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The use of NRCS synthetic unit hydrograph and Wackermann conceptual model in the simulation of a flood wave in an uncontrolled catchment

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Abstract

The paper presents the results of using two models: a conceptual model of Wackermann and a NRCS-UH synthetic unit hydrograph, for flow calculation in uncontrolled catchment of the Słonka, Poland. These models were chosen because of simplicity of models' parameters evaluation, what is important from engineering calculation point of view. Flows with the probability of exceed amounting to 0.5%, 1%, 2%, 5%, 10%, 20%, and 50% and for different levels of the catchment moisture were evaluated.

The flood waves generated in the Wackermann model were characterized by a short duration (over 2 hours), shorter concentration time (about 1 hour), and by about 70% higher peak flow values than those generated using the NRCS-UH method. A common feature of both methods were higher values of peak flows for the third level of the catchment moisture, as compared to the second level. It is also worth noticing that in both methods no flood wave was generated for the probabilities of 10, 20 and 50% and for the second level of the catchment moisture. It was assumed that hydrographs made with use Wackermann model better describe flood wave in mountain river, which Słonka is.

Key words: *effective precipitation, NRCS-UH method, uncontrolled catchment, Wackermann model*

INTRODUCTION AND AIM OF THE STUDY

Most catchments in Poland are covered by hydrological and meteorological measurements. Based on these observations, the data on basic hydrological characteristics, especially for large and medium-sized catchments, are collected. They are important for everyday functioning of the domains directly related to catchment-related phenomena. Sustainable watersheds management requires thorough knowledge of water resources, including streamflow [BELAYNEH, ADAMOWSKI 2013; NOOR *et al.* 2014; WOJAS, TYSZEWSKI 2013]. Economic development increased the need of considering small catchments in such fields as industry and agriculture. However, this is hindered by the lack of information, as these catchments are often not included in the hydrological monitoring network. In case, when streamflow, which will be modelling is uncontrolled, information about maximum flows are got from indirect methods with use hydrologic analogy (interpolation, extrapolation or differential catchments), empirical formulas or model such as rainfall-runoff. Models are recommended in by EXCIMAP [2007]. Mathematical models in hydrology are often used as a tool for flood analysis [GRIMALDI *et al.* 2012; MISHRA *et al.* 2013; VÁŇOVÁ *et al.* 2011]. Such an analysis is carried out to determine the magnitude of extreme flows with a low probability of occurrence, the so called design discharges. In case of uncontrolled catchments, designer must show an especially caution during calculations, because there is no possibility of verifying results with reference to real observations [IGNAR 1986; KAMALI 2009; WAŁĘGA *et al.* 2011; 2012]. Distributed hydrologic models have important applications in interpretation and prediction of the effects of land use change climate variability on water availability and quality, since they relate model parameters directly to physically observable land surface characteristics [ARNOLD *et al.* 1998; BUTTS *et al.* 2004; NEITSCH *et al.* 2011; NOOR *et al.* 2014].

In hydrologic practice, the most difficult issue is a study of transformation method of rainfall into surface runoff. This difficulty is caused by influence of many factors on process of rainfall transformation. Commonly, for rainfall transformation into surface runoff so called unit hydrographs are used. For the first time, they were described by Sherman [PONCE 1989; WAŁĘGA 2011].

So far, numerous methods of hydrograph simulation such as: Wackerman model, Nash model, geomorphoclimatic model, NRCS-UH, Snyder, Clark or Gray models, in the absence of detailed hydrometric data, have been developed.

One of the most often use model in hydrologic practice, because of its simplicity of use, is a Wackermann conceptual model. This model was described by IGNAR [1986] or BANASIK and IGNAR [1987]. The method assumes the equality of probabilities for design precipitation and discharge. The described algorithm consists of four stages leading to evaluation: total rainfall, effective rainfall, direct flow hydrograph and total flood flow hydrograph. A practical application of the method was carried out for a small agricultural watershed (area – 6.5 km^2) in east Holland [IGNAR 1986].

Recently, in hydrologic practice, more commonly are introduced so called synthetic unit hydrograph, in which parameters of model are established based on catchment characteristics. One of the most commonly use method of unit hydrographs approximation is its smooth by curve manually fitting to characteristic points on hydrograph [SINGH 1988]. An example of such hydrograph is Snyder model. In turn, National Resources Conservation Services put a simplification of unit hydrograph shape, transform into triangle form and on this basis findings its parameters [SCS 1972; WAŁĘGA 2011].

The aim of this study was to simulate a flood wave in an uncontrolled catchment, based on physical, soil-related and meteorological parameters of the catchment.

The study area included the catchment of the Słonka River, a right tributary of the Raba, in the southern Poland, Małopolska (Lesser Poland) province.

The peak flows with the probability of occurrence: 0.5, 1, 2, 5, 10, 20, and 50% were determined based on Wackermann and SCS hydrological models. These models were chosen because of simplicity of models' parameters evaluation, what is important from engineering calculation point of view and are very often use in hydrologic practice. The calculations were made for an average moisture level – II, and a high moisture level – III. The values of peak flows were also considered, and they enabled the comparison of different hydrological models and different exceedance probability.

METHODOLOGY OF THE STUDY

The first step of calculating the hypothetical peak flows in the Słonka catchment included a determination of baseline parameters for both models. As in this catchment no meteorological data on the frequency of precipitation of specific intensity and duration were available, these parameters were determined using empirical formulas. Then, a general relationship between precipitation intensity as a function of its duration and the probability of precipitation occurrence according to LAMBOR [1971], were established. This method was chosen because it is one of the most commonly-known and use in Poland. The precipitation of a specific probability of occurrence was calculated for the following probabilities: 0.5, 1, 2, 5, 10, 20, and 50%. For the need of the paper, authors used described by KUPCZYK and SULIGOWSKI [1997] method of hypothetic hyetograph. On the basis of pluwiographical data from years 1961-1990 for area of Poland, They distinguished three, genetic types of precipitations, in which the height of the precipitation is described by numerous analytical equations [KRZANOWSKI, WAŁĘGA 2007]. Because of similar topographic condition, all calculation were made for the Vistula station, which is representative for mountainous area. The equations, which describes the height of precipitation as a total sum, in function of time of duration are in KUPCZYK and SULIGOWSKI [1997].

NRCS-CN method (previously known as SCS--CN) is used to determine the effective precipitation. Effective rainfall is a part of total rainfall remaining after withdrawing of losses consisting of infiltration, evapotranspiration, interception and depression storage. This rainfall is transformed by the surface watershed into direct runoff. According to this method, the volume of effective rainfall is subjected to the *CN* (Curve Number) parameter depending on soil type, land use, soil conservation practices and antecedent moisture conditions [Deshmukh *et al.* 2013; Ignar 1986; Merz, Blöschl 2009].

NRCS-UH method was developed in the United States in the 1970s. According to this method, the effective precipitation depends on the soils covering the catchment area, land use, forested areas, and the initial catchment moisture. These factors were taken into account when establishing *CN* parameter, the values of which vary in the range from 0 to 100. The SCS method is based on the initial assumptions involving the cumulative infiltration, potential retention of a catchment, effective precipitation, and losses. *CN* parameter for different types of land and corresponding surfaces, for the second and third level of the catchment moisture, was defined as a weighted average, according to the methodology described by Ozga-Zielińska and Brzeziński [1997]. Then, the cumulative effective precipitation at any point in time was calculated [Ozga-Zielińska, Brzeziński 1997].

Part of the precipitation in these processes is referred to as the initial abstraction and is denoted as I_a. As the precipitation continues, the cumulative infiltration F increases, until the maximum retention S is achieved. This method assumes that the ratio of the actual cumulative infiltration F to the maximum retention S is equal to the ratio of effective precipitation P_{Ef} to the precipitation minus the initial abstraction [Ozga-Zielińska, Brzeziński 1997; Soczyńska *et al.* 2003].

The NRCS-UH method belongs to a group of unit wave methods. The peak flow is calculated based on the following formula [Wałęga *et al.* 2011]:

$$q_p = \frac{c\,A\,P_E}{T_P} \qquad (1)$$

$$T_P = \frac{D}{2} + T_{lag} \qquad (2)$$

where:

T_p – time to peak flow rate, h;
P_E – unit effective precipitation of a height of 1 mm;
A – catchment area, km^2;
T_{lag} – lag time (h) [Wałęga *et al.* 2009]:

$$T_{lag} = \frac{(L \cdot 3.28 \cdot 10^3)^{0.8} \cdot (\frac{100}{CN} - 9)^{0.7}}{1900\sqrt{I}} \qquad (3)$$

D – duration of the effective precipitation, h;
c – parameter ($c = 0.208$);
L – length of the watercourse, km;
CN – parameter (–);
I – catchment slope, %.

The maximum runoff during a flood was calculated using the following equation [Wałęga *et al.* 2009]:

$$Q_{\max} = \frac{0.208 A\,P_e}{T_P}\ (\mathrm{m^3 \cdot s^{-1}}) \qquad (4)$$

where:

A – catchment area, km^2;
P_e – cumulative effective precipitation, mm;
T_p – concentration time, h;

and flood wave coordinates [Wałęga *et al.* 2009]:

$$Q_i = yQ_{\max}\ (\mathrm{m^3 \cdot s^{-1}}) \qquad (5)$$

$$T_i = xT_P\ (\mathrm{h}) \qquad (6)$$

where:

x, y – coordinates of an average hydrograph.

The volume of the flood was calculated for following flood wave coordinates:
x: 0; 0.1; 0.2; 0.3; 0.4; 0.5; 0.6; 0.7 … 5.0,
y: 0; 0.03; 0.1; 0.19; 0.31; 0.47; 0.66; 0.82; 0.93; 0.99; 1.0; 0.99; 0.93; 0.86; 0.78; 0.68; 0.56; 0.46; 0.39; 0.33; 0.28; 0.207; 0.147; 0.107; 0.077; 0.055; 0.04; 0.029; 0.021; 0.015; 0.011; 0.005; 0.0.

Wackermann model is a conceptual one and it consists of two cascades and three parameters (k_1, k_2, β) [Nowicka, Wolska 2003]:

$$k_1 = 1.28(\frac{L}{I^{0.5}})^{0.159} \qquad (7)$$

$$k_2 = 0.893(\frac{L}{I^{0.5}})^{0.379} \qquad (8)$$

$$\beta = 1.04(\frac{L}{I^{0.5}})^{-0.403} \qquad (9)$$

where:

k_1, k_2 – water body retention coefficients for the first and second cascade, h;
β – coefficient of effective precipitation distribution between the two cascades (–);
L – length of the watercourse, km;
I – slope of the watercourse (–).

Ordinates of a hydrograph for a catchment runoff in the Wackermann model can be calculated by applying the principle of superposition [Banasik, Ignar 1984]:

$$Q_i = \sum_{j=1}^{\min(i,n)} h_k \cdot \Delta H_j \qquad (10)$$

$$k = i - j + 1, i == 0,1; 0,2, \dots, m + n - 1$$

where:

Q_i – direct runoff hydrograph ordinates, m^3·s^{-1};
ΔH_j – partial effective precipitation in the time interval, mm·h^{-1};
h_i – ordinates of the unit hydrograph, m^3·s^{-1}·mm^{-1};
m – number of unit hydrograph ordinates;
n – number of time intervals of the effective precipitation.

STUDY AREA

The Słonka is a river passing through the town of Rabka Zdrój, located in the Małopolska province. It is a right tributary of the Raba River. It originates on the slopes of Bardo (948 m) and Wierchowa (942 m), at a height of 760–890 m above sea level. In the first kilometer, the river flows in steep ravines cutting the wooded slopes, and then in a deep valley between the ridges of Bardo and Maciejowa (815 m a.s.l.) and the ridge of Szumiąca (841 m a.s.l.). Then, it reaches Kotlina Rabczańska and passes through densely built-up residential areas of Rabka-Zdrój, including Filasówka, Plasówka, Sołtysówka, Słone and Słoneczna housing estate. Finally, it enters the Raba near Sądecka housing estate at the height of 470 m above sea level [Wikipedia undated].

The Słonka length is 7.19 km, and its catchment area is 8.75 km^2. The Słonka catchment can be divided into 3 parts including the Słonka to the Luberdawy Potok (section length 3.71 km, mean width 4 m), the Słonka from the Luberdawy Potok to the Gorzki Potok (section length 2,12 km, mean width 4 m), and the Słonka from the Gorzki Potok to the mouth (section length 1.36 km, mean width 4 m). The river is engineered, except for the woodland section. The land use within the catchment (Fig. 1) is as follows: arable lands take up 43% of its area, 40% is covered by forests, and the remaining 16% are built-up areas. Meadows account for only 1% of the catchment area. The catchment is dominated by highly permeable soils, mostly sandy soils [PIETRUSIEWICZ 2014]. Chosen for researches Słonka catchment is uncontrolled one and also was chosen because of its area, it is small catchment (less than 10 km^2), its location (is located in mountainous area) and the land is mostly used by agricultural and is covered by forest, what is important in point of view of chosen methods.

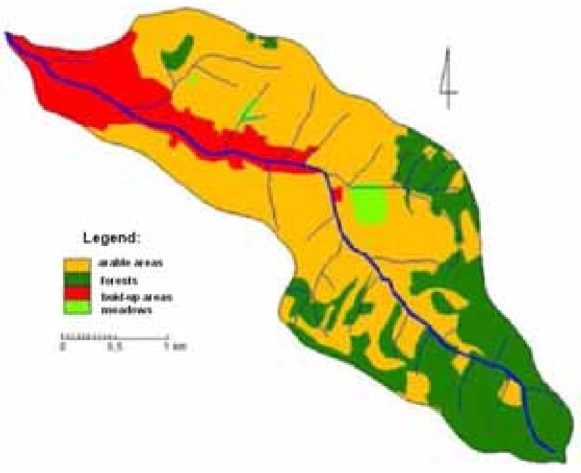

Fig. 1. The use of the Słonka catchment
source: own study

Annual rainfall in the catchment area does not exceed 900 mm. These are generally short-term rains, but of high intensity. Mean number of days with precipitation per year is 175, and most of them happen in the summer months. The average annual air temperature is 6.6°C. The hottest month is July, with an average temperature of 16.7°C, while the coldest month is February, when the average temperature is –3.5°C. Mean depth of snow is about 60 cm and the snow cover is there from December to mid-March [PIETRUSIEWICZ 2014].

STUDY RESULTS

The calculations made based on the Wackermann model were then used to compare the values of peak flow for the analyzed probabilities (Tab. 1). It was observed that an increase in the probability was accompanied by a decrease in peak flow values for both second and third level of the catchment moisture. The highest $Q_{\max}$ for the probability of 0.5% was 1.98 m^3·s^{-1} (moisture level II) and 18.41 m^3·s^{-1} (moisture level III). No runoff was generated for the second level of the catchment moisture and the probabilities above 10%, which indicated a total absorption of the effective rainfall (total precipitation is retained within the catchment). For an adverse moisture level (III) and the probability of 50%, $Q_{\max}$ was 3.00 m^3·s^{-1}.

Table 1. Summary of the calculations for the peak flows in the Wackerman and NRCS-UH models

Probability p, %	A km^2	CN		$Q_{\max}$ Wackerman model		$Q_{\max}$ NRCS-UH			
				m^3·s^{-1}					
		II	III	II	III	t_{pII}	t_{pIII}	II	III
0,5	8,75	69	50	1,98	18,41	2,86	4,58	0,72	5,17
1				1,68	15,80	2,81	4,58	0,45	4,42
2				1,45	12,90	2,76	4,58	0,23	3,71
5				0,23	9,80	2,71	4,58	0,05	2,81
10				–	7,00	2,51	4,58	–	1,98
20				–	5,18	2,51	4,58	–	1,42
50				–	3,00	2,51	4,58	–	0,77

Explanations: A – area, CN – parameter, $Q_{\max}$ – maximum flow.
Source: own study.

In the NRCS-UH model, the peak flows for specific probabilities and for the second level of the catchment moisture were lower than those obtained for the third level of the catchment moisture (Tab. 1). For example, for the probability of 0.5% and the second level of moisture, the peak flow $Q_{\max}$ = 0.72 m^3·s^{-1}, and for the third level $Q_{\max}$ = 5.17 m^3·s^{-1}. The values of peak flow decreased for both studied moisture levels, along with rising probability of the precipitation. In the NRCS-UH model, similarly as in the Wackermann model, no runoff was generated for the second level of the catchment moisture and the probabilities above 10%, which indicated a total absorption of the effective rainfall (total precipitation is retained within the catchment). Runoff for the probability of 50% and the third level of moisture was 0.77 m^3·s^{-1}.

The calculations of the peak flow for a specific probability of occurrence obtained with the use of the Wackermann model and NRCS-UH model enabled a comparison of their values (Fig. 2). The most notable discrepancy was the shape of the flood wave. The Wackermann model yielded a flood hydrograph typical for mountain rivers in which the wave first raises

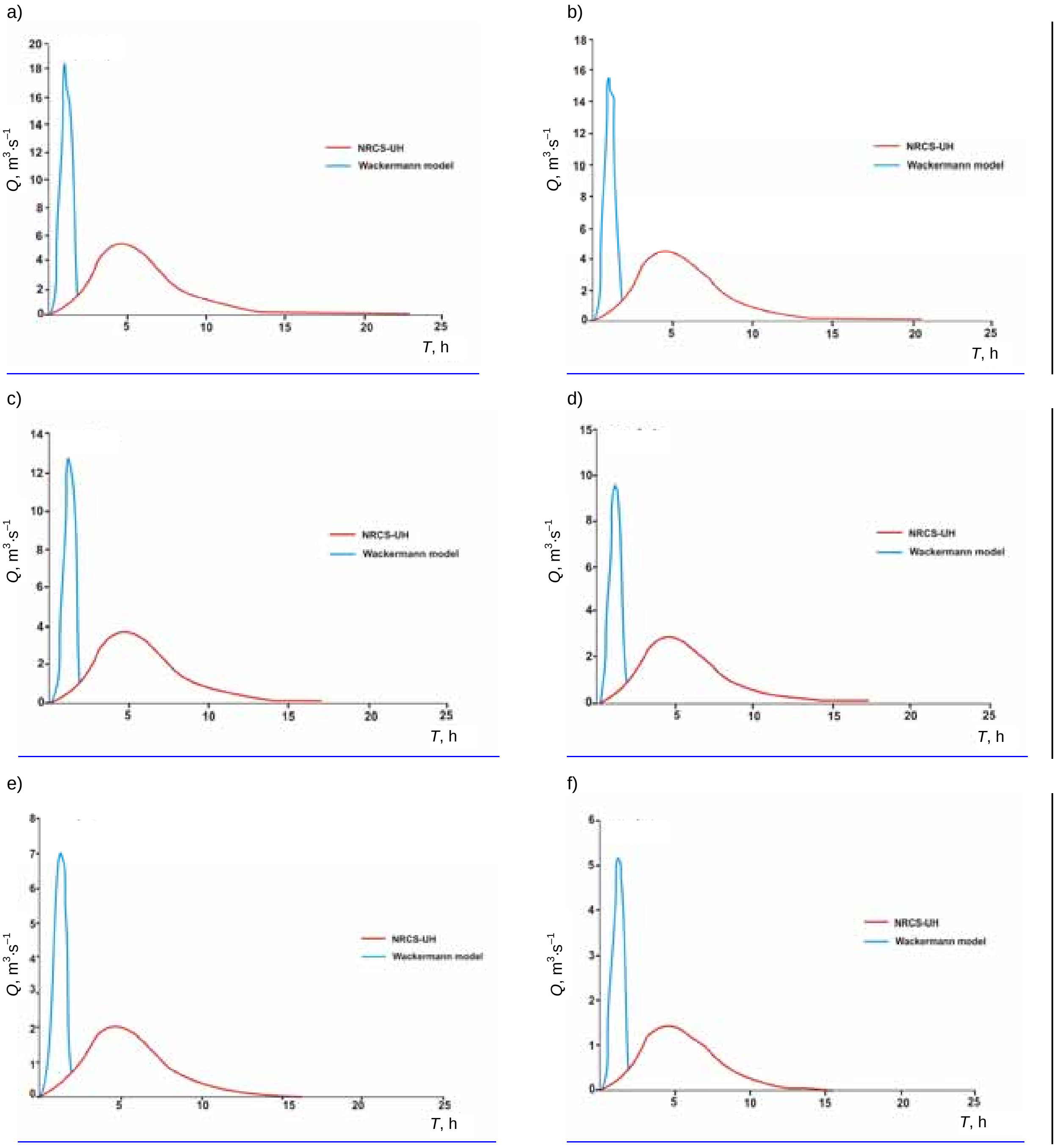

Fig. 2. Peak flow hydrographs for the Słonka River for the third level of the catchment moisture in the Wackermann and NRCS-UH model and the probability of a) 0.5%, b) 1%, c) 2%, d) 5%, e) 10%, f) 20%; source: own study

rapidly and then recedes in a similarly abrupt manner. In the NRCS-UH model, the wave raised less rapidly and receded very slowly, which did not reflect the character of this mountain river. Peak flow hydrographs in the Wackermann model and for every probability, were characterized by a shorter duration of the wave (about 2 hour), and consequently, a shorter concentration time and recession time. Additionally, the Wackermann model yielded a shorter time to the peak flow than the NRCS-UH method. In the Wackermann model, the peak flow was recorded after about one hour and it was from 3 $m^3 \cdot s^{-1}$ for the probability of 50% to over 18 $m^3 \cdot s^{-1}$ for the probability of 0.5%. This shape of the flood wave is typical for mountain rivers. However, in the NRCS-UH model the shape of the wave was more flattened and the duration of the wave was over 20 hours.

Another parameter distinguishing these two models was the volume of the simulated flood waves. In the Wackermann model, the peak flow values were much higher than those obtained in the NRCS-UH model. For example, the peak flow for the probability of 0.5% and the third moisture level was 18.41 $m^3 \cdot s^{-1}$ in the Wackermann model and 5.17 $m^3 \cdot s^{-1}$ in the NRCS-UH model.

A common feature of both methods was lack of flows for the probabilities above 10% and for the second level of the catchment moisture. In this case, the catchment retention was higher than the effective precipitation.

SUMMARY

The flood waves generated in the Wackermann model were characterized by a short duration (over 2 hours), shorter concentration time (about 1 hour), and by about 70% higher peak flow values than those generated using the SCS method. The hydrographs obtained in the Wackermann model exhibited the typical features of a flood wave in a mountain river. Flow hydrographs obtained in the SCS model were characterized by long wave duration – over 22 hours, low peak flows, from 5.15 to 0.05 $m^3 \cdot s^{-1}$, and a flattened shape of the wave, which is non-standard in the mountain rivers such as the Słonka. A common feature of both methods were higher values of peak flows for the third level of the catchment moisture, as compared to the second level. It is also worth noticing that in both methods no flood wave was generated for the probabilities of 10, 20 and 50% and for the second level of the catchment moisture.

The research shows that the Wackermann model better reflected the mountainous character of Słonka river in comparison to NRCS-UH model. The future research should attract the attention on verification models for hydrologic analysis, but for different type of catchments for example urbanized. And for better conclusions and verification obtained results, the researches should be conducted in controlled catchments.

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Zastosowanie syntetycznego hydrogramu jednostkowego NRCS oraz konceptualnego modelu Wackermana do symulacji fali wezbraniowej w zlewni niekontrolowanej

STRESZCZENIE

Słowa kluczowe: *metoda NRCS-UH, model Wackermana, opad efektywny, zlewnia niekontrolowana*

W pracy przedstawiono wyniki analiz z wykorzystaniem dwóch modeli – konceptualnego modelu Wackermana oraz syntetycznego hydrogramu jednostkowego NRCS-UH – do określenia przepływów w zlewni rzeki Słonka, znajdującej się na obszarze Polski. Wybrane modele charakteryzują się łatwością określenia danych wejściowych do modelu, co jest istotne w aspekcie obliczeń inżynierskich. Obliczenia wykonano dla przepływów o prawdopodobieństwie wystąpienia przekroczenia wynoszącym: 0,5%, 1%, 2%, 5%, 10%, 20% i 50 dla różnych poziomów uwilgotnienia zlewni.

Fale wezbraniowe, wygenerowane za pomocą modelu Wackermana, charakteryzowały się krótkim czasem trwania – ponad 2 godziny, krótszym czasem koncentracji – ok. 1 godziny i o ok. 70% większymi wartościami przepływów maksymalnych niż w przypadku fal wygenerowanych z wykorzystaniem metody SCS. Cechą wspólną obu metod były większe wartości przepływów maksymalnych dla III poziomu uwilgotnienia w stosunku do poziomu II. Można również zauważyć, że w przypadku obu metod oraz II poziomu uwilgotnienia zlewni nie wygenerowano fali wezbraniowej o prawdopodobieństwach przewyższenia 10, 20 i 50%.