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Parameter recalculation for a rainfall-runoff model with a focus on runoff curve numbers

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Abstract

One of the fundamental issues of hydrology is determination of total runoff volume from rainfall. The mutual relationship of these quantities can be experimentally determined by measuring rainfall and runoff. Rainfall-runoff models describe natural relations on the basis of variables determining physio-geographical conditions of a territorial unit as well as hydraulic properties of the respective river network. In the proposed paper, we focused on parameter recalculation of a rainfall-runoff model with focusing on runoff curve numbers (CN). The objective of this study was to update the data (CN) in the old modelling structures within the FLOREON+ (FLOods REcognition on the Net – Study Area) system and replace them with the new ones. The parameters of runoff CN were estimated according to available GIS layers primarily related to the existing soil conditions and land use. In the first phase, the calculation procedure was prepared for the smaller Porubka and Lubina basins, and then it was applied to the whole basin area. The results showed that the new runoff CN recalculation procedure resulted in reduction of the simulated runoff (peak discharge, volume) in the Odra River sub-basins, which also led to approximation to the real measured runoff in the Ostrava-Svinov profile. The derived method is applicable to other basins as well.

Highlights for public administration, management and planning:

- Runoff volumes resulting from rainfall significantly contribute to risk processes, such as soil erosion and floods.
- The partially automated procedure for rainfall-runoff estimation is preseted, based on data for soil conditions and land cover.
- Derivation is based on the original principles determined by the US Soil Conservation Service and can be applied to any river basin in the area of the Czech Republic.
- In the future, the proposed methodology will be adapted to run within the ArcMap application.

Keywords

Runoff curve numbers, Rainfall-runoff model, Odra River basin

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1 Introduction

Runoff volumes resulting from rainfall significantly contribute to risk processes, such as soil erosion and floods (e.g., Apel et al. 2006; Bracken & Croke 2007; Panagos et al. 2016). One of the crucial hydrological problems is therefore determination of total runoff volume from rainfall. The mutual relationship of these quantities can be experimentally determined by direct measurement of rainfall and runoff. However, for larger territorial units, certain model simplification, which still needs to be verified in available hydrometric profiles, is instrumental. For the purpose of basic simulation of the runoff volume from rainfall, several rainfall-runoff models have been developed. They describe natural relations based on the parameters determining physical geographical features of an area as well as hydraulic properties of a given river network. One of the most frequently used models is the HEC-HMS modelling system, which is a product of the US Army Corps of Engineers (Hydrologic Engineering Center 2016). It is a semi-distributed approach

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based on calculations of runoff volume in sub-basins and their mutual interconnection.

For determination of the runoff volume ratio from rainfall, the Runoff curve numbers (CN) method was selected with its parameters being dependent on soil conditions and hydrologic soil groups as well as on land use. The method was derived by the US Soil Conservation Service (SCS) (National Engineering Handbook 1972), and it has been widely applied so far. In the Czech Republic, it has been applied within the Protection of Agricultural Land from Erosion methodology (Janeček et al. 2012). Moreover, it is also employed by the Czech Hydrometeorological Institute for deriving potential hydrological characteristics (Šercl 2009).

The motivation of the current study was to update old modelling structures within the FLOREON+ (FLOods REcognition on the Net – Study Area) system and replace them with the new ones. Under the modelling structures, we mean Rainfall-Runoff models with all necessary input data sets. After a certain period of operating the monitoring and forecasting FLOREON+ system (IT4Innovations 2019), the decision was made about input data recalculations. Since the models are based on SCS-CN curve number method, the CN numbers, as initial data input, were decided to be the object of interest of this study. The second motivation was to propose a scheme for updating CN numbers automatically. The results uncovered what is the difference between old and newly computed CN numbers and how significant is the influence on simulations of runoff (study areas - Lubina and Porubka basins). Based on the results from pilot areas, the outputs served as a tool for decision making. If it is worthy to update CN numbers for whole Moravia-Silesian region (and how often) or keep them in the initial setup. This paper describes the first comparison results as well as it provides the first attempt to propose a process for automated updating. The process was partly implemented so far, but the further investigation still needs to be done. These results bring us one step closer to solving the problem of automatic CN recalculations. Automatic recalculations may resolve the problem with keeping CN numbers up to date without manual assistance.

2 Study area

In 2006, the FLOREON (FLOods Recognition on the Net) system for integration and operation of monitoring, modelling, prediction, and decision support for disaster management started to be developed in the Moravian-Silesian region at VŠB – Technical University of Ostrava (IT4Innovations 2019). A crucial part of this system was monitoring of water levels of water courses as well as runoff simulation based on measured and predicted rainfall.

Within this system, four main units, each of which is represented by the river flowing through it, were defined for the Odra River basin in the Moravian-Silesian region. They include the Odra River basin up to the confluence with the Opava River as well as the Opava, Ostravice, and Olše river basins. The first of these units was selected to verify the validity of the selected runoff CN parameters, and thus it has become the subject matter of this study.

The study area stretches from Oderské vrchy, where the Odra River has its spring, and the confluence of the Odra and Opava rivers in the southwestern periphery of the City of Ostrava. The main tributaries of Odra in this area include Husí potok and Bílovka and Jičínka, Lubina, and Ondřejnice flowing from Vítkovská vrchovina (highland) and Podbeskydská pahorkatina (upland), respectively. Just past the Odry town, Odra itself turns into a lowland river boasting a number of well-preserved natural meanders and medieval pond systems. For monitoring of water levels in this area, there are several hydrological stations operated by the Odra River Basin, state enterprise, on the Odra River as well as its tributaries.

In the first stage, input data were surveyed, and the calculation process was verified for the selected pilot basins, i.e. Porubka and Lubina, possessing different physical geographical features (geological structure, soil conditions, river basin gradients). After verification, obtaining of the runoff CN values was made automatic and applied to the entire study river basin (see Fig. 1).

3 Input data

The model of the Odra River basin up to its confluence with the Opava River has already been developed for 51 sub-basins. The input schematization has been performed over the Digital Elevation Model (DEM) with resolution of 25 meters (photogrammetric method). These sub-basins have also been used in this study. Other essential input data include layers representing the current soil conditions and land cover. For verification of the soil properties, the system of Evaluated Soil Ecological Units (ESEU) available via the public service provided by the Ministry of Agriculture of the Czech Republic (Ministerstvo zemědělství 2019). The information about the current land use within the given

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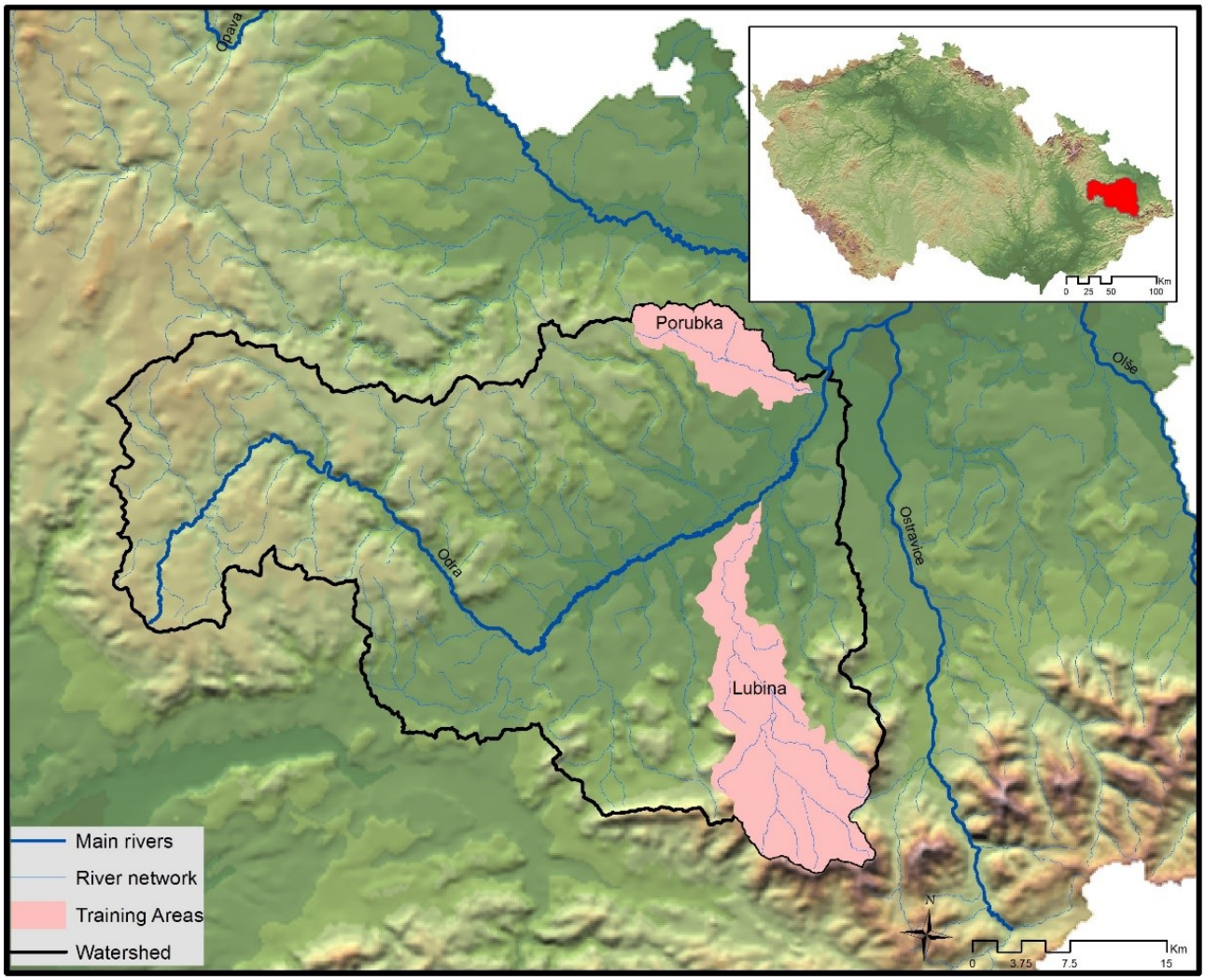


Fig. 1 Odra River basin up to the confluence with the Opava River

area has been acquired from the supporting material published by the European Environment Agency (European Environment Agency 2012), which provides information about the actual land use until the year 2012.

The basis for verifying the values of runoff CN values was the original data set up for land cover classes and hydrologic soil groups by the US Soil Conservation Service (SCS) (National Engineering Handbook 1972).

The measured total rainfall and discharge during the flood in September 2007 were used from the monitoring network of the Odra River Board Corp., state enterprise (IT4Innovations 2019). This particular emergency situation affected mainly the right tributaries of the Odra River. The most affected basins were those of the Jičínka and Porubka rivers, where 20-year discharge was reached (Řehánek 2008).

4 Methodology

Rainfall-runoff model parameters recalculation in this study was focused on verification of total runoff CN values in all territorial units of the Odra River basin up to the confluence with the Opava River, which are used for runoff simulations in the current FLOREON+ system (Svatoň et al. 2018). For this purpose, updated GIS layers of soil conditions and land cover the overlaying of which served as a base for detailed evaluation of the total runoff from every cell. Updated values of runoff CN, which were taken from the supporting documents refer-

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ring to the mean hydrological soil groups marked by symbol CN_{II} and published by the United States Department of Agriculture, were assigned to the resulting detailed units (National Engineering Handbook 2004). A similar approach is usually applied for calculating model hydrological statistics as well. The method for calculating total runoff CN values is based on the following equation (National Engineering Handbook 1972):

$$\frac{F}{S} = \frac{Q}{P} \tag{1}$$

where F stands for total retention, S stands for potential retention, Q for runoff, and P for total rainfall. By adjusting the formula and incorporating the initial runoff loss, the equation for determining direct runoff is obtained as follows:

$$Q = \frac{(P - 0.2 \cdot S)^2}{P + 0.8 \cdot S} \tag{2}$$

Potential retention is then derived from the following equation in inches or converted to SI units (Soulis & Valiantzas 2012):

$$S = \frac{1000}{CN} - 10 \tag{3}$$

In order to perform semi automation of calculation, the Model Builder software application implemented in ArcGIS 10.x was used. A flowchart containing the *select, clip, union, edit,* and *calculate* functions was created.

The resulting total runoff CN values for the subbasins of the study area were calculated in accordance with the initial method (National Engineering Handbook 2004) using the weighted average method.

4.1 Soil types

Soil types and their hydrological properties are one of the fundamental aspects for deriving the total runoff volume using the CN method. In the study area, several soil types occur. Their formation was affected by different rock composition of the Bohemian Massif and the Western Carpathians with the alluvial plain of the Odra River. In the Beskydy mountains part of the study basin, pseudogleys and anthrosols occur more significantly. However, the soil types such as podzols, rendzinas, pararendzinas, and eutrophic cambisols, which are totally absent in the Jeseníky mountains part of the study area, occur here.

The Main Soil Unit (MSU) is an umbrella term characterizing a group of genetic soil types, soil forming substrates, texture, soil depth, and area relief. This unit is listed as the second and third number of the Evaluated Soil Ecological Unit (ESEU) code (Novotný & Vopravil 2013). The evaluation classification system includes altogether 78 MSUs, and their updated values are available via the public service operated by the Ministry of Agriculture of the Czech Republic (Ministerstvo zemědělství 2019). According to the prevailing water infiltration rate, four hydrologic soil groups (HSG) are classified and symbolized by letters A, B, C, and D, where group A and D is characterized with the highest and lowest water infiltration rate, respectively. The act of assigning MSU to HSG was performed according to the method (Janeček et al. 2012). In the case of forest soils, however, no ESEUs are set. Identification of the soil properties in these areas can be performed only experimentally by means of probes exploring, for example, the depth of topsoil and its degree of compaction. This study is therefore based on mean forest hydrologic conditions taking into consideration the HSG values in the adjacent agricultural areas with the prevailing HSG group of B.

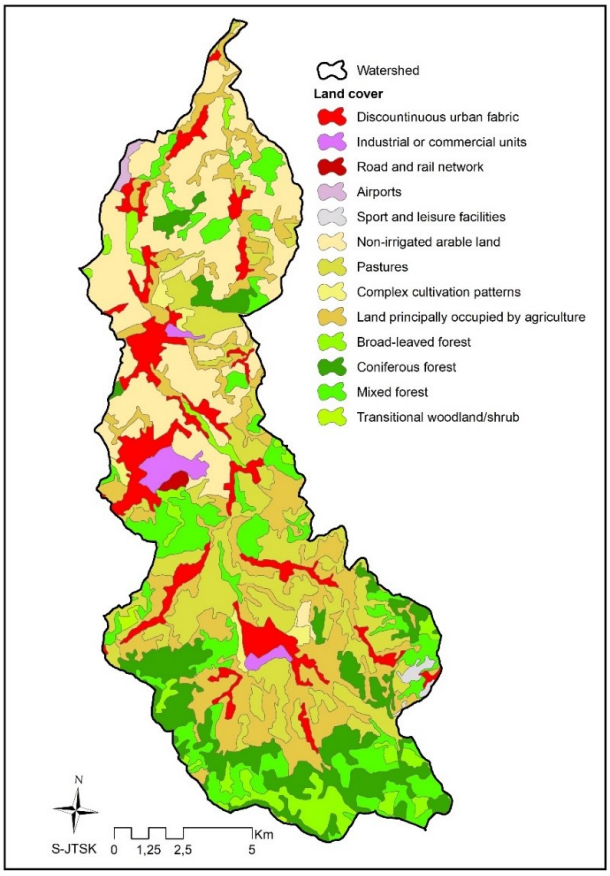


Fig. 2 Cover classes for the pilot Lubina River basin

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4.2 Land cover

The second important aspect for deriving runoff CN values is vegetation and other land cover. Current studies used HEC-HMS as a tool for analyzing the impact of land use and cover change on surface runoff (Younis & Ammar 2018). The study (Al-Zahrani 2018) focused on land-use changes, and HEC-HMS modelling tool was applied for results evaluations. In this study, we used the land cover classification by the European Environment Agency into 44 classes called CORINE Land Cover (CLC) (European Environment Agency 2000), the 32 of which occur in the study area (see Fig. 2). The available layer of land use at the time of the article´s processing refers to the situation in 2012 (European Environment Agency 2012).
Land cover classes, for which the values of runoff CN (National Engineering Handbook 2004) were determined by the US Soil Conservation Service, should be classified according to the current land use defined by the European Environment Agency (European Environment Agency 2000). Some classes were totally identical such as continuous urban fabric, natural grasslands, or forests. In the case of other classes, this classification was performed in a way which best suited the description of a given land use. As a result, an original table containing values of runoff CN for the land use classes as well as for hydrologic soil types was compiled (see Table 1).

4.3 Calculation of CN values

The prepared maps and tables were used in semi-automated calculation of runoff CN values for the study area mainly performed using the ArcGIS 10.x software application. Using the Model Builder application, a flowchart containing three defined input layers was created. These layers include area units (river basins) defined by the watershed divides, a layer containing ESEU characteristics, and areas containing data about their land cover. After defining the extent of the area analysed according to the unique classification feature, e.g. hydrological sequence number (HSN), the layers containing applicable ESEU and CLC are attributed to this area, clipped, and displayed. In the next calculation step, the created layers are unified and as a result, the areas of the respective ESEU characteristics as well as with the corresponding CLC land cover class are overlaid. In the attributed table of such generated layer, any unnecessary entries are then removed, and the total surface area of individual unified areas is calculated. The resulting GIS layer and table contain all components needed for determining the desired values of runoff curve numbers (see Fig. 3).

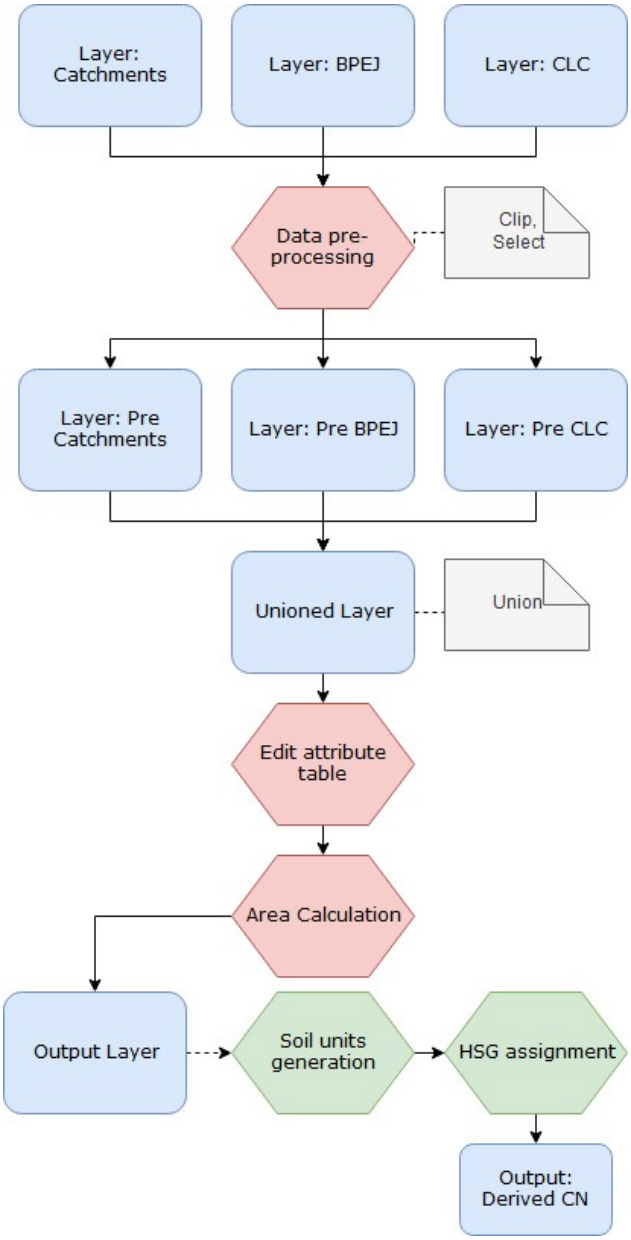


Fig. 3 Flowchart describing the runoff CN calculation process

The final calculation takes place in the spreadsheet processor, where MSU are automatically generated from the ESEU code, being then attributed the corresponding HSG as well as CLC with defined CN values. The final step is to calculate weighted mean of CN values and the size of areas for individual unified entries within a particular sub-basin.

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Table 1 CN values for cover classes and hydrologic soil groups

Class	Land Cover classes	CN for hydrologic soil group			
		A	B	C	D
111	Continuous urban fabric	89	92	94	95
112	Discountinuous urban fabric	77	85	90	92
121	Industrial or commercial units	81	88	91	93
122	Road and rail networks and associated land	83	89	92	93
124	Airports	83	89	92	93
131	Mineral extraction sites	81	88	91	93
132	Dump sites	81	88	91	93
133	Construction sites	77	86	91	94
141	Green urban areas	49	69	79	84
142	Sport and leisure facilities	49	69	79	84
211	Non-irrigated arable land	60	72	80	84
221	Vineyards	43	65	76	82
222	Fruit trees and berry plantations	43	65	76	82
231	Pastures	30	58	71	78
241	Annual crops associated with permanent crops	58	72	81	85
242	Complex cultivation patterns	59	74	82	86
243	Land principally occupied by agriculture	59	74	82	86
244	Agro-forestry areas	43	65	76	82
311	Broad-leaved forest	36	60	73	79
312	Coniferous forest	36	60	73	79
313	Mixed forest	36	60	73	79
321	Natural grassland	39	61	74	80
322	Moors and heathland	77	86	91	94
324	Transitional woodland/shrub	35	56	70	77
331	Beaches, dunes and sand plains	55	72	81	86
332	Bare rock	77	86	91	94
333	Sparsely vegetated areas	74	83	88	90
334	Burnt areas	77	86	91	94
411	Inland marshes	98	98	98	98
412	Peatbogs	98	98	98	98
511	Water courses	100	100	100	100
512	Water bodies	100	100	100	100

For the Odra River basin up to the confluence with the Opava River, the calculations comprised of thousands of unified entries, and as such they provide an immensely detailed view of the up-to-date curve numbers of this area unit. The newly derived values correspond with the mean hydrological conditions of soils denoted by symbol CN_{II}.

5 Results

The new parameters of the runoff CN have been incorporated into the original project for the Odra River basin up to its confluence with the Opava River in the HEC-HMS 3.5 Rainfall-Runoff model[1]. The comparative calculations were then feasible for totally identical territorial extent as well as a defined rainfall episode and thus study the role of the newly derived values of runoff CN played in runoff simulation carried out for the sub-basins within the study area. The pilot calculations performed for the Porubka and Lubina River basins suggested that the CN values used in the year 2007 overestimated the water runoff as the newly derived curve numbers provided lower values.

By comparing the original and new values of the runoff CN for the sub-basins within the study area, it was found that in all cases their reduction was achieved. The lowest difference was achieved in the small Odra River sub-basin located past the Porubka River mouth (5 %), and the biggest difference, on the other hand, was achieved in the Odra River sub-basin located between Libavský and Plazský potok (23 %). It can be generally monitored that certain differences were achieved in the upper part of the study area, which is less affected by human activities and is partially located in the Libavá Military Training Area. Smaller differences were then found in areas more affected by agricultural and industrial activities as well as urban areas (see Table 2). More accurate method of runoff CN values calculation has, of course, affected the simulated flood waves on watercourses within the study area. In comparison with the original derivation of the hydrological situation in September 2007, this time reduction in peak discharge as well as volume of flood waves has been achieved along with shape approximation of the derived runoff to the actually observated ones. The simulated flood waves in the upper, unaffected part of the study basin area have better matched the observed flow rates. In the profile of the Odra hydrological station on the Odra River, the maximum peak discharge of 87 $m^3.s^{-1}$ was achieved after adjustment of CN values, which has thus become very closely aligned with the actual measured value of 79 $m^3.s^{-1}$. Moreover, shape approximation in the area of flood wave rise was achieved (see Fig. 4). Less favourable comparison so far has been generated for the lower part of the Odra River, which indicates the need for adjustment of other parameters affecting the formation of surface runoff in the part of the study basin with intensive anthropogenic use.

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Table 2 Comparison of original and newly derived runoff curve numbers (CN)

ID	Stream	Watershed	CN old [-]	CN new [-]	Diff. [%]
1	Odra	R300W300	73.90	59.62	-19.3
2	Libavský potok	R150W150	75.90	62.41	-17.8
3	Odra	R290W290	75.50	57.92	-23.3
4	Plazský p.	R340W340	74.30	60.49	-18.6
5	Odra	R160W160	74.40	59.05	-20.6
6	Lazský p.	R140W140	74.50	59.68	-19.9
7	Odra	R80W80	77.70	61.91	-20.3
8	Budišovka	R30W30	79.80	65.19	-18.3
9	Odra	R120W120	75.50	65.73	-12.9
10	Něčínský p.	R170W170	79.20	66.95	-15.5
11	Odra	R190W190	78.50	64.17	-18.3
12	Čermná	R70W70	80.00	68.04	-15.0
13	Odra	R260W260	79.50	67.32	-15.3
14	Suchá	R320W320	78.90	68.93	-12.6
15	Odra	R330W330	80.70	71.66	-11.2
16	Luha	R450W450	80.70	72.97	-9.6
17	Odra	R430W430	81.80	72.58	-11.3
18	Jičínka	R510W510	75.40	68.04	-9.8
19	Zrzávka	R460W460	77.70	69.11	-11.1
20	Jičínka	R440W440	83.20	76.70	-7.8
21	Odra	R420W420	83.10	74.45	-10.4
22	Husí p.	R280W280	81.20	68.71	-15.4
23	Gručovka	R110W110	80.20	69.01	-13.9
24	Husí p.	R390W390	82.50	74.29	-10.0
25	Děrenský p.	R350W350	81.20	71.30	-12.2
26	Husí potok	R380W380	83.80	76.71	-8.5
27	Odra	R400W400	83.60	75.39	-9.8
28	Bartošovický p.	R410W410	82.30	74.87	-9.0
29	Odra	R360W360	84.60	77.77	-8.1
30	Sedlnice	R370W370	82.80	74.43	-10.1
31	Odra	R270W270	84.80	78.88	-7.0
32	Bílovka	R130W130	76.70	68.88	-10.2
33	Jamník	R100W100	80.90	71.44	-11.7
34	Bílovka	R180W180	84.00	75.05	-10.7
35	Sezina	R20W20	75.80	69.14	-8.8
36	Bílovka	R230W230	83.40	75.94	-8.9
37	Odra	R200W200	85.10	77.89	-8.5
38	Lubina	R490W490	72.20	66.84	-7.4
39	Bystrý p.	R500W500	69.50	65.56	-5.7
40	Lubina	R470W470	78.40	68.26	-12.9
41	Tichávka	R480W480	78.30	70.58	-9.9
42	Lubina	R240W240	83.30	76.31	-8.4
43	Trnávka	R250W250	83.30	73.47	-11.8
44	Lubina	R220W220	84.40	74.46	-11.8
45	Odra	R210W210	83.70	75.75	-9.5
46	Ondrejnice	R310W310	79.50	72.99	-8.2
47	Odra	R90W90	83.70	74.44	-11.1
48	Polančice	R60W60	82.30	73.35	-10.9
49	Odra	R50W50	82.60	74.74	-9.5
50	Porubka	R10W10	80.69	72.87	-9.7
51	Odra	R40W40	83.40	79.38	-4.8

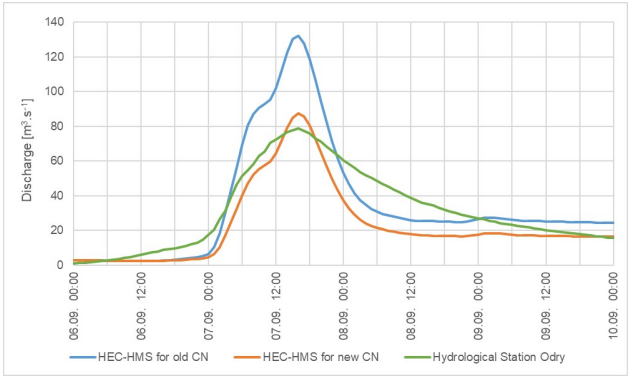


Fig. 4 Comparison of simulated and observated discharges in the Odra profile on the Odra River in September 2007

Justifiability of the assumption of the need for adjustment of runoff CN values as one of the important parameters determining the rainfall-runoff ratio has been verified not only for the flood episode in September 2007 but also during the last bigger discharges occurring in the study area in April 2017 and July 2018. It concerns two different hydrological situations because the episode from April 2017 was mainly caused by melting snow whereas the episode from July 2018 was caused by prolonged intensive precipitation. In the FLOREON+ system user interface, hydrological analysis of these two situations were performed including configuration of the derived parameters of runoff CN. The simulation results have confirmed that the proposed adjustment of runoff curve numbers values provides a better approximation to the observated discharges (see Fig. 5). A similar study focused on flood wave simulations on small ungauged areas was presented by (Shakti et al. 2017). Although the assumption of the need for adjustment of runoff CN values parameters was justified, it is generally known that formation of surface runoff is also affected by other factors such as initial loss dimension. These parameters shall thus become the subject matter of further research with the objective to further approximate towards the measured discharge rates at hydrological stations. Within the Rainfall-Runoff model, the newly derived values of runoff CN will be integrated to the map interface of the FLOREON+ system. The results of this study shall thus be applied in practice in order to give more precision to the simulated discharge.

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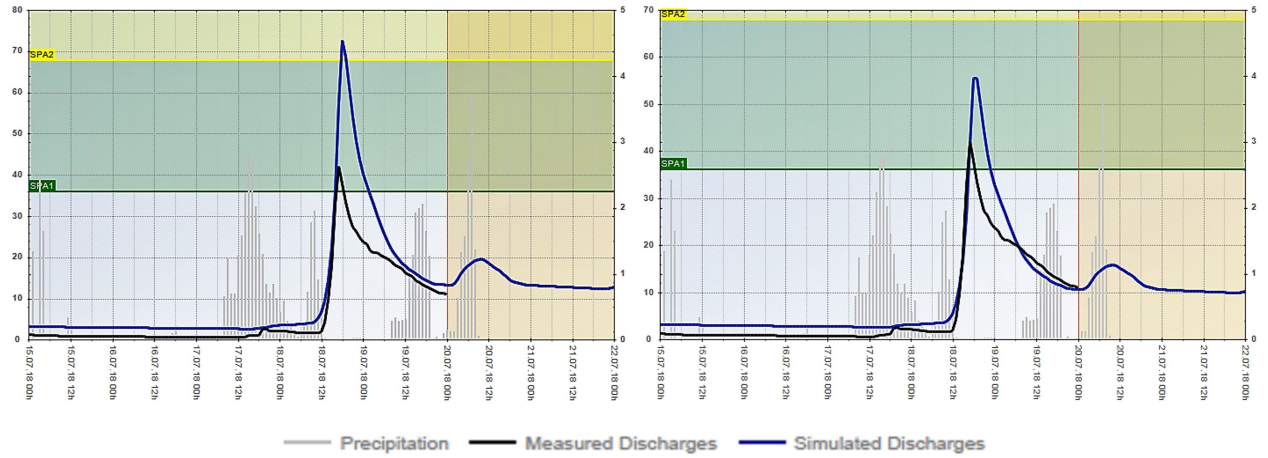


Fig. 5 Comparison of original and newly simulated discharges in the pilot Lubina River basin in July 2018

6 Conclusion

The curve numbers method for simulating surface runoff has been applied for several years now. The main contribution of the proposed study, however, was the derivation of the partially automated procedure using the state-of-the-art computer technology as well as up-to-date maps showing soil conditions and land cover. The above-mentioned procedure allowed us to recalculate runoff ratio up to the smallest area scale possible as a result of intersection of hydrologic soil groups with the respective land cover type. Derivation is based on the original principles determined by the US Soil Conservation Service and can be applied to any river basin in the area of the Czech Republic. Further studies will be aimed at verification of runoff CN for other parts belonging to the Odra River basin in the Moravian-Silesian region. It should be followed by focusing on increasing accuracy of other parameters having an effect on formation of surface runoff as well. Recalculation of runoff CN parameters has been tested in the case of the pilot Porubka and Lubina River basins. It has then been executed for the entire Odra River basin up to the confluence with the Opava River. The results have shown that the runoff curve numbers represent one of the most essential parameters used in Rainfall-Runoff models for recalculation of the rainfall volume to the discharge of water through riverbeds. The quality of their derivation can be retrospectively verified in profiles of hydrological stations where discharge is directly measured. The proposed procedure allowed us to find closer relation between simulated surface runoff and actually evaluated data. The derived method can be applied to any other river basins as well.

Notes

[1] Older version of the HEC-HMS was used in order to ensure compatibility of the input datafiles resulting from calculations made during the previous research.

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