ISSN 1644-0765
DOI: http://dx.doi.org/10.15576/ASP.FC/2017.16.1.187
www.formatiocircumiectus.actapol.net/pl/

ACTA SCIENTIARUM POLONORUM

Acta Sci. Pol. Formatio Circumiectus 16 (1) 2017, 187–207

COMPARISON OF DIRECT OUTFLOW CALCULATED BY MODIFIED SCS-CN METHODS FOR MOUNTAINOUS AND HIGHLAND CATCHMENTS IN UPPER VISTULA BASIN, POLAND AND LOWLAND CATCHMENT IN SOUTH CAROLINA, USA

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Abstract. The aim of the study is to compare direct outflow from storm events estimated using modifications of original SCS-CN procedure. The study was conducted in a mountainous catchment of Kamienica river and a highland catchment draining Stobnica river located in Upper Vistula water region, both in Poland, and a headwater lowland watershed WS80 located at the Santee Experimental Forest in South Carolina, USA. For estimating the event outflows for the Kamienica and Stobnica River basins, the initial data on observed rainfall-runoff events for years 1980–2012 were obtained from Institute of Meteorology and Water Management, National Research Institute in Warsaw, Poland. Similarly, data on rainfall-runoff events for watershed WS80 for a period of 2008 to 2011 were obtained from the United States Department of Agriculture (USDA) Forest Service, Santee Experimental Forest in South Carolina, USA. Following methods were used for the evaluation of event outflows for the three study sites: SCS-CN, Ajmal method, MS method, Sahu 1p and 3p methods. Results from the examined models revealed that the best results of estimated direct event outflow, based on model evaluation statistics (Nash-Sutcliff efficiency parameter), for analyzed catchments were obtained using the Sahu 3p model. However, direct outflow estimated using the original

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SCS-CN method was underestimated in comparison to the observed ones for most of the analyzed episodes.

Key words: rainfall-runoff episodes, direct outflow, SCS-CN method, antecedent moisture

INTRODUCTION

In recent years, the rainfall-runoff models have been commonly used to simulate the hydrological phenomena in uncontrolled catchments. By using these methods, it is not only possible to calculate the design flows necessary for the design of hydraulic facilities, but also to determine the flood parameters (peak flood rate, duration, time to peak, flood volume, etc.), and to analyze the catchment response to the changes triggered, e.g., by human activities [Arnold et al. 2015] compared to predevelopment conditions in the catchment to ensure water resource protection [Blair et al. 2012, Epps et al. 2013]. However, hydrological modeling requires inputs consisting of a large number of parameters that are sometimes difficult to determine [Malone et al. 2015, Wałęga and Rutkowska 2015]. The Soil Conservation Service Curve Number (SCS-CN) method [USDA 2004] (now National Resources Conservation Service NRCS) is one of the most widely used methods for computing the surface runoff depth for a given rainfall event from small watersheds [Michel et al. 2005]. This model is easily applicable for estimation of runoff from ungauged watersheds, because of the smaller number of parameters required. The runoff-producing capability essentially depends on a single parameter, i.e., curve number (*CN*), which reflects the watershed characteristics including soil type, land use/treatment, surface conditions, and antecedent moisture conditions (AMCs) [Ajmal et al. 2015, Epps et al. 2013, Malone et al. 2015].

Research studies investigating the applicability of the SCS-CN method suggested a need for its improvement [Blair et al. 2012, Caviedes-Voullième et al. 2012, Efstratiadis et al.2014, Miler 2012a and 2012b, Ponce and Hawkins 1996, Wałęga and Rutkowska 2015, Wałęga et al. 2015]. Sahu et al. [2012] described some limitation of that the original SCS-CN method like: sudden jumps in the *CN* with change antecedent moisture condition (AMC), lack of clear guidance on how and in what conditions to vary these AMCs and lack of explicit dependency between the initial abstraction and the antecedent moisture. Michel et al. [2005] critically reviewed the soil moisture assessing procedure behind the SCS-CN method and unveiled major inconsistencies in the treatment of antecedent conditions in the SCS-CN procedure. Also, the SCS-CN method is not recommended for use for winter season or for snow precipitation, respectively [Jurik et al. 2013].

In light of the above mentioned limitations of the widely used SCS-CN method and several other modifications of the method published in the literature in recent years, there is a critical need for identifying more accurate and reliable methods for estimating direct outflow for storm events. So, the aim of this paper is to conduct an comparison of direct outflow values estimated using of the original SCS-CN method and its modifications in incorporating the effects of the AMCs, on the catchments of varying sizes, land uses, and topographic gradients located in Poland and the Atlantic Coastal Plain in USA.

CATCHMENTS DESCRIPTION

The first two study catchments are located in the area of Dunajec and Vistula basins in Poland shown in Figure 1. Kamienica River is a right tributary of Dunajec River. Its catchment area at Łabowa river gauge is 64,878 km^2. Mean catchment exposition has a southern aspect. The mountainous catchment area, with a mean slope of 29.42%, is mainly covered by forests (about 76.4%), dominated by coniferous trees. About 23.2% of the catchment is covered by agricultural area and the other remaining (about 0.4%) is on developed lands. The catchment area includes alluvial soils, river sands and gravels, as well as shales, marls, and sandstones.

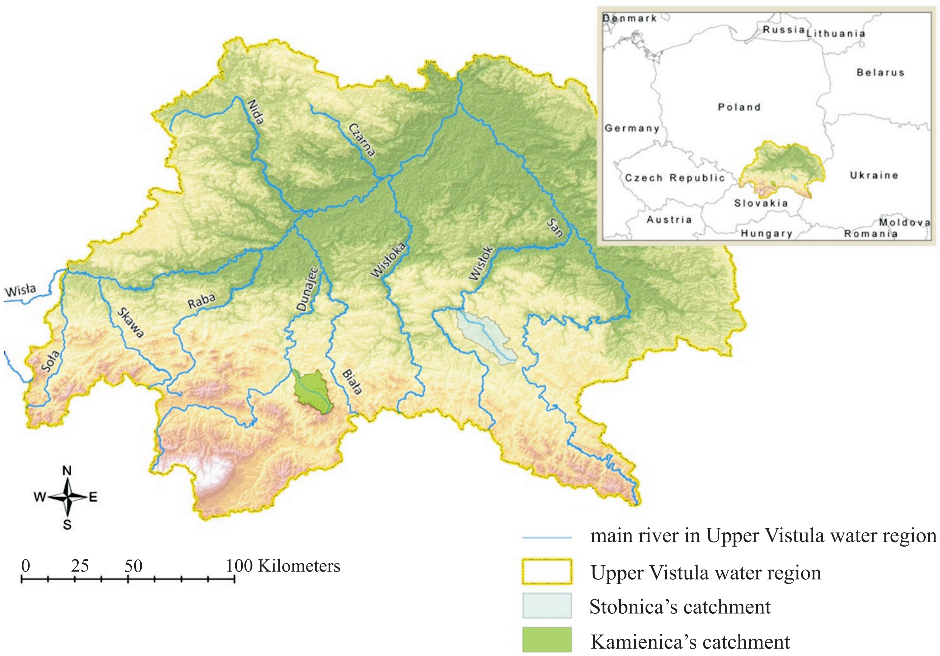


Fig. 1. Location of study catchments
Ryc. 1. Lokalizacja badanych zlewni

The Stobnica River is also a right tributary of Wisłoka River. The catchment area at the river gauge in Godowa is 328,635 km^2. Mean catchment exposition has an eastern aspect. The highland Stobnica catchment, with a mean slope of 19.5%, is mainly used for agricultural purposes (about 62.3%). The 33.7% of its land use is dominated by coniferous and mixed forests. The other remaining area (about 4%) are on developed lands. In the analyzed watershed quaternary deposits lay on the Miocene clays: sands with boulders, boulder clays and fluvial sands. The watershed is dominated by well and average permeable soils.

The third study site Watershed 80 (WS80) is the smallest of the three sites draining a 1st order headwater stream, a tributary of Huger Creek (Fig. 2), The site is located at the USDA Forest service Santee Experimental Forest (33.15°N 79.8°W) which is about 60 km from the City of Charleston, South Carolina (SC), USA. This long-term experimental forest watershed, the control in a paired system, had initial drainage area of 206 ha that was reduced to 160 ha in 2001. The watershed is characterized by low gradient topography (< 3% slope) and shallow water table conditions [Harder et al. 2007]. The watershed is currently comprised of about 70% of the area in mixed pine and hardwoods stands and the remaining 30% in forested wetlands. The WS80 soils are on poorly drained soils dominated by Wahee type with high field capacity and have lower permeability than sandy soils [Harder et al. 2007].

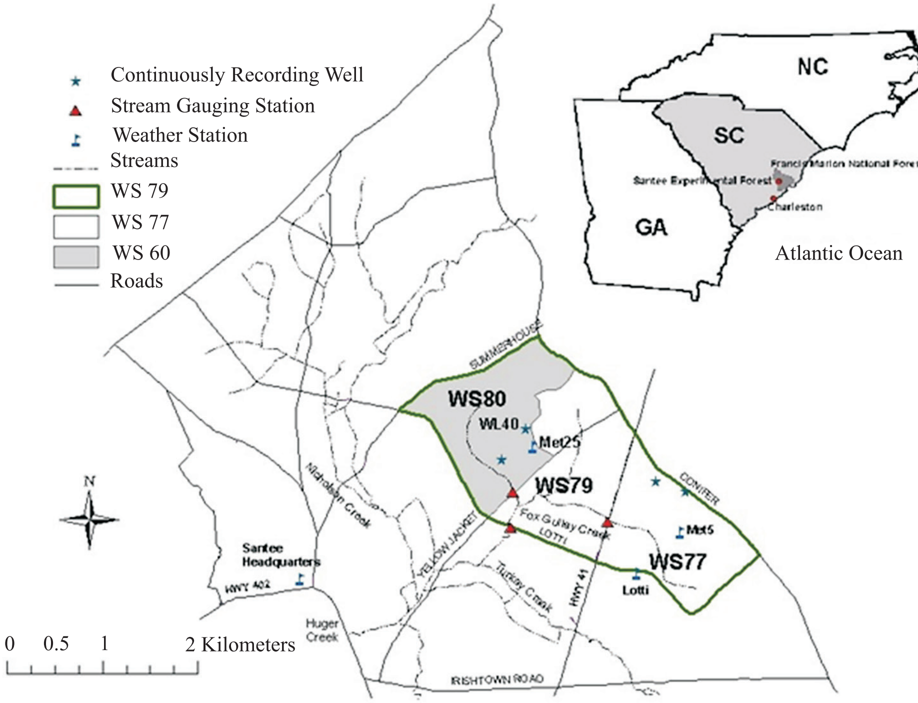


Fig. 2. Location map and experimental layout of study watershed WS80 along with other adjacent watersheds at Santee Experimental Forest in Atlantic Coastal Plain of South Carolina (SC), USA [after Harder et al. 2007]

Ryc. 2. Lokalizacja zlewni eksperymentalnej W80 w odniesieniu do innych zlewni Santee Experimental Forest w Atlantic Coastal Plain of South Carolina (SC), USA [wg Harder I in. 2007]

MATERIAL AND METHODS

For the Kamienica and Stobnica River catchments the initial data on measured precipitation and storm event outflow values for the analysis were obtained from Institute of Meteorology and Water Management, National Research Institute in Warsaw, Poland. The 24-hour time step data were for both the precipitation and outflow for years

1980–2012. The outflow data were measured at the river gauging stations at the catchments, Łabowa for Kamienica River and Godowa for Stobnnica River, respectively. For the Stobnica catchment the precipitation data was spatially averaged with use Le Thiessen method for two gauges [Hingray et al. 2014]. For the Kamienica catchment, areal curve reduction method was used to assess the average precipitation (only one guage in this catchment) [Ven Te Chow et al. 1988]. For the Watershed WS80 site in SC, USA, the precipitation data was collected at an automatic recorder backed up by a manual gauge at Met25 located within the watershed (Fig. 2). The instantaneous breakpoint rainfall was converted into 24-hour daily time steps. The outflow data was computed using stage heights measured at the compound V- and flat crested weir outlet of the watershed with a continuous automatic sensor/datalogger. Data collected during 2008 to 2011 for identifying individual storm events by Epps et al. [2013] in another study were used for this study also. More details of the study site including hydrometeorologic measurements are given elsewhere [Amatya and Trettin 2007, Harder et al. 2007]. Similarly, all data for this study site can be accessed at http://www.srs.fs.usda.gov/charleston/santee/data.html.

Before the actual analysis the individual storm event hydrograph data were separated into the base flow and direct runoff. This was made by drawing a straight line on a hydrograph from the point where the flow increase begins to the point on the descending part, where the direct runoff ends [Ponce 1989]. This procedure allowed us to determine the actual amount of the direct runoff layer for individual episodes. However, for the smallest watershed WS80 at the SC, USA site procedures reported by Epps et al. [2013] were followed to separate the storm event outflow into the base flow and direct runoff.

Empirical values of curve number, CN_{emp}, were determined based on the observed rainfall-runoff events. Following equation was used to calculate the empirical value of potential maximum retention S_i parameter in the CN equation [Hawkins 1993]:

$$S_i = 5 \cdot \left(P_i + 2 \cdot H_i - \sqrt{4 \cdot H_i^2 + 5 \cdot P_i \cdot H_i}\right) \tag{1}$$

where:
P_i – total precipitation amount causing i flow event, mm,
H_i – direct runoff, mm.

The observed value of CN, CN_{obs}, parameter was calculated according to the formula [Deshmukh et al. 2013]:

$$CN_{obs} = \frac{25400}{254 + S_i} \tag{2}$$

In the next step, a theoretical amount of the direct runoff was calculated, using the following methods: (1) Original SCS-CN model [USDA 2004], (2) Ajmal model [Ajmal et al. 2015], (3) Mishra-Sighn model (MS model) [Mishra and Singh 2002], (4) Sahu 1p model, and (5) Sahu 3p model [Sahu et al. 2007].

Original SCS-CN model

The SCS-CN method is based on the water balance equation and two fundamental hypotheses. The first hypothesis (1) equates the ratio of actual amount of direct surface runoff Q to the total precipitation P (or maximum potential surface runoff) to the ratio of actual infiltration (F) to the amount of the potential maximum retention S. The second hypothesis relates the initial abstraction (I_a) to the potential maximum retention (S). A general form of the SCS-CN model is expressed by the following equations [USDA 2004]:

$$Q = \frac{(P - I_a)^2}{P - I_a + s} \quad if\ P > I_a \tag{3}$$

$Q = 0$ otherwise and

$$I_a = \lambda S \tag{4}$$

where:
- Q – direct runoff, mm,
- P – total precipitation, mm,
- I_a – initial abstraction, mm,
- S – potential maximum retention, mm
- λ – initial abstraction coefficient (dimensionless) which is assumed as 0,20 (according to USDA 2004).

In equation (3), S was calculated by equation (5):

$$S = \frac{25400}{CN} - 254 \tag{5}$$

where CN is the curve number, which depends on the soil type, land cover and land use, hydrological conditions, and antecedent moisture condition (AMC). In the calculations the AMC value was adopted based on observed rainfall episodes prior to the event analyzed. For all the catchments CN was determined according the USDA [2004] tables.

Ajmal model

The Ajmal model [Ajmal et al. 2015] was conceptualized after combining the concept of the CN model, the Soil Moisture Antecedent (SMA) procedure from Michel et al. [2005], and the event-based empirical GR4J model. The GR4J is a four free parameter-based French empirical rainfall-runoff model. This model was originally developed as GR3J (a three free parameter-based model) [Edijatno et al. 1999] and then successively improved to GR4J [Perrin et al. 2003]. Ajmal model is described by the following equations:

$$Q = P \cdot \frac{(P + 0.15 \cdot S)^2}{P + 0.8 \cdot S} \quad if\ P > 0.2 \cdot S \cdot \left[\frac{P}{P + P_5}\right] \quad \text{for AMCI} \tag{6}$$

$$Q = P \cdot \frac{(P + 0.25 \cdot S)^2}{P + 0.8 \cdot S} \ \ if \ P > 0,2 \cdot S \cdot \left[\frac{P}{P + P_5}\right] \ \text{for AMCI} \tag{7}$$

$$Q = P \cdot \frac{(P + 0.32 \cdot S)^2}{P + 0.8 \cdot S} \ if \ P > 0.2 \cdot S \cdot \left[\frac{P}{P + P_5}\right] \ \text{for AMCIII} \tag{8}$$

where:

P_5 – the amount of antecedent 5-day rainfall,
S – potential maximum retention (mm) (eq. 5).

Mishra-Singh model (MS model)

Mishra and Singh (2002) modified the above equation (3) for direct runoff with antecedent moisture *M* to:

$$Q = \frac{(P - I_a) \cdot (P - I_a + M)}{P - I_a + M + S} \tag{9}$$

where *M* is the antecedent moisture (mm):

$$M = 0.5 \cdot \left[-(1 + \lambda)S + \sqrt{(1 - \lambda)^2 \cdot S^2 + 4 \cdot P_5 \cdot S}\right] \tag{10}$$

Here, I_a and λ are the same as in Equation (4) and P_5 denotes the amount of antecedent 5-day rainfall. Equation (10) represents the amount of moisture *M* added to the dry soil profile by rain P_5.

Sahu 1p model

Since the three AMC levels (I, II, and II) used with the original SCS-CN method [USDA 2004] yield unreasonable sudden discontinuity in *CN*, a continuous equation is needed to accurately estimate the antecedent moisture for all conditions. Sahu et al. [2007] developed two versions of a model determining the volume of direct runoff in the form of an equation comprising of one or three parameters.

For the simulations carried out in 82 catchments in India by the authors, α and β parameters in the three-parameter model were 0.1 and 0.4, respectively; mean and median values for each of these two parameters were almost the same, and these simplifications yielded a one-parameter model − Sahu 1p, which is described by the following set of equations:

$$V_0 = 0.4 \cdot P_5 \ if \ P_5 \leq 0.1 \cdot S \tag{11}$$

$$V_0 = S \cdot \left(\frac{0.44 \cdot P_5 - 0.004 \cdot S}{P_5 + 0.9 \cdot S}\right) if \ P_5 > 0.1 \cdot S \tag{12}$$

where V_0 is the soil moisture store level at the beginning of the rainfall event (mm). Other symbols are as in the previous formulas. When V_0 is known, Q can be computed as follows:

$$\textit{if } V_0 + P \le 0.1\, S \text{ then } Q = 0 \tag{13}$$

$$\textit{if } 0.1 \cdot S < V_0 + P \le 0.1 \cdot S + P \text{ then } Q = \frac{(P + V_0 - 0.1 \cdot S)^2}{P + V_0 + 0.9 \cdot S} \tag{14}$$

$$\textit{if } 0.1 \cdot S \le V_0 \le 1.1 \cdot S \text{ then } Q = P \cdot \left(1 - \frac{(1.1 \cdot S - V_0)^2}{S^2 + (1.1 \cdot S - V_0) \cdot P}\right) \tag{15}$$

The value of S parameter was calculated in a similar way as in the above-mentioned methods.

Sahu 3p model

The antecedent or initial soil moisture V_0 depends not only on P_5 but also on S. The dependency on S is based on the fact that the watershed with larger retention capacity S must retain higher moisture compared to the watershed with lesser S for a given P_5. Sahu et al. [2007] derived the following equations for different conditions:

$$V_0 = V_{00} + \beta \cdot P_5 \quad \text{for } V_{00} \le S_a - P_5 \tag{16}$$

$$V_0 = V_{00} + \beta \cdot \left[P_5 - \frac{(P_5 + V_{00} - S_a)^2}{P_5 + V_{00} - S_a + S}\right] \quad \text{for } S_a - P_5 < V_{00} \le S_a, \tag{17}$$

$$V_0 = V_{00} + \beta P_5 \cdot \left[\frac{(S + S_a - V_{00})^2}{s^2 + (S + S_a - V_{00}) \cdot P_5}\right] \quad \text{for } S_a \le V_{00} \le S_a + S. \tag{18}$$

where:

V_{00} – the old moisture level available for 5 days before the rainfall,
S_a – an intrinsic parameter of soil moisture ($S_a = \alpha \cdot S$),
α – a parameter (fraction),
β – an additional model parameter ranging from 0 to 1.

Analyses performed by these authors indicated that $V_{00} = 0$. This simplification in the Sahu model resulted into a three parameter model that is referred to as the Sahu 3p model. The direct runoff was calculated using the following equations:

$$Q = 0 \;\textit{for } V_0 \le S_a - P_5, \tag{19}$$

$$Q = \frac{(P + V_0 - 0.1 \cdot S_a)^2}{P + V_0 - S_a + S} \;\textit{for } S_a - P_5 < V_0 \le S_a, \tag{20}$$

$$Q = P \cdot \left[1 - \frac{(S + S_a - V_0)^2}{S^2 + (S + S_a - V_0) \cdot P} \right] \quad for\ S_a \le V_0 \le S_a + S, \tag{21}$$

This method involved optimization of α and β parameters.

Verification of the methods

Root mean square error (*RMSE*) and Nash-Sutcliffe model efficiency (*EF*) [Nash and Sutcliffe (N-S) 1970] parameters were used as goodness of fit criteria to assess the model performance. RMSE and EF were expressed as below:

$$RMSE = \sqrt{\frac{1}{N} \cdot \sum_{i=1}^{N} (Q_{obs,i} - Q_{calc,i})^2} \tag{22}$$

$$EF = 1 - \frac{\sum_{i=1}^{N} (Q_{obs,i} - Q_{calc,i})^2}{\sum_{i=1}^{N} (Q_{obs,i} + \bar{Q}_{obs})^2} \tag{23}$$

where:

Q_{obs} – the observed storm runoff, mm,
Q_{calc} – the calculated runoff, mm,
$\bar{Q}_{obs}$ – a mean of the observed runoff values in the catchment,
N – the total number of rainfall-runoff events,
i – an integer varying from 1 to *N*.

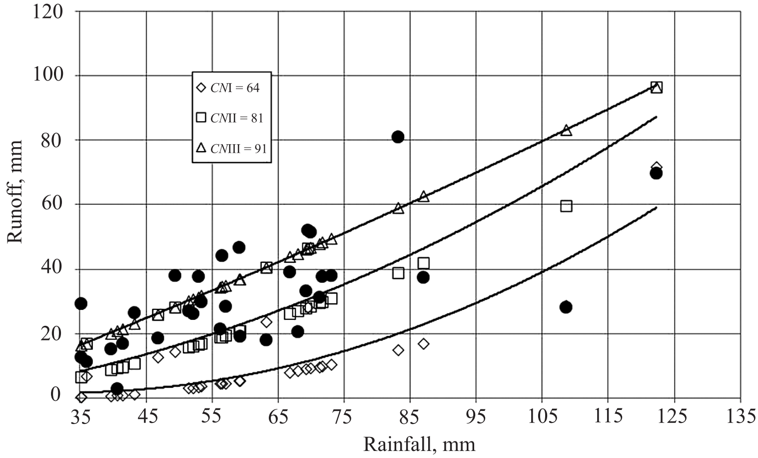
The lower the *EF* or higher *RMSE*, the poorer is the performance of the model, and vice versa. *EF* = 1,00 or *RMSE* = 0,00 exhibits a perfect fit. *EF* has the advantages of having the same units (dimensions) as the variable, properly accounting for the degrees of freedom and being valid for nonlinear as well as linear models.

RESULTS AND DISSCUSION

Despite of wide applicability of SCS-CN method one of the most important problems in its practical applications is an assumption of proper initial conditions of ground moisture, before the initiation of rainfall causing a runoff event. Assumption of inappropriate initial moisture conditions can lead to underestimation or overestimation of calculated direct outflow [Fennessey and Hawkins 2001, Banasik and Woodward 2010, Epps et al. 2013, Kowalik and Walega 2015, Krzanowski et al. 2013, Rutkowska et al. 2015, Wałęga et al. 2015]. Such a problem as an example for the mountainous Kamienica catchment in Poland is shown on Fig. 3a and an example for the lowland WS80 watershed in SC, USA in Fig. 3b.

It can be observed, that points (black circles) representing observed rainfall-runoff events for mountain catchment (Fig. 3a) in most cases were located in the neighborhood of theoretical curve representing third, the highest antecedent moisture stage (AMCIII).

a)



b)

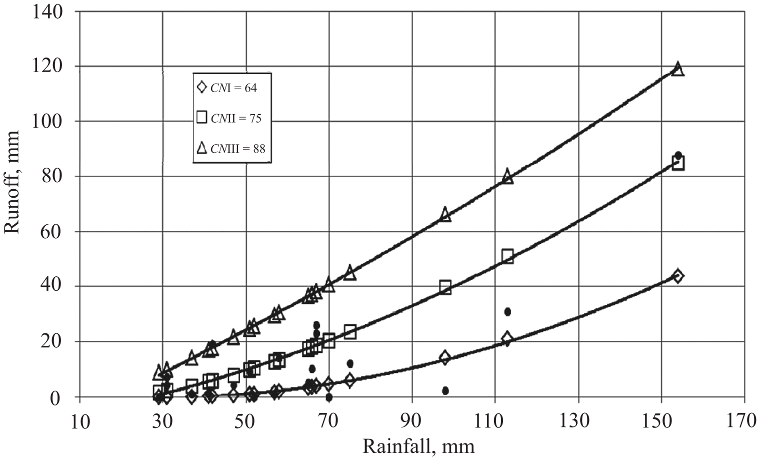


Fig. 3. The observed rainfall-runoff events and direct outflow calculated according to SCS-CN method for different *CN* values, corresponding to three antecedent moisture conditions for: a) the Kamienica catchment, b) the WS80 watershed

Ryc. 3. Obserwowane epizody opad-odpływ oraz obliczony wg SCS-CN odpływ bezpośredni dla różnych wartości *CN*, odpowiadających trzem poziomom uwilgotnienia w zlewni: a) Kamienicy, b) W80

This shows, that in case of the selected storm events the outflow responded for relatively small initial precipitation losses, indicating that the rainfall causing the runoff occurred on the already moist ground with a small storage. On the other hand, for the lowland watershed WS80, most of the rainfall-runoff events (small back circles) were found to be located near theoretical curve representing dry moisture conditions (AMCI) (Fig. 3b). In general engineering practice, for event outflow calculations in ungauged catchments the second (or average) ground moisture stage (AMCII) is adopted. As a result, in above described cases a much more underestimation of calculated values of direct event outflow can be expected for the mountainous Kamienica catchment and an overestimation for the lowland WS80 watershed. Similar observations have been reported in other recent studies by several authors [Wałęga et al. 2011, de Paola et al. 2013, Banasik et al. 2014, Kowalik and Wałęga 2015]. In this context, therefore, there is a need of finding alternative methods of direct outflow estimation, that provides results that are closest to the observed ones with a minimal error. The basic statistical characteristics for measured event precipitation (P) and outflow (Q_{obs}) values along with the calculated event outflows using the above five methods (models) for the analyzed periods are shown in Tables 1, 2, and 3 for the Kaminieca catchment, Stobnica catchment, and the WS80 watershed, respectively.

Table 1. Summary statistics of the measured storm event data sets (number of storm events $N = 30$) and model outputs for the Kamienica catchment
Tabela 1. Statystyki podstawowe danych (liczba epizodów $N = 30$) i wyników z modeli dla zlewni Kamienica

Statistic	P	Q_{obs}	SCS-CN	Ajmal method	MS model	Sahu 1p	Sahu 3p
Mean, mm	54.66	29.43	26.29	32.31	26.57	33.77	32.00
Min, mm	20.80	2.80	0.93	6.51	6.57	6.72	6.42
Max, mm	108.60	81.10	59.16	64.91	68.97	83.12	80.69
Median, mm	54.75	27.65	28.40	35.68	22.56	30.95	29.13
Standard deviation, mm	20.09	14.63	12.69	13.13	15.54	15.80	14.34
Skewness	0.51	1.46	0.31	0.17	0.85	1.13	1.28
Kurtosis	0.32	4.33	0.42	0.15	0.29	2.64	3.39
25th percentile, mm	39.93	20.90	17.07	22.47	16.32	25.30	24.27
75th percentile, mm	68.88	37.73	31.66	38.48	37.76	40.86	40.82

Table 2. Summary statistics of the measured storm event data sets ($N = 14$) and model outputs for the Stobnica catchment
Tabela 2. Statystyki podstawowe danych ($N = 14$) i wyników z modeli dla zlewni Stobnica

Statistic	P	Q_{obs}	SCS-CN	Ajmal method	MS model	Sahu 1p	Sahu 3p
Mean, mm	41.87	25.91	21.86	32.86	25.97	29.86	27.69
Min, mm	16.50	8.80	3.60	11.06	9.96	11.99	9.80
Max, mm	80.40	72.40	56.53	70.75	72.92	75.71	73.36
Median, mm	37.15	18.90	16.56	29.35	19.45	25.00	19.80
Standard deviation, mm	20.31	19.02	16.62	18.27	18.74	18.59	18.79
Skewness	0.47	1.37	0.83	0.75	1.51	1.40	1.33
Kurtosis	–1.07	1.33	–0.40	–0.36	1.76	1.52	1.22
25th percentile, mm	24.65	12.68	8.61	18.01	13.25	17.35	14.44
75th percentile, mm	57.00	33.48	34.62	43.71	31.19	36.05	36.05

Table 3. Summary statistics of the measured storm event data sets (N = 20) (from Epps et al. 2013) and model outputs for the WS80 watershed
Tabela 3. Statystyki podstawowe danych i wyników z modeli dla zlewni W80

Statistic	P	Qobs	SCS-CN	Ajmal method	MS model	Sahu 1p	Sahu 3p
Mean, mm	62.55	12.85	11.74	20.30	12.55	20.81	23.24
Min, mm	29.00	0.00	0.04	5.28	0.00	2.13	5.66
Max, mm	154.00	88.00	84.73	96.11	83.39	94.21	101.26
Median, mm	57.50	6.00	5.19	14.59	3.54	11.00	18.56
Standard deviation mm	30.46	20.00	18.51	19.58	20.34	22.48	21.31
Skewness	1.65	3.06	3.52	3.31	2.53	2.20	2.86
Kurtosis	3.36	11.00	14.00	12.78	7.46	5.43	9.72
25th percentile, mm	41.75	1.00	2.00	9.27	0.28	7.52	11.57
75th percentile, mm	67.75	15.25	15.04	24.50	21.16	28.27	24.48

In case of the Kamienica and Stobnica upland catchments, the highest mean outflow was obtained for Ajmal model, and the lowest for the original SCS-CN method. For the Kamienica catchment the mean outflow closest to the observed one was calculated for Sahu 3p method with a difference of 8.7%, followed by the Ajmal method (9.9%). For the Stobnica catchment, the mean outflow estimated by the MS model was in close agreement with the observed one. The similar results with the difference of 6.9% between the observed and calculated outflows were also obtained in case of the Sahu 3p method. In case of the Stobnica catchment the major differences of results were also found, with higher values of standard deviation and lower kurtosis, an evidence of the wider distribution. Computed values of event outflow did not show the characteristics of normal distribution with a right-hand skewness in both the catchments.. For the lowland WS80 watershed, the highest mean outflow was calculated for Sahu 3p, and the lowest for SCS-CN method. The closest agreement of the computed outflow with the observed outflow was obtained for the MS model with the difference of only 2.3%, followed by the SCS-CN method with the difference of 8.6%.

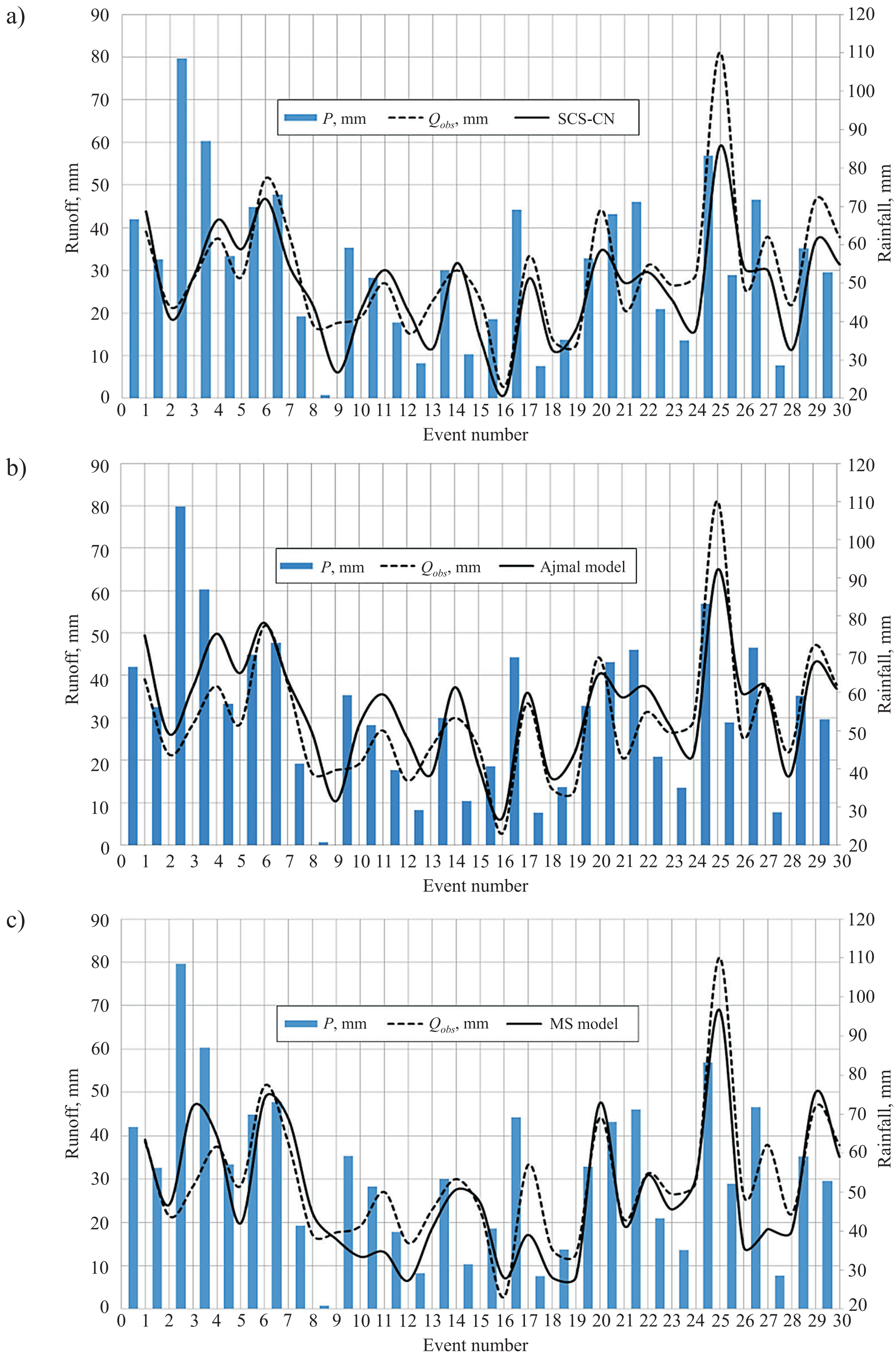
The computed statistics for efficiency of the models evaluated expressed by *RMSE* and *EF* (Eqs. 22 and 23) are shown in Table 4. Based on the criteria presented by Moriasi et al. [2007], model evaluated is considered very good for $EF > 0.75$, good for $0.65 \leq EF < 0.75$, satisfactory for $0.50 \leq EF < 0.65$, and unsatisfactory for $EF < 0.50$. Recently, Ritter and Muñoz-Carpena [2013] established a hydrologic model performance rating criteria where an $EF < 0.65$ was deemed a lower threshold for unsatisfactory. Other model performance ratings were as follows: acceptable ($0.65 \leq EF < 0.80$), good ($0.80 \leq EF < 0.90$), and very good ($EF > 0.90$). Using these criteria for computed efficiency statistics shown in Table 3, in case of Kamienica and Stobnica catchments, the best performing model was found to be the Sahu 3p model, that yielded the lowest values of *RMSE* and the highest of *EF*.

Also especially interesting to note for the Stobnica catchment is that both the MS model and Sahu 1p model can be considered very good (MS model had in this case the lowest value of *RMSE* error). However, the promising results were obtained for the Ajmal model. In the Kamienica catchment, it yielded good acceptable computed efficiency statistics according to both the criteria, but in case of the Stobnica catchment this model was good or very good. Similar high model efficiency statistics for the Kamienica catchment were obtained for the SCS-CN method (*EF* = 0.72, *RMSE* = 7.63 mm), deeming it good or acceptable model. However, for the Stobnica catchment this model performed very poor – unsatisfactory based on the efficiency statistics. For the lowland W80 watershed the best efficiency statistics were calculated for the MS model finding it as very good. These results show that MS model is the most appropriate one for calculation of direct outflow for both the lowland (WS80 in SC, USA) and highland (Stobnica, Poland) catchments than for the mountain catchment (Kaminieca). According to the calculations conducted in this study it can be stated that some of the modifications of the SCS method allows for a relatively better estimation of direct event outflow values in highland catchment compared to the mountainous catchment.

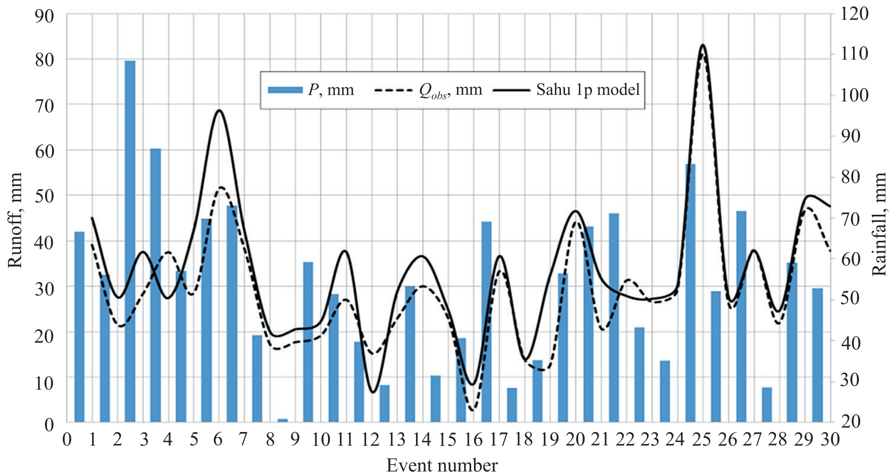
Table 4. Computed efficiency statistics for 5 models applied on three study catchments
Tabela 4. Wyniki jakości modeli dla analizowanych zlewni

Model	The Kamienica catchment		The Stobnica catchment		The WS80 watershed	
	RMSE mm	*EF*	*RMSE* mm	*EF*	*RMSE* mm	*EF*
SCS-CN	7.63	0.72	17.18	0.12	12.59	0.58
Ajmal model	7.86	0.70	6.08	0.89	8.94	0.79
MS Model	8.01	0.69	1.58	0.99	3.79	0.96
Sahu 1p model	7.63	0.72	5.20	0.92	10.26	0.72
Sahu 3p model	2.97	0.96	2.14	0.99	11.12	0.67

Plots in Figure 4a–e and the plots in Figure 5a–e illustrate the comparisons of individual runoff events predicted by five different models obtained by the modifications of the original SCS-CN model with those from the observed data in the Kamienica catchment and on W80 watershed, respectively. It was evident from Fig 4a and 5a that SCS-CN model underestimated the runoff for majority of the events. On the contrary, the Ajmal model predicted runoff was overestimated for the majority of the events in comparison to the measured runoff shown in Fig. 4b and 5b. Results in Fig 4c and 5c showed that MS model underestimated the runoff in the mountainous Kamienica catchment for majority of the events but this model performed well in predicting measured runoff events for the lowland W80 watershed. The Sahu 1p model very often overestimated runoff at both the study sites (Fig. 4d and 5d). The Sahu 3p model performed the best in predicting the runoff compared to the other models in the Kamienica catchment (Fig. 4e) but overestimated runoff for majority of events for lowland watershed WS80 (Fig. 5e).


a)
P, mm
Qobs, mm
SCS-CN
Runoff, mm
Rainfall, mm
Event number
b)
P, mm
Qobs, mm
Ajmal model
Runoff, mm
Rainfall, mm
Event number
c)
P, mm
Qobs, mm
MS model
Runoff, mm
Rainfall, mm
Event number

d)



e)

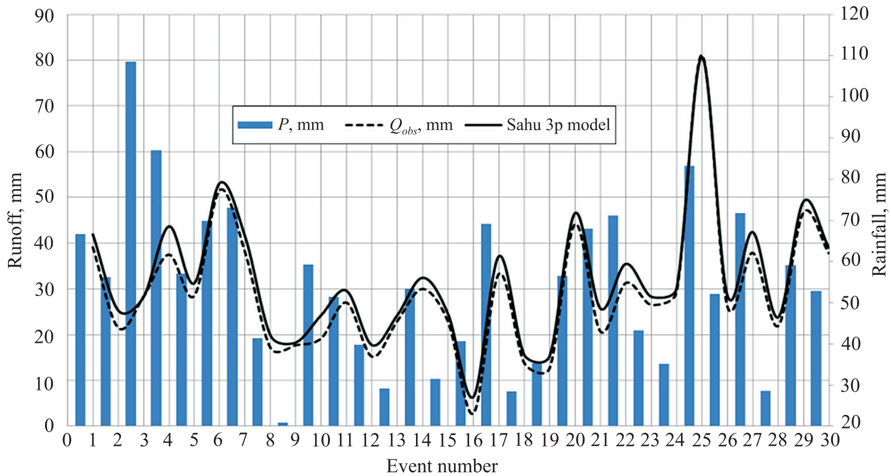
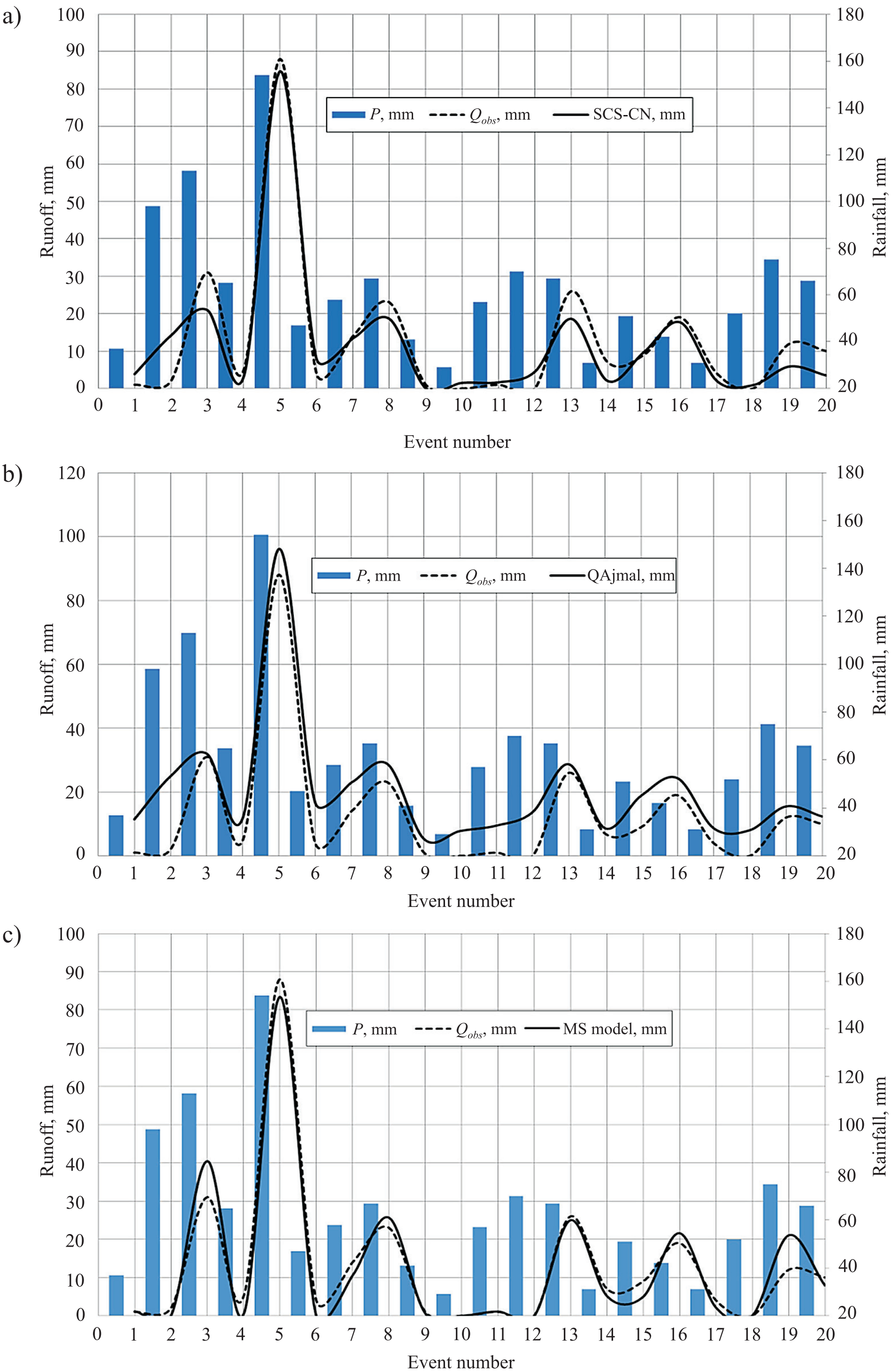
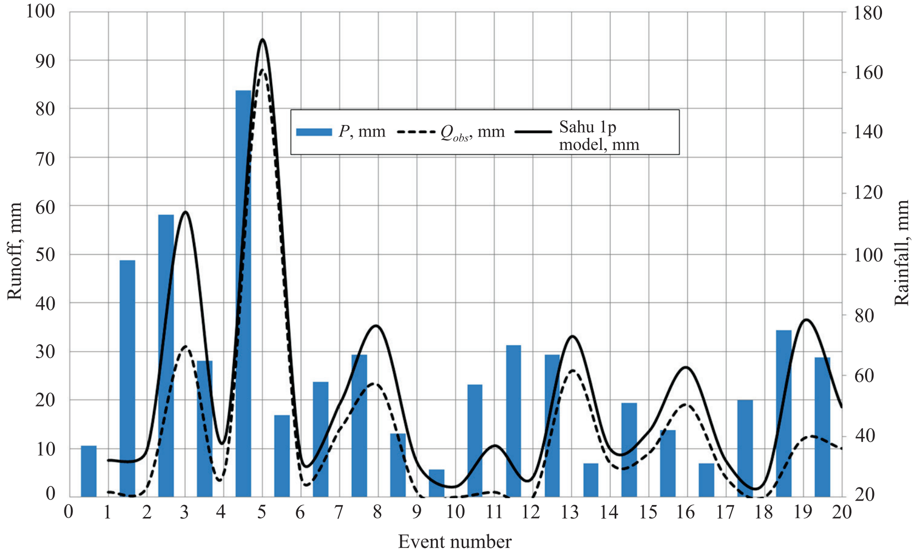


Fig. 4. Visual assessment of runoff predicted by 5 different models with those from the measured runoff (Q_{obs}) for 30 individual runoff events for the mountainous Kamienica catchment in Poland

Ryc. 4. Wizualna ocena poszczególnych 30 epizodów w górskiej zlewni Kamienicy dla których odpływ oszacowany był różnymi modelami oraz porównanie do odpływu pomierzonego (Q_{obs})


a)
P, mm
Qobs, mm
SCS-CN, mm
Runoff, mm
Rainfall, mm
Event number
b)
P, mm
Qobs, mm
QAjmal, mm
Runoff, mm
Rainfall, mm
Event number
c)
P, mm
Qobs, mm
MS model, mm
Runoff, mm
Rainfall, mm
Event number

d)



e)

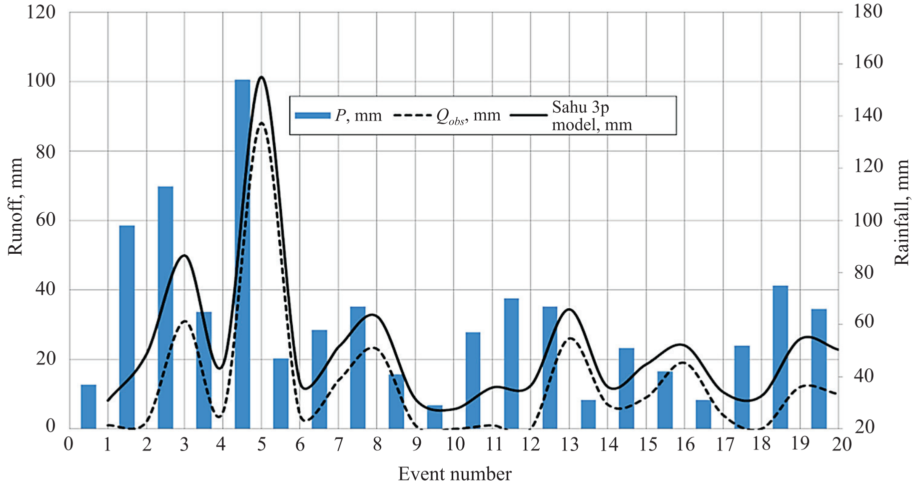


Fig. 5. Visual assessment of runoff predicted by 5 different models with those from the measured runoff (Q_{obs}) for 20 individual runoff events for the WS80 watershed in SC, USA

Ryc. 5. Wizualna ocena poszczególnych 20 epizodów w zlewni eksperymentaknej W80 w USA dla których odpływ oszacowany był różnymi modelami oraz porównanie do odpływu pomierzonego (Q_{obs})

CONCLUSION

Based on the analysis of estimating runoff for individual storm events conducted using five different modified versions of the original SCS-CN method for three study sites (two large mountainous and upland catchments in Poland and a small headwater lowland watershed in South Carolina, USA) following conclusions were formulated:

1. The values of direct outflow or runoff estimated using the original SCS-CN method did not match the real outflow obtained from measurements. In most cases, the SCS-CN method underestimated the measured event outflows, warranting investigation of alternative methods which allow for more precise estimation of this critical hydrological variable.
2. Taking the antecedent moisture due to precipitation prior to the storm event of concern into consideration in various methods modifying the original SCS-CN model can considerably improve the results of estimated event runoff values.
3. The visual evaluation of the predicted events by the five models for mountain catchment showed that the best results of estimated direct outflow were obtained by the Sahu 3p model when compared with the observed data. The best results for highland watershed were obtained by the MS model. Based on the efficiency quality criteria also, this model performed very good for both the mountainous and highland catchments.
4. In the present situation owing to necessity of multi-parameter calibration in other rainfall-runoff models, the Sahu 3p model can be used in Polish conditions for the catchments, that have the event-based precipitation and flow measurements. There is a need of further research on extensive data measurements from multiple catchments to further evaluate the parameters values of Sahu 3p model, which will take into consideration the regional climatic and spatial variability. In future studies, it provides a basis for application of this method for reliably estimating event outflows on ungauged catchments.
5. For the lowland watershed (the WS80 watershed in South Carolina, USA) although the SCS-CN model yielded a good assessment of direct outflow, the best results were, however, achieved for the MS model based on the efficiency criteria. This model was found to be appropriate for calculation of direct outflow for the lowland and highland catchments than for the mountainous catchment.

ACKNOWLEDGEMENT

The authors would like to thank Institute of Meteorology and Water Management National Research Institute, for hydrometeorology datas for the Kamienica and Stobnica catchments and USDA Forest Service Santee Experimental Forest for the hydro-meteorology data for the Watershed WS80 in South Carolina. Source of financial of this paper is DS/3347/KISiGW/2016.

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PORÓWNANIE WIELKOŚCI ODPŁYWU BEZPOŚREDNIEGO OBLICZONEGO WEDŁUG ZMODYFIKOWANYCH WERSJI METODY SCS-CN W ZLEWNI GÓRSKIEJ I WYŻYNNEJ DORZECZA GÓRNEJ WISŁY I NIZINNEJ W POŁUDNIOWEJ KAROLINIE, USA

Streszczenie. Celem pracy jest ocena wielkości odpływu bezpośredniego oszacowanego według metod, stanowiących modyfikację oryginalnej procedury SCS-CN. Badania prowadzono w zlewni górskiej Kamienicy, wyżynnej – Stobnicy, zlokalizowanych w regionie wodnym górnej Wisły oraz w nizinnej zlewni W80 zlokalizowanej w Południowej Karolinie, USA. Materiałem wyjściowym do obliczeń były zaobserwowane epizody opad-odpływ pozyskane z Instytutu Meteorologii i Gospodarki Wodnej Państwowego Instytutu Badawczego w Warszawie z wielolecia 1980–2012. W przypadku zlewni W80 dane w postaci epizodów opad-odpływ pochodziły z zasobów Departamentu Rolnictwa Stanów Zjednoczonych. Zastosowano następujące metody: SCS-CN, Ajmala, Mishra i Sighn (MS), Sahu 1p i Sahu 3p. Z pośród rozpatrywanych modeli najlepsze wyniki obliczeń odpływu bezpośredniego dla analizowanych zlewni uzyskano z modelu Sahu 3p. Odpływ bezpośredni obliczony z metody oryginalnej SCS-CN w większości analizowanych epizodów był niedoszacowany w stosunku do obserwowanego.

Słowa kluczowe: epizody opad-odpływ, odpływ bezpośredni, metoda SCS-CN, wilgotność początkowa

Accepted for print – Zaakceptowano do druku: 11.01.2017

For citation: Wałęga, A., Cupak, A., Amatya, Devendra M., Drożdżal, E. (2017). Comparison of direct outflow calculated by modified SCS-CN methods for mountainous and highland catchments in upper Vistula basin, Poland and lowland catchment in south Carolina, USA Acta Sci. Pol., Formatio Circumiectus, 16(1), 187–207.