff condition	NEH row crops -straight row with crop residue cover hydrologic soil group B hydrologic condition		Moisture condition	Maize strip-tillage	Maize no-tillage	Hops with catch crops	Potatoes aerated during vegetation
	good	poor					
ARC III	88	91	saturated soil – second simulation	88	88	90	92
ARC II	75	80	natural moisture – first simulation	56	67	72	82
ARC I	57	63					

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Table 4. Statistical difference of the resulting curve number (CN) values during the first simulation

Group	Crop and technology	Sample size (n)	Arithmetic mean ($\bar{x}$)	CN median	CN 10 %	CN 90 %	SD	Shapiro-Wilk test P-value α = 0.05
1	maize conventional tillage	44	80	81	69	89	7.7	0.088
2	maize strip-tillage	12	56	56	42	70	10.6	0.486
3	maize no-tillage	15	66	67	50	81	12.1	0.323
Mann-Whitney U test one tails right		hypothesis H1		group 1 > group 2			group 1 > group 3	
		Z value		4.86			3.96	
		P-value α = 0.05		5.95E-07			3.68E-05	
1	hops conventional tillage	13	83	83	75	89	5.4	0.934
2	hops with catch crops	18	70	72	53	85	12.3	0.676
Mann-Whitney U test one tails right		hypothesis H1			group 1 > group 2			
		Z value			2.91			
		P-value α = 0.05			1.83E-03			
1	potatoes conventional tillage	13	86	86	81	91	3.9	0.672
2	potatoes aerated during vegetation	19	82	82	76	87	4.9	0.004
Mann-Whitney U test one tails right		hypothesis H1			group 1 > group 2			
		Z value			2.18			
		P-value α = 0.05			0.01			

SD – standard deviation

surface runoff within the lower soil saturation. Cover crops on the soil surface can have different efficiency which depends on the cover quality and degree of their decomposition. The cover crops' quality in soil conservation technologies changes throughout the years. Thus, the standard deviation of the CN values is higher in soil conservation technologies with cover crops than the standard deviation of the CN values in technologies without cover crops (all conventional technologies and the technology of potatoes aerated during vegetation).

Statistical difference between the measured CN values conventional and soil conservation technologies. A significant statistical difference was proven between the measured CN values and the conventional and soil conservation technologies in all the evaluated

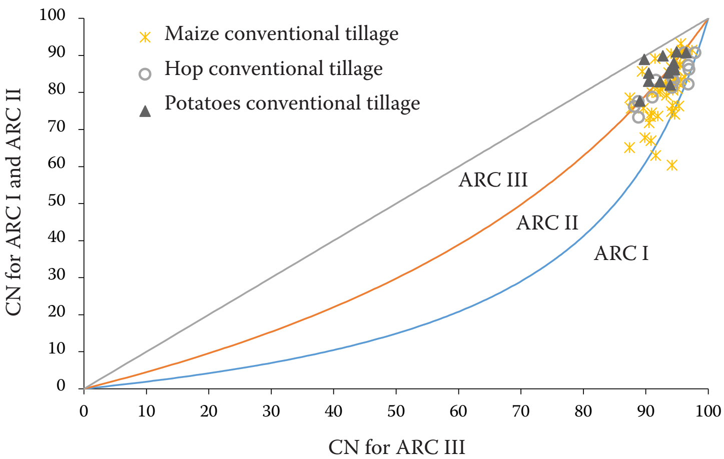

Figure 2. Curve number (CN) values corresponding to the first simulation according to the ARC III curve for the conventional technologies of cultivating row crops

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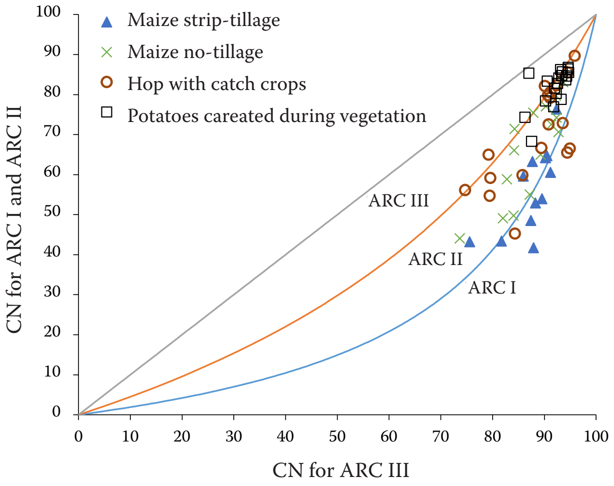

Figure 3. Curve number (CN) values corresponding to the first simulation according to the ARC III curve for the soil conservation technologies of cultivating row crops

crops during the first simulation (Table 4). The lowest *P*-values were achieved in both soil conservation technologies of cultivating maize; however, very good results were also achieved in hops with a catch crop. In the case of the technology of potatoes aerated during vegetation, the *P*-value was found to be the highest of all the assessed soil conservation technologies. Nevertheless, at a significance level of α = 0.05, it was still demonstrably statistically different from the CN value for the conventional technology. In the case of the second simulation, a significant statistical difference was proven between the technologies in the soil conservation technologies of cultivating maize and hops (Table 5). Likewise, the first simulation, the lowest *P*-values were determined for maize with the strip-till and no-till technologies. A slightly higher *P*-value was then found in the technology of hops with a catch crop. However, at a significance level of α = 0.05, this technology is still significantly different from the conventional one. In the last assessed technology for potatoes, it was not possible to reject the hypothesis of conformity of the assessed files of the resulting CN values, where the *P*-value value only reached 0.16. Thus, the technology of potatoes aerated during the growing season was not statistically different from the conventional method of cultivating potatoes.

Table 5. Statistical difference of the resulting curve number (CN) values during the second simulation

Group	Crop and technology	Sample size (n)	Arithmetic mean ($\bar{x}$)	CN median ($\tilde{x}$)	CN 10 %	CN 90 %	SD	Shapiro-Wilk test *P*-value α = 0.05
1	maize conventional tillage	44	93	94	90	96	2.5	0.004
2	maize strip-tillage	12	87	88	82	92	4.4	0.017
3	maize no-tillage	15	87	88	80	93	5.4	0.207
Mann-Whitney U test one tails right		hypothesis H1		group 1 > group 2			group 1 > group 3	
		Z value		4.38			4.19	
		P-value α = 0.05		5.95E-06			1.37E-05	
1	hops conventional tillage	13	94	94	88	97	3.5	0.180
2	hops with catch crops	18	88	90	80	95	6.4	0.030
Mann-Whitney U test one tails right		hypothesis H1			group 1 > group 2			
		Z value			2.23			
		P-value α = 0.05			0.01			
1	potatoes conventional tillage	13	93	93	90	96	2.4	0.053
2	potatoes aerated during vegetation	19	92	92	89	95	2.6	0.011
Mann-Whitney U test one tails right		hypothesis H1			group 1 > group 2			
		Z value			1.01			
		P-value α = 0.05			0.16			

SD – standard deviation

CONCLUSION

As the results of the CN values show, the conventional row crop technology reported in the NEH methodology for ARC II and III was only slightly lower compared to the values found in this study, however, it generally coincides with them. In the case of the soil conservation technologies, the achieved CN values for the second simulation were practically the same as in the methodology corresponding to ARC III. A disproportionately larger difference was found in the first simulation, in which the achieved values for the soil conservation technologies were closer to the values of ARC I. In this respect, there was only one exception for the technology of aerated potatoes during vegetation, with the CN value corresponding more to ARC II. However, the reason for this is the fact that this soil conservation technology is based only on regular aeration without any additional soil cover outside the main crop. Based on our findings, we can state that the NEH methodology and the reported CN values correspond relatively well to the hydrologic soil group B in the Czech Republic. Only for some soil conservation technologies, which NEH does not distinguish for the time being, the CN values can, under certain conditions, be higher than stated.

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