The usability of the Nash cascade-submerged cascade rainfall-runoff model with regard to other conceptual models

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Abstract: Conceptual hydrological models are an effective tool used to forecast runoff from catchments and assess changes in catchment dynamics. The article presents a modified concept of the Diskin parallel cascade model, with the replacement of one of the cascades with the submerged cascade model – the Nash cascade-submerged cascade model (NCSC2). Considering a watershed as a system where total runoff is determined by amounts of both surface and subsurface runoffs, the use of different model structures as surface and subsurface runoffs is reasonable. Adopting 13 different objective functions, the comparative analysis of NCSC2, Nash cascade, Diskin model, single linear reservoir and submerged reservoir cascade (SC2) models has been carried out in the catchment of six Polish rivers. The research has shown that the use of the submerged cascade as one of the Diskin model cascades positively affects the quality of the model.

Keywords: rainfall-runoff process, hydrological modelling, conceptual models, parameters estimation

INTRODUCTION

In the era of climate change, characterized by an increased risk of drought and flooding, increasing attention is being paid to the problem of water management and retention. Mathematical rainfall-runoff models enable watershed dynamic characteristics to be obtained based on precipitation and river flow data, making them an effective tool in introducing and observing changes in the management of water resources in a given area (Krężałek 2022). Moreover, in extreme cases of a lack of observational data, rainfall-runoff models are the only way to obtain information about flood hydrographs (Onyando et al. 2003, Janicka 2023). Unit hydrograph (UH) parameters can be expected to relate to such physical catchment characteristics as slope, drainage network density, and land use, leading to the estimation of UH for uncontrolled catchments (Littlewood 2002). That is why rainfall-runoff relation methods are recommended by the Ministry of Transportation in Poland to determine flow values in the ungauged catchments, necessary for the design of bridges and culverts (Rymsza et al. 2021).

The development of technologies and numerical techniques has provided new tools for modeling the dependence between precipitation and runoff, such as: artificial neural networks, data-based mechanistic modeling (DBM), and physically meaningful models (Liu & Todini 2002). While data-driven models are devoid of physical justification, the high complexity of physical processes and increasing urbanization result in significant simplifications

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of physically meaningful model structures (Zhang & Savenije 2005, Bardossy 2007). Unfortunately, most of necessary data, like e.g. effective rainfall, cannot be physically measured and must be estimated on the basis of available information (Bardossy 2007), which generates an additional error at the stage of preparing the input data. As a result of the inability to obtain the necessary measurement data for the structures of hydrological models, parameters whose values are determined in the optimization process were introduced. It is claimed that results obtained from reservoir models are determined by the objective function used at the optimization stage (Byczkowski 1996, Krause et al. 2005, Moussa & Chahinian 2009). Therefore, the usefulness of the model does not depend solely on its structure, but also on the rational selection of appropriate estimation criteria. As a consequence, despite years of development, it has still not been possible to create a universal and reliable model of precipitation to runoff transformation.

Many modifications have been made based on the original concept of the single linear reservoir model, the most popular of which are the Nash model and the two-cascade Diskin model. Their structure seems to consider only one sort of river supply – surface outflow. Although it is currently impossible to precisely determine the subsurface resources of the catchment, i.e. a full characterization of the subsurface and underground flow, it is known that surface and subsurface supply affect the generated runoff in different ways. The structure of the submerged reservoirs cascade model introduced by Kurnatowski (2017) can imitate the subsurface supply of the river.

It was noted that simple models using a few parameters necessary for the presentation of the basic quantities characterizing outflow are advantageous due to the fact that they minimize the problem of excessive parameterization and the associated uncertainty in calibrating a set of parameters (Crooks & Naden 2007). The thesis of van Dijk's work (2010) even states that the best predictions are obtained from the model with the fewest parameters. That statement complies with the parameter estimation theory that estimated parameters uncertainty increases fast with the number of parameters (Spada et al. 2015). Moreover, Chiew et al. (1993) showed that simple conceptual model structures can be used for larger timescales (months, years). Refsgaard and Knudsen (1996) claimed that both distributed models based on the physic equations and lumped conceptual model performed equally well in their research. A similar performance of lumped and distributed models was also observed by Vilaseca et al. (2021) in the case of watershed with no significant reservoirs and Reed et al. (2004) who have shown that lumped parameter models are generally at least as efficient as models with distributed parameters. Perrin et al. (2001) showed that complex lumped models exceed simple models in calibration but not in verification. The reasons for this are being sought in model structure errors, the inconsistency between available and required data, and the level of complexity resulting in an excessive number of parameters, which in consequence leads to an increase in their uncertainty.

Most conceptual models belong to the group of lumped models ignoring the spatial variety of variables and parameters (Zhang & Savenije 2005). Their use is justified when the scope of consideration is limited to values obtained in the section closing the catchment. That is why their application is eligible for flood predictions or culvert design, when available data is limited so the complex models cannot be used (Sikorska et al. 2013). Moreover, considerable attention is currently paid to the problem of regionalization, in particularly to the importance of simplified models application describing only the essential elements of precipitation-runoff processes with a minimum number of parameters (Patil 2008). According to Moussa and Chahinian (2009), most of the forecasting models used in France are lumped ones.

THE NASH CASCADE-SUBMERGED CASCADE RAINFALL-RUNOFF MODEL (NCSC2)

Considering a catchment as a system where the volume of total runoff is determined by both surface runoff and subsurface runoff, the modified conception of the Diskin model, where one of the Nash cascades is replaced by the cascade of submerged reservoirs, i.e. SC2 (Kurnatowski 2017) was proposed (Fig. 1). The basic problem that arises in multi-cascade modeling is the division of external input signals into linear submodel inputs (Kundzewicz & Napiórkowski 1986). The influence of cascades on the final runoff hydrograph is presented in a way similar to the Diskin model, by the use of β coefficient but the difference is in its interpretation. While in Diskin model β coefficient presents participation of impervious area (Diskin 1980), in NCSC2 coefficient β presents participation of subsurface runoff.

It is estimated that the volume of subsurface runoff in non-urbanized areas may be as much as 15% to 50% of the surface runoff (Wicherek 1995). The adoption of the concept of a submerged reservoirs cascade to simulate this phenomenon seems to be reasonable, due to the high degree of similarity between the model structure and the features of subsurface water flow. The difference in the retention of two adjacent reservoirs in SC2 model can be seen analogously to the hydraulic gradient of the groundwater table, therefore the SC2 model is a conceptual interpretation of Darcy's law. This analogy allows us to consider the usefulness of the SC2 model in relation to the base flow modeling (Kurnatowski 2017). The split of effective precipitation into two cascades is determined analogously to the Diskin model. The instantaneous unit hydrograph function yields:

$$u_N(t) = \beta \sum_{j=1}^{N_1} C_j \cdot e^{-\left[2+2\cos\left(\frac{2j-1}{2N_1}\cdot\pi\right)\right]k_1 t} + \frac{(1-\beta)}{k_2\Gamma(N_2)}\left(\frac{t}{k_2}\right)^{N_2-1} e^{\frac{-t}{k_2}} \qquad (1)$$

where: $u_N(t)$ is an instantaneous unit hydrograph equation, β – a precipitation distribution coefficient between two cascades, C – a vector of coefficients depending on initial conditions (j index refers to the number of reservoirs in the cascade of submerged reservoirs), Γ – a gamma function, N_1 and N_2 are numbers of reservoirs, k_1 and k_2 – retention coefficients in the cascade of submerged reservoirs and the Nash cascade respectively.

To determine the integration constants contained in the equation of outflow from the last reservoir of the submerged cascade, it is necessary to solve the following equation:

$$C = \gamma^{-1} \cdot Q(0) \qquad (2)$$

where:

$$Q_1(0) = k_1, \quad Q_2(0) = \ldots = Q_N(0) = 0 \qquad (3)$$

For any number of reservoirs in the set, the above equation can be solved numerically by calculating the invert matrix γ^{-1}, which elements have the form (Kurnatowski 2017):

$$\gamma_{i,j}^{-1} = (-1)^{N_1-1}\frac{2}{N_1}\cos\left[(N_1-j)\frac{2i-1}{2N_1}\pi\right] \qquad (4)$$

The matrix γ^{-1} in general form can be written as follows:

$$\gamma^{-1} = \begin{bmatrix} (-1)^{N_1-1}\frac{2}{N_1}\cos\left[(N_1-j)\frac{2i-1}{2N_1}\pi\right] & (-1)^{N_1-2}\frac{2}{N_1}\cos\left[(N_1-2)\frac{1}{2N_1}\pi\right] & \cdots & -\frac{2}{N_1}\cos\frac{1}{2N_1}\pi & \frac{1}{N_1} \\ (-1)^{N_1-1}\frac{2}{N_1}\cos\left[(N_1-1)\frac{3}{2N_1}\pi\right] & (-1)^{N_1-2}\frac{2}{N_1}\cos\left[(N_1-2)\frac{3}{2N_1}\pi\right] & \cdots & -\frac{2}{N_1}\cos\frac{3}{2N_1}\pi & \frac{1}{N_1} \\ \cdots & \cdots & & \cdots & \cdots \\ (-1)^{N_1-1}\frac{2}{N_1}\cos\left[(N_1-1)\frac{2N-3}{2N_1}\pi\right] & (-1)^{N_1-2}\frac{2}{N_1}\cos\left[(N_1-2)\frac{2N_1-3}{2N_1}\pi\right] & \cdots & -\frac{2}{N_1}\cos\frac{2N_1-3}{2N_1}\pi & \frac{1}{N_1} \\ (-1)^{N_1-1}\frac{2}{n}\cos\left[(N_1-1)\frac{2N_1-1}{2N_1}\pi\right] & (-1)^{N_1-2}\frac{2}{N_1}\cos\left[(N_1-2)\frac{2N_1-1}{2N_1}\pi\right] & \cdots & -\frac{2}{N_1}\cos\frac{2N_1-1}{2N_1}\pi & \frac{1}{N_1} \end{bmatrix} \qquad (5)$$

Unlike the Nash cascade the SC2 model does not allow an application of a sub-integer number of reservoirs. Like the Diskin model, the NCSC2 model is a five-parameter one (N_1, N_2, k_1, k_2, β). Although these parameters have no direct physical interpretation, the need to recalibrate the model for a given catchment over time indicates a change in catchment dynamics.

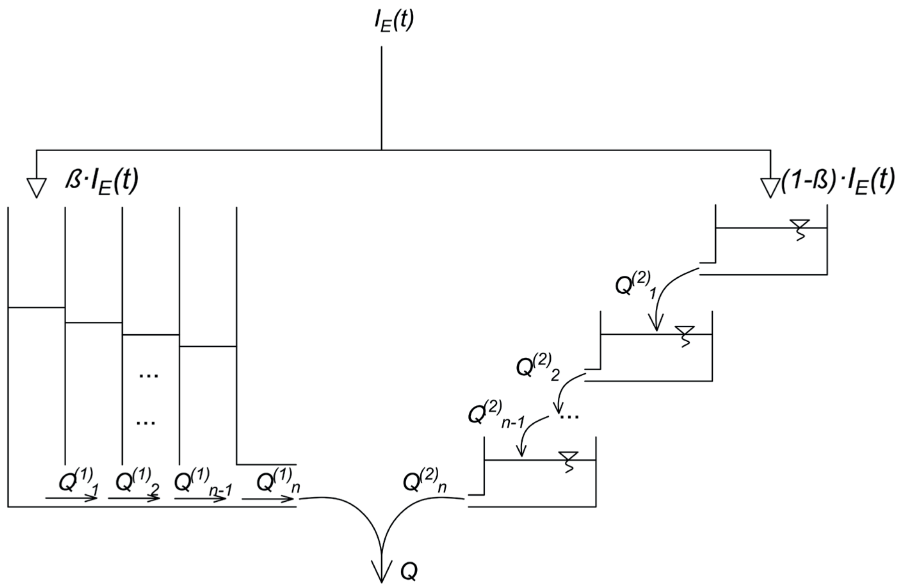

Fig. 1. The conception of the Nash cascade-submerged cascade rainfall-runoff model NCSC2 model, where: $I_E(t)$ – an effective rainfall; β – a precipitation distribution coefficient between two cascades; $Q^{(1)}_i$, $Q^{(2)}_i$ – outflow from the i-th reservoir of the submerged cascade and Nash cascade respectively; Q – total runoff

METHODS

Study area

The quality of the NCSC2 model was assessed by comparing the obtained simulations of 10 exemplary flood events to real ones in comparison with simulations obtained using the single linear reservoir model (SLR), the Nash cascade, the SC2, and the Diskin model. Research work was carried out for five Polish rivers: Pasleka (Pasłęka), Zebrowka (Żebrówka), Brynica, Czerwona Woda, and Piotrowka (Pietrówka, Piotrówka). The location of the studied catchment areas is shown in Figure 2 (on the interleaf). The choice was determined by catchment area less than 200 km^2, which reduces the disturbances in the relation between rainfall and runoff, the location of the precipitation station which is supposed to be in or close to the analyzed catchment area, and the variety of hydrological types of rivers. The location of water gauges and precipitation stations are shown in Figures 2A–2E.

A brief analysis of the most important hydrological data of selected rivers is presented in Table 1. The values of the river slopes and characteristic flows indicates that Czerwona Woda and Piotrowka are a mountain hydrological type of river, whereas the Pasleka, Zebrowka and Brynica present a lowland hydrological type of river. For each of these rivers, two flood events were selected and modeled using 13 different estimation criteria, which in total gives 130 simulations. The criterion for selecting a flood event was the clear response of the catchment in the form of a flood wave to the rainfall was used. The dates of selected flood events are presented in Table 2.

The dailyamount of precipitation in the catchment was determined on the basis of a single precipitation station. Such an approach is commonly used in hydrological research because of the small number of precipitation stations (Schuurmans & Bierkens 2007, Sikorska et al. 2012).

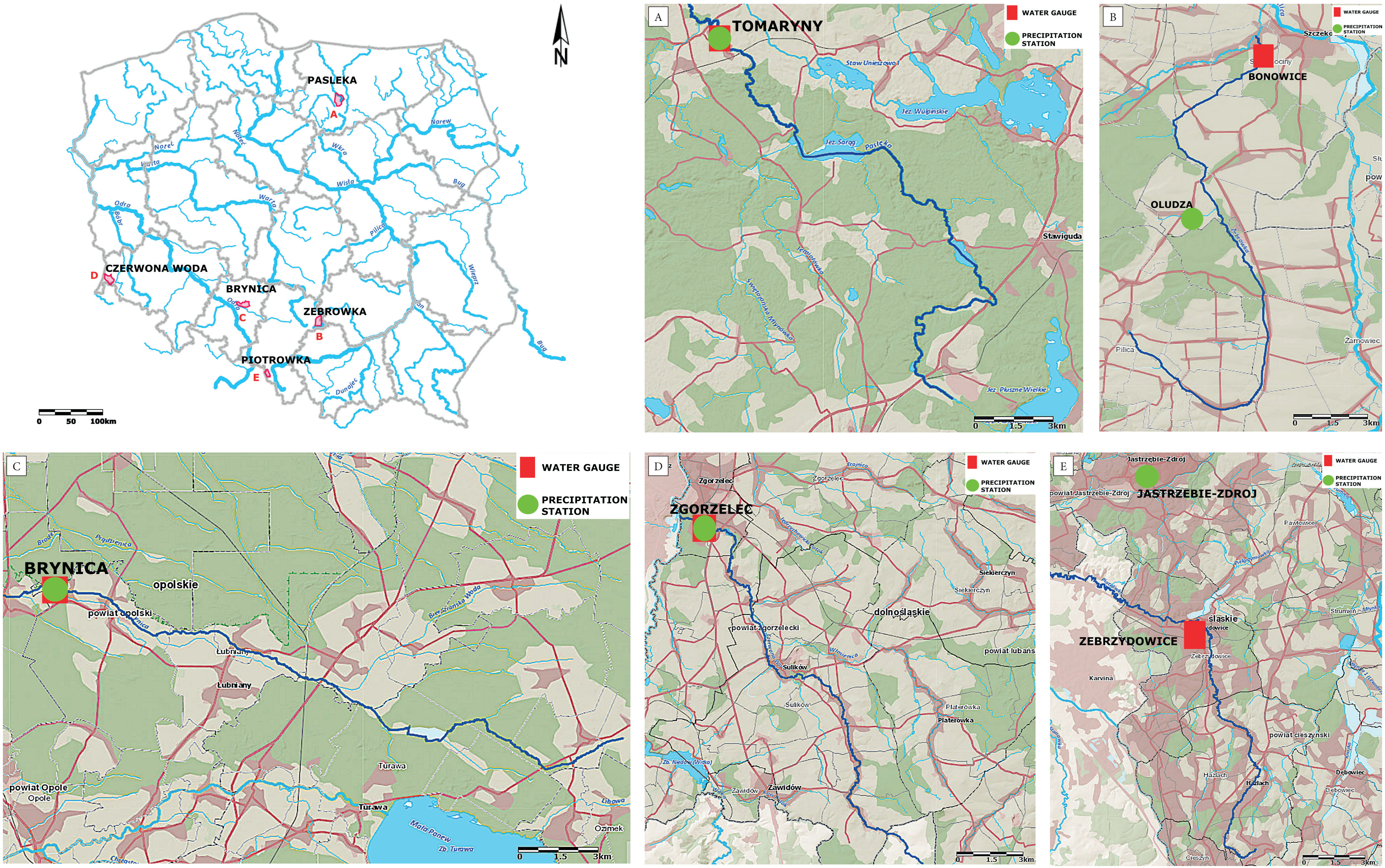

Fig. 2. The location of the studied catchments areas with enlarged fragments of a raster map showing the section of: A) the Pasleka River from its source to the Tomaryny water gauge; B) the Zebrowka River from its source to the Bonowice water gauge; C) the Brynica River from its source to the Brynica water gauge; D) Czerwona Woda River from its source to the Zgorzelec water gauge; E) Piotrowka River from its source to the Zebrzydowice water gauge (based on https://isok.gov.pl/hydroportal.html)

Table 1
Selected hydrological characteristics of the studied rivers

River	Precipitation station	Water gauge	Catchment area [km^2]	MLQ [L/(s·km^2)]	MMQ [L/(s·km^2)]	MHQ [L/(s·km^2)]	LQ [m^3/s]	HQ [m^3/s]	River slope [‰]
Pasleka	Tomaryny	Tomaryny	183	1978–1982					2.13
				2.95	7.10	13.39	0.39	2.95	
Zebrowka	Oludza	Bonowice	129	1976–1980					2.52
				3.26	5.12	10.23	0.09	5.80	
Brynica	Brynica	Brynica	98.2	1976–1980					2.12
				2.55	6.52	18.74	0.04	7.00	
Czerwona Woda	Zgorzelec	Zgorzelec	128	1961–1965					9.17
				3.44	6.41	30.08	0.24	26.60	
Piotrowka	Jastrzebie-Zdroj	Zebrzydo-wice	115	1971–1975					6.92
				5.65	11.22	53.74	0.40	22.70	

Explanation: MLQ – arithmetic mean of the lowest annual flows in the indicated period per 1 km^2 of the catchment area; MMQ – arithmetic mean of the mean annual flows in the indicated period per 1 km^2 of the catchment area; MHQ – arithmetic mean of the highest annual flows in the indicated period per 1 km^2 of the catchment area; LQ – the lowest observed flow in the indicated period; HQ – the highest observed flow in the indicated period.

Table 2
Dates of modeled flood events

Flood number	Pasleka	Zebrowka	Brynica	Czerwona Woda	Piotrowka
1	18.06–3.07.1981	26.05–6.06.1981	26.04–4.05.1981	26.04–5.05.1978	7.03–12.03.1978
2	16.07–27.07.1981	10.09–22.09.1981	7.09–22.09.1981	5.05–13.05.1978	28.04–8.05.1978

Effective rainfall determination

In order to determine the amount of effective rainfall, the instantaneous runoff coefficient method presented by Soczyńska (1990) was adopted.

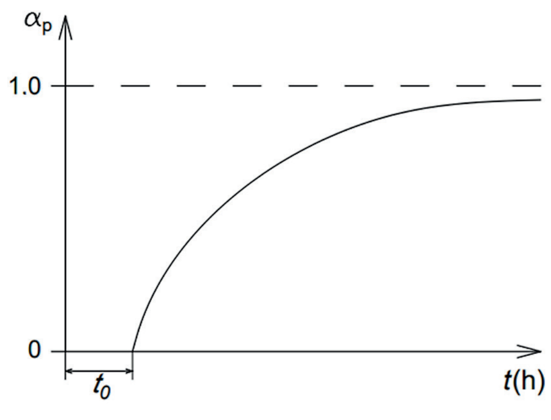

Fig. 3. *The variety of instantaneous runoff coefficient (Soczyńska red. 1990), where α_p is an instantaneous runoff coefficient, t_0 is a runoff delay time, and t is rainfall duration time*

The course of instantaneous runoff coefficient α_p curve is presented in Figure 3. The advantage of the instantaneous runoff coefficient method is that it enables the consideration of the time-varying conditions of surface runoff formation, as the values of the runoff coefficient can be determined for any point in time using the equation:

$$\alpha_p\left(t\right)=\frac{2}{\pi}\cdot\text{arctg}\frac{t-t_0}{n} \tag{6}$$

where: t – time from the beginning of a rainfall, t_0 – parameter indicating the runoff delay time, depends on catchment retention capacity and rainfall intensity in the initial period of its duration, n – shape coefficient of the curve $\alpha_p(t)$.

The shape coefficient of the instantaneous runoff coefficient n was determined for each event as one of the model parameters subjected to estimation procedure.

Parameter estimation procedure

The parameter values estimation procedure used in the research is based on the method of successive approximations. For single-cascade models the search range for the number of reservoirs in a cascade N was assumed to be from one to seven, while for two-cascade models the maximum number of reservoirs in one cascade was reduced to five because of calculation time. The coefficient of effective rainfall distribution β was assumed in the range 0.25–0.75 with a step of Δβ = 0.25. The initial search range for n and k_i parameter values is 1–118 for single cascade models and 1–91 in two-cascade models. Significantly prolonged calculations in the case of two-cascade models forced the narrowing of the sets of parameter values, as the search for solutions was performed in six-dimensional space.

The conceptual models are sensitive to the objective functions used in the optimalisation procedure, therefore 13 different objective functions were used to estimate model parameter values. Objective functions used in the optimalisation procedure are presented in Table 3 (indexes m and p refer to the model and observation, respectively).

Table 3
Objective functions used in the optimalisation procedure

No.	Objective function	Symbol Unit	Equation
1	Difference between hydrograph peak values	$\Delta y_{\max}$ [m³/s]	$\Delta y_{\max} = \left\| y_{\max,m} - y_{\max,p} \right\|$ (7)
2	Compliance of the time of occurrence of the peak flood value	Δt_p [day]	$\Delta t_p = \left\| t_{p,m} - t_{p,p} \right\|$ (8)
3	Flood volume difference	ΔV [m³]	$\Delta V = \left\| V_m - V_p \right\|$ (9)
4	Nash–Sutcliffe coefficient of efficiency	NSE [–]	$NSE = 1 - \frac{\sum_{i=1}^{n}\left(y_{p,i} - y_{m,i}\right)^2}{\sum_{i=1}^{n}\left(y_{p,i} - \overline{y_p}\right)^2}$ (10)
5	Mean squared error	MSE [m³/s]²	$MSE = \frac{1}{n}\sum_{i=1}^{n}\left(y_{p,i} - y_{m,i}\right)^2$ (11)
6	Mean absolute percentage error	$MAPE$ [%]	$MAPE = \frac{100\%}{n}\sum_{i=1}^{n}\left\| \frac{y_{p,i} - y_{m,i}}{y_{p,i}} \right\|$ (12)
7	Ratio estimator	R [–]	$R = \frac{\overline{y_m}}{\overline{y_p}}$ (13)
8	Pearson correlation coefficient	r [–]	$r = \frac{\sum_{i=1}^{n}\left(y_{p,i} - \overline{y_p}\right)\left(y_{m,i} - \overline{y_m}\right)}{\sigma_p \sigma_m}$ where: σ_p, σ_m are standard deviations of p and m respectively (14)
9	The maximum error of the corresponding output quantities	ME [m³/s]	$ME = \max_{i=1,2\ldots,N} \left\| y_{m,i} - y_{p,i} \right\|$ (15)
10	Mean absolute error	MAE [m³/s]	$MAE = \frac{1}{n}\sum_{i=1}^{n}\left\| y_{p,i} - y_{m,i} \right\|$ (16)

***Table 3** cont.*

11	Sum of squared error	SSE [m³/s]	$$SSE = \sum_{i=1}^{n}\left(y_{p,i} - y_{m,i}\right)^2 \quad (17)$$
12	Spearman's rank correlation	r_s [–]	$$r_s = 1 - \frac{6\sum_{i=1}^{n} d_i^2}{n\left(n^2 - 1\right)} \quad (18)$$
15	Nash–Sutcliffe coefficient based on reciprocal of flow	NSE_i [–]	$$NSE_i = 1 - \frac{\sum_{i=1}^{N}\left(\frac{1}{y_{p,i}} - \frac{1}{y_{m,i}}\right)^2}{\sum_{i=1}^{N}\left(\frac{1}{y_{p,i}} - \frac{1}{\overline{y_p}}\right)^2} \quad (19)$$

To verify the models, the analysis of the time functions of the modeled values $y_m(t)$ and the measured values $y_p(t)$ was used.

Assumptions and calculation constraints

Measurement data of the amount of precipitation and flow obtained from the public database of the Polish Institute of Meteorology and Water Management–National Research Institute (IMGW-PIB) available at www.danepubliczne.imgw.pl were used for the research. For each catchment, precipitation data obtained from the only station located in the considered catchment or a single station located as close as possible to the considered catchment were adopted. Limiting the source of precipitation information to one measurement point does not allow a full spatial distribution of the phenomenon in the catchment area to be obtained, which in consequence may demonstrate inappropriate relationships between precipitation and runoff. However, this uncertainty is reduced when the analyzed catchment area is small and the precipitation station is located within its boundaries.

The determination of the catchment runoff delay time coefficient t_0 is necessary for the use of instantaneous runoff coefficient method. Unfortunately, no relevant data was available in this regard, therefore a simplification was adopted in the form of a rapid run-up time in the catchment, i.e.: $t_0 = 0$. Such an assumption is subject to some degree of error, but is justified by the small catchment areas.

Since only daily measurements of precipitation and flows were available, a daily time step of $\Delta t = 24$ h was adopted for the calculations.

Calculations were carried out for the following values of the effective precipitation distribution coefficient β: 0.25, 0.50 and 0.75. To consider the case in which two-cascade models limit their structure to one type of cascade, i.e. the Nash or SC2 cascade (β = 1 or β = 0), the values of the estimation criteria obtained in the course of calculation for the two- and one-cascade models were compared, and then a set of parameters for which a more satisfactory obtained value was assigned to the two-cascade model.

RESULTS

Depending on the estimation criterion used for calibration, different sets of parameters for each analyzed model structure were obtained.

The assessment of the quality of the models was carried out on the basis of a comparison of the modeled and observed hydrographs (Figs. 4, 5) and a comparison of the obtained values of the objective functions.

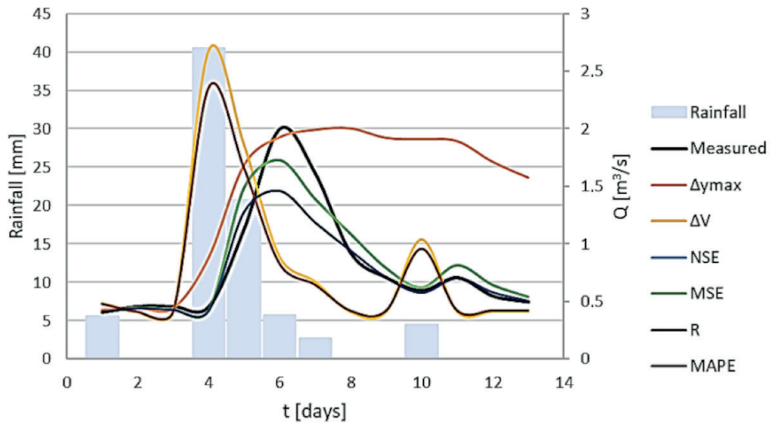

Fig. 4. *Hydrographs obtained with the NCSC2 model using objective functions: Δymax, ΔV, NSE, MSE, R, MAPE; Zebrowka – flood event no. 2*

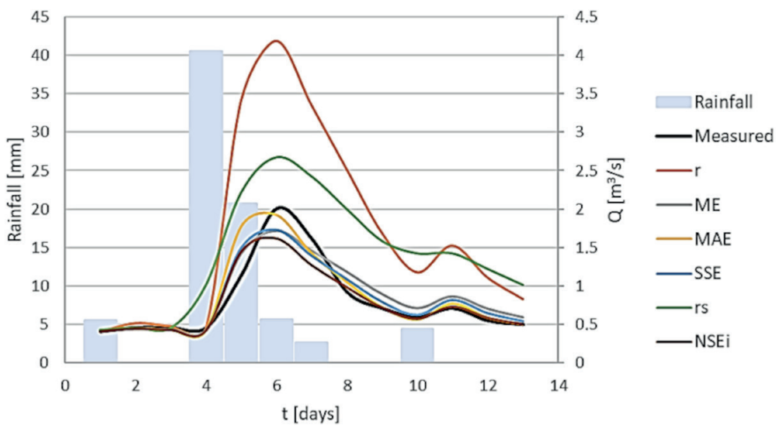

Fig. 5. *Hydrographs obtained with the NCSC2 model using objective functions: r, ME, MAE, SSE, r_s, NSE_i; Zebrowka – flood event no. 2*

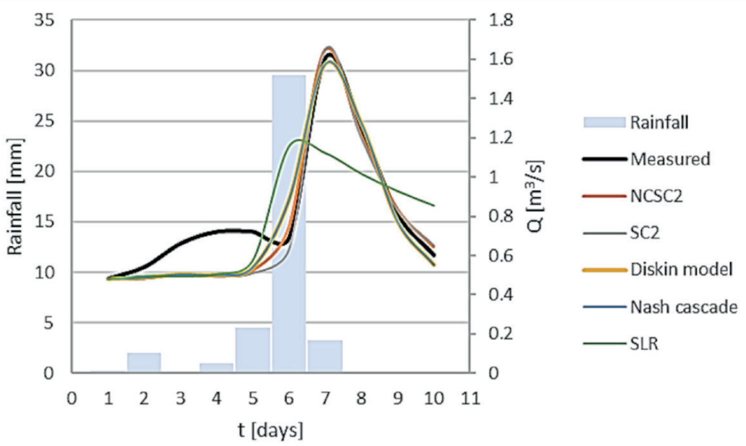

Fig. 6. *Modeled hydrographs obtained using NSE estimation criterion; Czerwona Woda – flood event no. 1*

The main method used to compare the quality of the structures of the conceptual models was a common chart of modeled hydrographs obtained by different model structures using the same parameters estimation criterion (Figs. 6–9). This method also allowed to observe whether the superiority of a given structure over the others depends on the estimation criterion used. In addition to the graphical method described above, a comparative analysis of the quality of the models based on the comparison of the values of the objective functions was conducted.

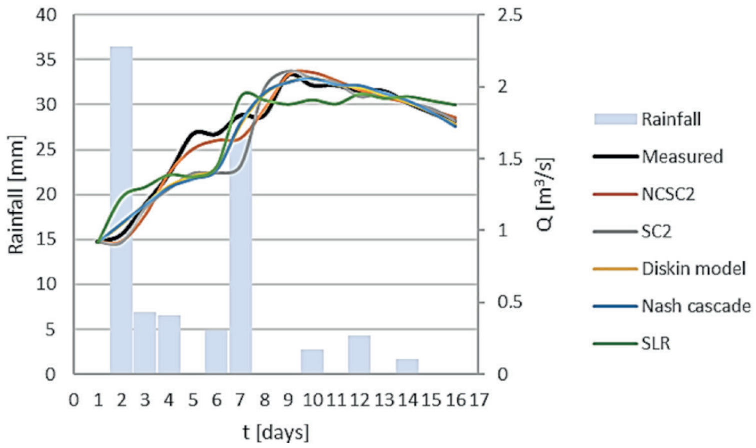

Fig. 7. *Modeled hydrographs obtained using MAPE estimation criterion; Pasleka – flood event no. 1*

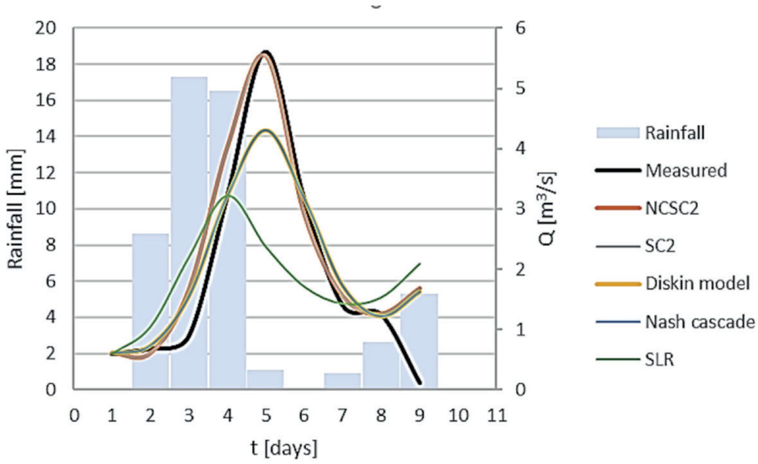

Fig. 8. *Modeled hydrographs obtained using MAE estimation criterion; Czerwona Woda – flood event no. 2*

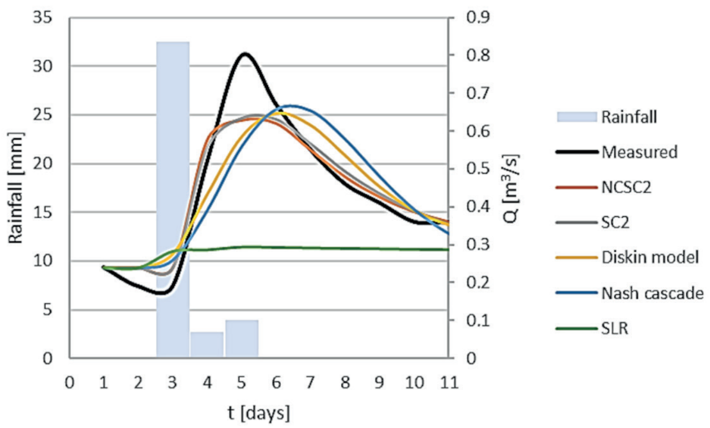

Fig. 9. *Modeled hydrographs obtained using NSEi estimation criterion; Zebrowka – flood event no. 1*

DISCUSSION

The ranges of estimation criteria values obtained for the individual model structures are presented in Table 4. The best values of each criterion are underlined.

As shown in Table 4, in the prevailing number of cases the most satisfactory minimum and maximum values of each of the estimation criteria were obtained using the NCSC2 model. The use of the Diskin model did not significantly improve the minimum and maximum values of the estimation criteria attained by the Nash cascade. Although Nourani analyzed single floods in a very small mountain catchment (Nourani 2008), the ranges of *NSE* and *r* values obtained in the study for a calibration of the Nash cascade were smaller than the analogous values specified by Nourani. The maximum *NSE* and *r* values achieved are higher than those obtained by Nourani (Nourani: $NSE = 0.88$, $r = 0.95$; obtained in research: $NSE = 0.981$, $r = 0.991$), and the minimum values are higher (Nourani: $NSE = 0.38$, $r = 0.678$; obtained in studies: $NSE = 0.528$, $r = 0.733$). According to Crooks and Naden (2007), *NSE* values higher than 0.6 may be assumed to indicate satisfactory compliance between the observed and the modeled flows, especially for a large catchment, but it may also be applicable for small catchments. Analysis of the course of the hydrographs showed that hydrographs obtained using the correlation coefficient, unlike *NSE*, need to be rescaled. In the research it was noticed that the Nash cascade model simulates the most overestimated flood peak values when Δt_p estimation criterion is used.

The analysis of the final results indicates that the best estimation criteria values were most often obtained by the use of NCSC2, i.e. in 121 among 130 processed cases. The second best model in terms of quality turned out to be the Diskin model, which achieved the most satisfactory result in 68 cases. Only in 8 cases were the best values obtained using SLR. The structure of the submerged reservoirs cascade allowed for the best results in 27 cases, and the Nash cascade in 59. Littlewood (2002) stated that for a large number of analyzed UK catchments using daily data, a better presentation of river flow dynamics was obtained by the model assuming two parallel reservoirs than by configuration of single reservoir or two in a row. The same conclusions can be drawn from the research conducted.

Table 4
Minimum and maximum values of the estimation criteria obtained for each model structure

Estimation criteria	SLR		Nash cascade		SC2		Diskin model		NCSC2	
	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
Δy_{max}	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Δt_p	0.000	2.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
ΔV	1.390	57.367	0.045	19.850	0.059	144.588	0.045	14.270	0.024	11.327
NSE	0.322	0.838	0.528	0.981	0.413	0.970	0.528	0.981	0.528	0.981
MSE	0.005	1.856	0.002	0.455	0.003	0.361	0.002	0.455	0.002	0.353
MAPE	4.646	90.082	2.679	89.680	3.369	89.680	2.679	89.680	2.631	89.680
R	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
r	0.580	0.917	0.733	0.991	0.666	0.993	0.733	0.991	0.733	0.994
ME	0.107	2.396	0.077	1.419	0.076	1.283	0.077	1.417	0.075	1.109
MAE	0.061	0.958	0.027	0.428	0.038	0.408	0.027	0.428	0.027	0.408
SSE	0.063	16.700	0.015	4.097	0.023	4.238	0.015	4.097	0.015	3.893
r_s	0.733	0.979	0.817	0.992	0.852	0.996	0.842	0.993	0.876	0.996
NSE_i	0.177	0.881	0.197	0.967	0.200	0.993	0.197	0.967	0.201	0.967

So far, the use of the NCSC2 structure has only been considered as a data-driven lumped model. The research has shown that the development of the Nash cascade model with a parallel cascade of submerged reservoirs improves the simulation quality better than the model of two Nash cascades in parallel. NCSC2 is more sensitive to estimation criteria than the other considered models, which translates into the quality of matching the simulated hydrographs to the real ones. It can be explained by different cascade equations included in the model response equation. On the other hand, NCSC2, like the Diskin model, is a five-parameter data-driven model, which makes its uncertainty greater than that of the Nash cascade. Moreover, the higher degree of complexity of the model significantly affects the model calibration time.

CONCLUSIONS

At the current stage of work on conceptual mathematical models of the rainfall-runoff relationship, there are no universal criteria for estimating the parameters of these models. Different criteria, applied to the same flood event, lead to different sets of these parameters. The lack of the universality of parameter estimation criteria imposes the individualization of the criteria applications depending on the modeling purpose and forces a particularly thorough analysis of the validity of adopting a specific criterion for the assumed purpose. It is inadvisable to mechanically apply a specific, even universally recognized, criterion (e.g. *NSE*) without taking into account the practical purpose of modeling.

Based on the conducted research and literature analysis, it is concluded that increasing the degree of the complexity of the structure does not guarantee a significant increase in simulation quality, although complex models perform unsatisfactorily in a smaller number of cases, as noted in the work of van Esse et al. (2013). Van Dijk (2010) showed using the Nash–Sutcliffe efficiency coefficient (*NSE*) that models with six parameters have the greatest predictive power, but very similar quality can be achieved using three parameters. The two- and three-parameters models generate similar *NSE* values. Considering *NSE* values in the presented research, the two-parameter Nash cascade model performed as well as the five-parameter Diskin model. Although the maximum and minimum *NSE* values obtained with the NCSC2 model were the same as those obtained with the Nash cascade, the NCSC2 model generated the highest *NSE* for each flood event. The original concept of the NCSC2 model turns out to be statistically the best model structure, as the most satisfying values of applied estimation criteria were obtained for it in most of the cases. Replacing one of the Nash cascades in the Diskin model with a cascade of submerged reservoirs, as an element imitating subsurface runoff, the quality of the simulations increased, which proves that the structure of this model better represents the operation of the catchment system.

Although the NCSC2 model performed the best in the study, its performance needs to be checked against continuous simulations or using a smaller time step. Such an analysis will enable the verification of the model's sensitivity to the variability of precipitation data and, in the case of a smaller time step, the possibility of obtaining a precise simulation of the dynamics of the process of transforming rainfall into runoff depending on actual rainfall intensity.

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