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COMPARISON OF METHODS TO SELECT THE MAXIMUM VALUES TO DEVELOP A MATHEMATICAL MODEL OF EXTREMELY HIGH RAINFALL IN THE RIVER BASIN

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The scope of this study was to indicate difference in developed probabilistic models for maximum rainfall in Kaczawa river basin, based on a 50-year series of pluviographic records chosen with AMP and POT criterion. To describe the measurement data there were used Gamma, Generalized Exponential (GED), Gumbel, Log-normal and Weibull distributions. Estimators of parameters for particular distributions were developed using maximum likelihood method. Conformity of the analyzed theoretical distributions with measured data was inspected using the Anderson-Darling test (A^2), while choosing the best distribution was made using bayesian information criterion of Schwartz and also by the relative residual mean square error (RRMSE).

KĽÚČOVÉ SLOVÁ: maximum rainfall, probabilistic distributions, river basin

POROVNANIE METÓD VÝBERU MAXIMÁLNEJ HODNOTY PRE VÝVOJ MATEMATICKÉHO MODELU EXTRÉMNE VYSOKEJ ZRÁŽKY V POVODÍ RIEKY. Cieľom tejto štúdie bolo uviesť rozdiely vo vyvinutých pravdepodobnostných modeloch pre maximálne zrážky v povodí Kaczawa, na základe 50-ročného radu zrážok vybraných podľa AMP a POT kritérií. K popisu meraných údajov boli použité Gamma, generalizované exponenciálne (GED), Gumbelovo, Log-normálne a Weibullovo rozdelenie. Odhady parametrov pre jednotlivé rozdelenie boli urobené pomocou metódy maximálnej podobnosti. Zhoda analyzovaných teoretických rozdelení s nameranými dátami bola kontrolovaná testom Anderson-Darling (A^2), zatiaľ čo výber najlepšieho rozdelenia bol urobený pomocou Schwartzovho bayesiánského informačného kritéria a tiež pomocou relatívnej reziduálnej strednej kvadratickej chyby (RRMSE).

KEY WORDS: maximálne zrážky, rozdelenia pravdepodobnosti, povodie rieky

Introduction

In Poland, the maximum rainfall models for a given duration and probability of exceedence so far have been developed only for a few urban catchments among others in Wroclaw, Lublin, Krakow, Lodz or Czestochowa [Kaźmierczak, Kotowski 2012, Mrowiec 2014, Suligowski 2014, Twardosz 2005, Zawilski, Brzezińska 2014]. This problem has been properly solved in Germany, where the unit of the reference rainfall intensity can be found in KOSTRA atlas individually for each urban basin. Much earlier similar work was carried out in the USA [Hershfield 1961]. In Poland, for hydrological modeling purposes there were developed nationwide models characterized by lower accuracy due to the large spatial variability of precipitation and based on the data from 1960 to 1990 [Bogdanowicz, Stachy 1998]. From 1990 on Oder and Vistula there were at least two catastrophic floods in 1997 and 2010. The main reason for the lack of availability of local models in Poland is limited access to archival pluviographic records. Although the measurements are carried out by the Institute of Meteorology and Water Management - National Research Institute (IMWM-NRI) across the whole country for decades, but only for recent few years a uniform digital recording of rain was made. Therefore multiyear measurement series are available only in the form of paper strips whose preparation consumes much time due to the need to use precipitation with specific

durations [Suligowski 2014]. In order to develop a reliable maximum rainfall model for hydrological modeling or even designing and modeling cities drainage systems (for *C* from 1 to 50 years) should be used at least 50 years of rainwater series (relatively 30 years with subsequent extrapolation). However, it should be noted that the short data series, for example. 30-years, do not always include a wide range of natural variability of rainfall. Depending on the available measurement data there can be used various methods to select the maximum values. The main objective of this study was to compare the results of probabilistic models of maximum rainfall developed on AMP and POT data selection method.

Material and methods

Precipitation data

In the paper there were used precipitation data from meteorological station in Kaczawa river basin. The Kaczawa catchment is one of the major left tributaries of the Odra, located at Sudeten foothills of Lower Silesia (Fig. 1). Its catchment area takes 1807 km^2. Kaczawa catchment has very differentiated landscape, with a specific climate typical for mountain and mountain-foot regions. The average annual air temperature is lower than 7°C and the average annual precipitation varies from 500 to 800 mm. Snow cover remains for about 40-45 days a year. At the final water gauge – Piatnica, the maximum discharge (418 m^3s^{-1}) was recorded during flood in July 1997 [Kuchar et al. 2014a, 2014b]. In Kaczawa river basin there are 11 rain gauges, 1 synoptic station in Legnica and 10 water level gauges. 6 meteorological stations operate as automatically rainfall record. In order to determine the relationship between amount of precipitation from duration and probability of exceedance h(t,p), the selection of data of which the relationship will be developed must be done. Elaborating archival pluviographs authors limited period of analysis to months from May to October (V–X) in the years from 1961 to 2010. In the project there were analyzed rainfall durations: 60 min (hourly rainfall) and 1440 min (daily rainfall). Due to the lack of hourly data from all measuring stations in the long-term period, data from the synoptic station in Legnica were taken as representative of whole river basin.

For the purpose of this paper, using total review method there were isolated from the tested 50-years period top 50 maximum amount (h, mm) of precipitation in measurement material using two methods: annual maximum precipitation (AMP) and peak over treshold (POT), recommended in many sources [Helsel, Hirsch 2002, Hershfield 1961, Kotowski et al. 2010, Kysely et al. 2010, Shinyie et al.. 2014, Storch, Navarra 1999, Suligowski 2014, Wilks 2006, Weglarczyk 2010]. For POT data selection there were used Chomicz criterion of maximum rainfall intensity [Kaźmierczak, Kotowski 2012, 2014, Kotowski et. al 2010, Kotowski, Kaźmierczak 2013, Kotowski 2015]. Comparison of the amount of rainfall selected by methods AMP and POT for hourly and daily rain were shown in Figures 2 and 3.

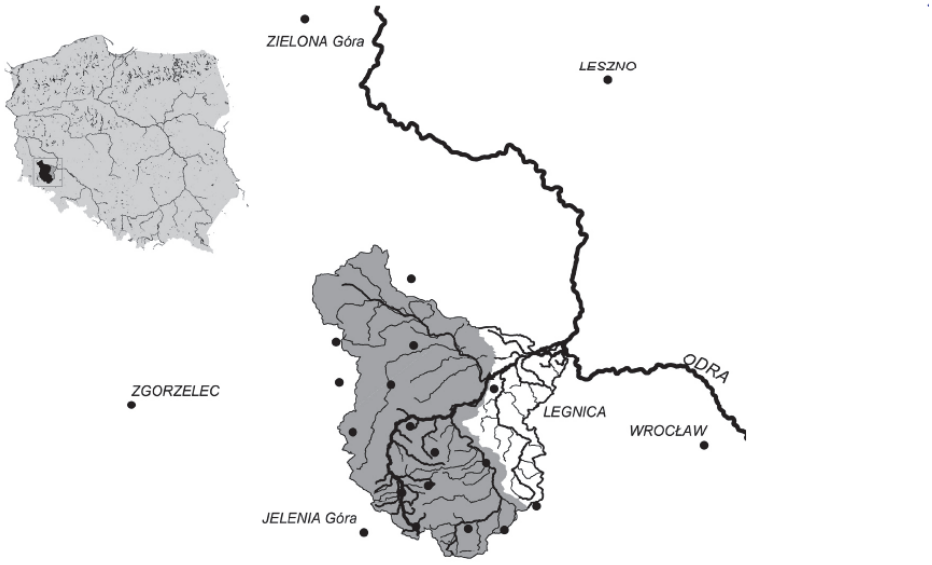


Fig. 1. The Kaczawa River catchment and location of measurement stations [Kuchar et al., 2014a].
Obr. 1. Povodie Kaczawa a umiestnenie meracích staníc [Kuchar et al., 2014a].

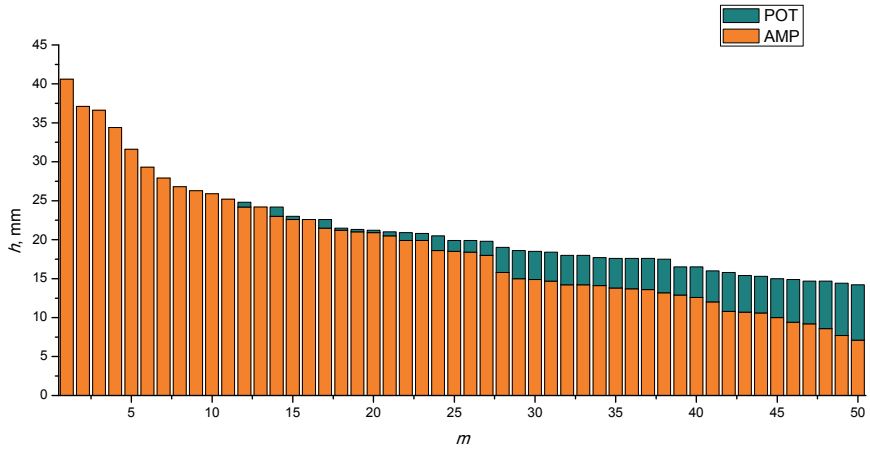


Fig. 2. Maximum houly rainfall amounts selected with AMP and POT methods in long-term period 1961-2010 in Legnica [authors development].
Obr. 2. Maximálne hodinové zrážky vybrané podľa AMP a POT z viacročného obdobia 1961-2010 v Legnici. [výber podľa autorov].

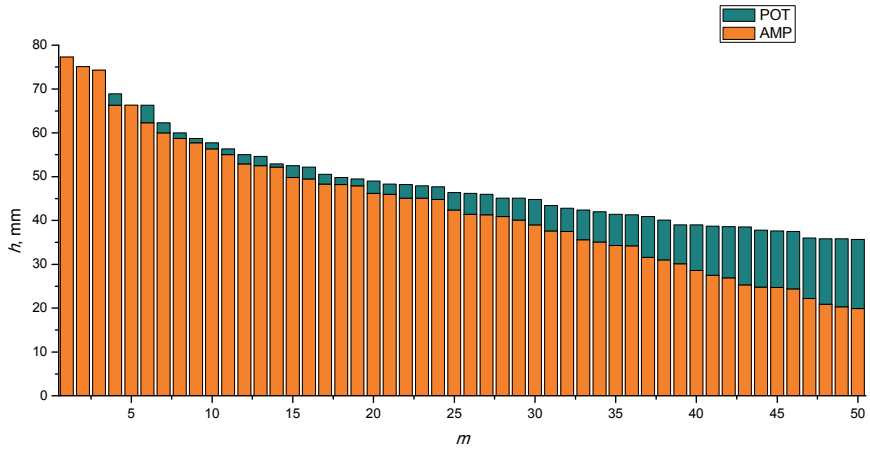


Fig. 3. Maximum daily rainfall amounts selected with AMP and POT methods in long-term period 1961-2010 in Legnica [authors development].
Obr. 3. Maximálne denné zrážky vybrané podľa AMP a POT z viacročného obdobia 1961-2010 v Legnici. [výber podľa autorov].

Prababilistic distributions

In the first place the top 50 amounts of precipitation were ordered decreasing (in 20 groups of a time duration from 5 minutes to 6 days), and then successively assigned to them according to (1) empirical probability of exceedance from p = 0,020 (for the highest value) to p = 0,980 (for the lowest value):

$$p(m,n) = \frac{m}{n+1} \quad (1)$$

where m is the sequence number within a decreasing ordered string of the number of n.

It should be noted that the greatest probability estimation errors should be expected for extreme elements of the investigated string [Helsel, Hirsch 2002, Storch, Navarra 1999, Wilks 2006, Weglarczyk 2010]. In Table 1 there were shown the amount of rainfall recorded for selected values of empirical probability.
To describe the measurement data there were used theoretical distributions: Gamma, Generalized exponential (GED), Gumbel, Log-normal and Weibull [Ben-Zvi 2009, Gupta, Kundu 2007, Overeem et al. 2008, Węglarczyk 2010].
Likelihood functions of these designated distributions are shown in Table 2.

Table 1. Maximum amounts of precipitation (h, mm) for the selected values of empirical probability of exceedance
Tabuľka 1. Maximálne množstvo zrážok (h mm) pre vybrané hodnoty empirických pravdepodobností prekročenia

Method	*t*, min	*m* = 1	*m* = 5	*m* = 10	*m* = 25	*m* = 50
		p = 0,020	*p* = 0,098	*p* = 0,196	*p* = 0,490	*p* = 0,980
AMP	60	40,6	31,6	25,9	18,5	7,1
AMP	1440	77,3	66,3	56,3	42,4	19,9
POT	60	40,6	31,6	25,9	19,9	14,2
POT	1440	77,3	66,3	57,7	46,4	35,7

Table 2. Log-likelihood function for the investigated distributions (α, β, γ, λ, μ - the parameters of particular distributions)
Tabuľka 2. Log-pravdepodobnostná funkcia, pre sledované rozdelenia (α, β, γ, λ, μ - parametre jednotlivých rozdelení)

Distribution	Likelihood function	Equation numer
Gamma	$\ln L = (\alpha-1)\sum_{i=1}^{n}\ln(x_i-\gamma) - n\ln\Gamma(\alpha) - n\alpha\ln\beta - \frac{1}{\beta}\sum_{i=1}^{n}(x_i-\gamma)$	(2)
GED	$\ln L = n\ln\alpha + n\ln\lambda - \sum_{i=1}^{n}\left(\lambda(x_i-\gamma)\right) + (\alpha-1)\sum_{i=1}^{n}\ln\left(1-e^{-(x_i-\mu)\lambda}\right)$	(3)
Gumbel	$\ln L = -n\ln\alpha - \sum_{i=1}^{n}\left(\frac{x_i-\gamma}{\alpha}\right) - \sum_{i=1}^{n}\exp\left(-\frac{x_i-\gamma}{\alpha}\right)$	(4)
Log-normal	$\ln L = -\sum_{i=1}^{n}\ln(x_i-\gamma) - n\ln\sigma - \frac{n}{2}\ln(2\pi) - \frac{1}{2\alpha^2}\sum_{i=1}^{n}(\ln(x_i-\gamma)-\mu)^2$	(5)
Weibull	$\ln L = n\ln\alpha - n\alpha\ln\beta + (\alpha-1)\sum_{i=1}^{n}\ln(x_i-\gamma) - \sum_{i=1}^{n}\left(\frac{x_i-\gamma}{\beta}\right)^{\alpha}$	(6)

Conformity of theoretical distributions with measured data was examined using the Anderson-Darling test for statistics [D'Agostino, Stephens 1986, Hongjoon et al. 2012]:

$$A^2 = -n - \frac{1}{n}\sum_{i=1}^{n}(2i-1)\left[\ln F(x_i) + \ln\left(1-F(x_{n-i+1})\right)\right] \quad (7)$$

where
x_i - i-th value in the decreasing ordered random sample,
F(x) - cumulative distribution function for the theoretical distribution.

The null hypothesis H_0 (when the measurement data matches with analyzed theoretical distribution) were taken on a significance level of 0,05 when the A^2 test statistic was less than the critical value A^2_{kr}. The alternative hypothesis (when the measurement data mismatches with analyzed distribution) was taken otherwise. The critical values were read from statistical tables [D'Agostino, Stephens 1986].
The best of remaining distributions were determined using the Bayesian information criterion of Schwartz, *BIC* [Konishi, Kitagawa 2008, Laio et al. 2009], in the form of:

$$BIC = -\frac{2\ln L}{n} + \frac{k\ln n}{n} \quad (8)$$

where
L - likelihood function of the tested distribution,
k - number of estimated parameters,
n - number of observations.

To evaluate the aptitude of investigated distributions to describe the measurement data we also used relative residual mean square error (*RRMSE*) [Lee, Maeng 2003]:

$$RRMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(\frac{h_{t,i}-h_{m,i}}{h_{m,i}}\right)^2}\cdot 100\% \quad (9)$$

where
h_t - the theoretical amount of precipitation (mm),
h_m - amount of precipitation from measurements (mm).

Differences between measurement data and modeled maximum rainfall were shown on h-h plot using quantile of the random variable Weibull distribution which takes the form of the following formula:

$$h(p) = \gamma + \alpha(-\ln p)^{\frac{1}{\beta}} \quad (10)$$

Results and discussion

Estimators parameters for particular distributions were determined by maximum likelihood method (MLM), through a numeric maximizing likelihood function (or its logarithm), taking into account the range of variability of investigated parameters (2) - (6). The results of the estimation of parameters for both maximum rainfall data selection methods (AMP and POT) were summarized in Table 3.

The calculation results for Anderson-Darling statistics (7) were shown in Table 4. All of the analyzed distributions, (Gamma, GED, Gumbel, Log-normal and Weibull) fulfill the compliance criterion for each AMP and POT of the two analyzed rainfall durations. There were no A^2 values higher than the critical value A^2_{kr}, and for the GED it was almost equal.

According to (8) *BIC* criterion consists of two parts. The first describes the measure of fit of the model, and the second determines its simplicity. For the best it is deemed to such a model, for which the information criterion obtained the lowest value. *BIC* values for the analyzed distributions are summarized in Table 5. For the sake of clarity, the smallest values for each duration *t* were bolded.

BIC criterion indicates a Weibull as the probabilistic distribution that is best representing the distribution of measured data (the lowest value of *BIC* for duration of 60 min in POT and daily rainfall in AMP). For the 60 min in AMP method Gumbel was best fitted distribution and for 1440 min in POT it was assigned to GED. It should be noticed that differences between the four recently used distributions: GED, Gumbel, Gamma and Weibull were minor (Tab. 5).

Based on (9) there were also calculated the *RRMSE* statistics, covering the entire range of data for 60 and 1440 minutes in both AMP and POT maximum values selection method. Applying *RRMSE* criterion for selected rainfall durations, the best turns out to be a Weibull distribution as shown in Table 6. It should be noted that, BIC criterion also pointed for Gumbel and GED distributions but the RRMSE factor for 60 min AMP and 1440 POT were one of the highest – respectively 5,081% and 3,427%. Other distributions describe the measurement data slightly worse but none of them is significant and does not exceed 5% which appears to be sufficient for practical reasons. The quality of this distribution fit to the empirical distribution of the amount of precipitation in Legnica, with different parameters for particular rainfall durations (Tab. 3) using (10), were shown in *h-h* plot (Fig. 4, Fig. 5).

As shown in Figures 4 and 5 the amount of precipitation from Legnica are well described by Weibull distribution using both AMP and POT methods for data selection. However, a better fit of the model values to the measurement data falls to a POT method in the both rainfall durations 60 minutes and 1440 minutes.

Table 3. Values of the parameter estimates (by MLM) for the investigated distributions for AMP and POT

Tabuľka 3. Hodnoty odhadov parametrov (MLM) pre skúmané rozdelenia pre AMP a POT

Method	t, min	Gamma	GED	Gumbel	Log-normal	Weibull
AMP	60	α = 2,40577 β = 5,50762 γ = 5,85993	α = 2,71991 λ = 0,129613 γ = 5,67004	α = 6,32288 γ = 15,3916	α = 0,436755 μ = 2,83433 γ = 0,433264	α = 1,55065 β = 13,8238 γ = 6,65178
AMP	1440	*α = 3,910* *β = 7,943* *γ = 12,05*	*α = 4,345* *λ = 0,070* *γ = 12,66*	*α = 12,610* *γ = 35,994*	α = 0,257 μ = 4,030 γ = -15,02	α =1,726 β = 28,472 γ = 17,65
POT	60	α = 1,1032 β = 6,5764 γ = 14,18	α = 1,0808 λ = 0,1448 γ = 14,19	α = 4,2603 γ = 18,75	α = 0,7413 μ = 1,9003 γ = 12,79	α = 1,1009 β = 7,5060 γ = 14,18
POT	1440	α = 0,9378 β = 13,9617 γ = 35,69	α = 0,9206 λ = 0,0725 γ = 35,69	α = 7,8361 γ = 43,95	α = 0,6942 μ = 2,5786 γ = 32,30	α = 1,0275 β = 13,2160 γ = 35,69

Table 4. Anderson-Darling statistics values for analyzed distributions (the critical values was given in brackets in the heading of the table)
Tabuľka 4. Anderson-Darling štatistiky pre analyzované rozdelenia (kritické hodnoty sú uvedené v zátvorke v záhlaví tabuľky)

Method	*t*, min	Gamma (0,762)	GED (0,723)	Gumbel (0,757)	Log-normal (0,752)	Weibull (0,757)
AMP	60	0,234	0,266	0,313	0,275	0,195
AMP	1440	0,351	0,459	0,357	0,281	0,321
POT	60	0,275	0,311	0,536	0,261	0,220
POT	1440	0,699	0,722	0,491	0,303	0,565

Table 5. BIC values of analyzed distributions (the smallest values bolded)
Tabuľka 5. BIC hodnoty pre analyzované rozdelenia (najmenšie hodnoty tučne)

Method	*t*, min	Gamma	GED	Gumbel	Log-normal	Weibull
AMP	60	7,0558	7,0686	**7,0210**	7,0845	7,0316
AMP	1440	8,3991	8,4268	8,3538	8,4159	**8,3525**
POT	60	6,1921	6,1932	6,3151	6,2744	**6,1847**
POT	1440	7,3763	**7,3747**	7,5070	7,4999	7,3780

Table 6. RRMSE values of analyzed distributions (the smallest values bolded)
Tabuľka 6. RRMSE hodnoty pre analyzované rozdelenia (najmenšie hodnoty tučne)

Method	*t*, min	Gamma	GED	Gumbel	Log-normal	Weibull
AMP	60	4,447	4,640	5,081	4,736	**4,195**
AMP	1440	4,758	5,414	4,937	4,776	**4,594**
POT	60	2,456	2,516	5,193	2,710	**2,421**
POT	1440	3,351	3,427	3,686	2,842	**2,618**

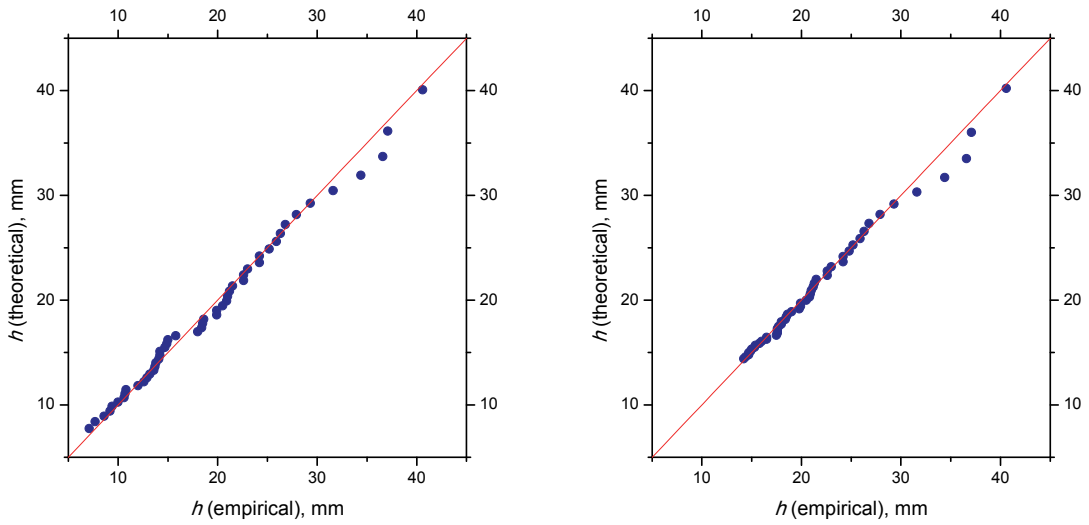


Fig. 4. h-h plot for the Weibull distribution for AMP (left) and POT (right) hourly measurement data for Legnica in the years 1961–2010 [authors development].
Obr. 4. h-h graf pre Weibullovo rozdelenie pre AMP (vľavo) and POT (vpravo) z hodinových údajov v Legnici v rokoch 1961-2010 [výber podľa autorov].

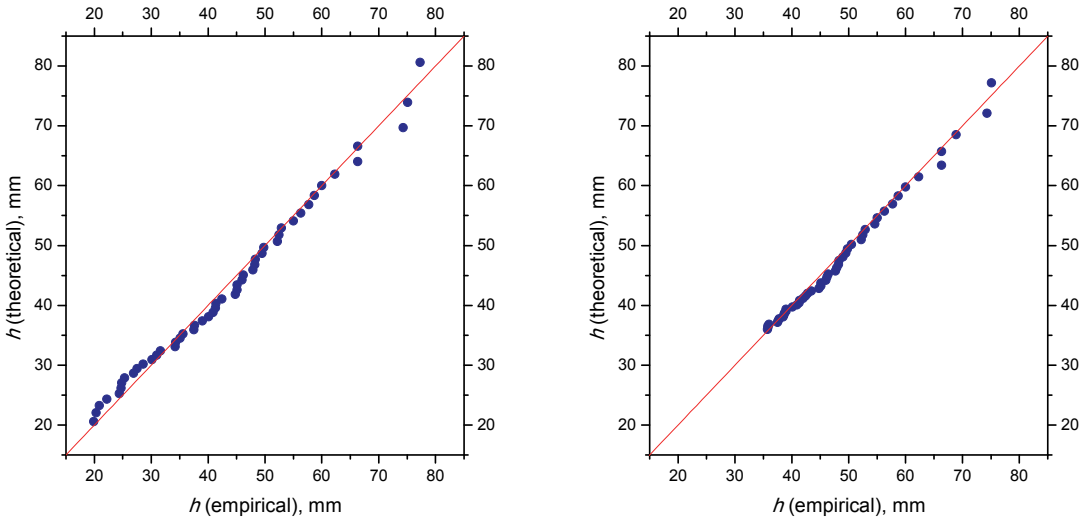


Fig. 5. h-h plot for the Weibull distribution for AMP (left) and POT (right) daily measurement data for Legnica in the years 1961–2010 [authors development].
Obr. 5. h-h graf pre Weibullovo rozdelenie pre AMP (vľavo) and POT (vpravo) z denných údajov v Legnici v rokoch 1961-2010 [výber podľa autorov].

Conclusion

In order to determine which method of maximum rainfall data selection is more accurate to describe the long-term precipitation extremes in river basin there was developed probabilistic model based on probabilistic distributions like Gamma, Generalized Exponential (GED), Gumbel, Log-normal and Weibull. Probabilistic distributions were developed using maximum precipitation data selected by two methods AMP and POT. Estimators of parameters for particular distributions were developed using maximum likelihood method.
Conformity of the analyzed theoretical distributions with measured data was inspected using the Anderson-Darling test, while choosing the best distribution was made using bayesian information criterion of Schwartz (BIC) and also by the relative residual mean square error (RRMSE). Considering the two used criteria as best of the selected distributions for the rainfall duration 60 min and 1440 min, was considered Weibull. Analysis of the criteria for probability distributions fit to the measured values showed that several types of indicators should be used. Especially important it seems to be to combine evaluation for criterion BIC with RRMSE, where in case of Legnica for BIC there was indicated Gumbel, Weibull and GED distributions and for RRME Weibull in all rainfall durations. Finally both of the methods for selecting the maximum value of precipitation can be used to analyze the extremes in long-term periods (such as 1961-2010) however models based on the POT method were better suited to measuring values.

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POROVNANIE METÓD VÝBERU MAXIMÁLNEJ HODNOTY PRE VÝVOJ MATEMATICKÉHO MODELU EXTRÉMNE VYSOKEJ ZRÁŽKY V POVODÍ RIEKY

V článku boli použité zrážky z meteorologickej stanice v povodí Kaczawa. V povodí Kaczawa je 11 zrážkomerov, 1 synoptická stanica v Legnici a 10 vodomerných staníc. 6 meteostaníc funguje na automatický záznam zrážok. Pre určenie vzťahu medzi množstvom zrážok daného trvania a pravdepodobnosťou prekročenia h (t, p) bolo potrebné vybrať potrebné hodnoty zrážok. Pri spracovaní archívnych pluviografov sa autori obmedzili na mesiace od mája do októbra (V-X) v rokoch 1961 až 2010. V rámci projektu boli analyzované trvania zrážok: 60 min (hodinové zrážky) a 1440 minút (denná zrážok). Vzhľadom na nedostatok hodinových údajov zo všetkých meracích staníc v dlhodobom horizonte, údaje zo synoptickej stanice v Legnici boli vzaté ako reprezentatívne pre celé povodie. Cieľom je určiť, ktorá metóda výberu maximálnych zrážok dokáže presnejšie popísať dlhodobé zrážkové extrémy v povodí. Boli vyvinuté pravdepodobnostné modely založené na pravdepodobnostných rozdeleniach, ako je gamma, všeobecné exponenciálne (GED), Gumbelovo, Log-normálne a Weibullovo. Pravdepodobnostné rozdelenia boli vyvinuté pomocou maximálnej zrážky zvolenej dvoma spôsobmi: AMP a POT. Odhady parametrov pre jednotlivé rozdelenia boli urobené pomocou metódy maximálnej podobnosti. Zhoda analyzovaných teoretických rozdelení s nameranými dátami bola kontrolovaná testom Anderson-Darling (A2), zatiaľ čo výber najlepšieho rozdelenia bol urobený pomocou Schwartzovho bayesiánskeho informačného kritéria a tiež pomocou relatívnej reziduálnej strednej kvadratickej chyby (RRMSE). Ako najlepšie z rozdelení bolo vybrané Weibullovo rozdelenie, pre obe kritétiá výberu ako i pre obe doby trvania zrážok 60 minút a 1440 minút. Analýza kritérií pre zhodu rozdelení pravdepodobnosti s nameranými hodnotami ukazuje, že by mali byť použité viaceré druhy ukazovateľov. Zvlášť dôležité sa zdá byť spojiť hodnotiace kritérium BIC s RRMSE, kde v prípade Legnice pre BIC boli lepšie Gumbelovo, Weibullovo a GED rozdelenia a pre RRMSE Weibullovo pre všetky dĺžky trvania. Nakoniec obe metódy pre výber maximálnej hodnoty zrážok môžu byť použité na analýzu extrémov v dlhodobom období (1961 - 2010), ale modely založené na metóde POT lepšie vystihovali merané hodnoty.

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