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Methodology for flood frequency estimations in small catchments

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Abstract

Estimations of flood frequencies in small catchments are difficult due to a lack of measured discharge data. This problem is usually solved in the Czech Republic by hydrologic modelling when there is a reason not to use the data provided by the Czech hydrometeorological institute, which are quite expensive and have a very low level of accuracy. Another way is to use a simple method which provides sufficient estimates of flood frequency based on the available spatial data. Such a method is being developed at the Czech Technical University in Prague. The methodology is being developed with consideration of all important factors affecting flood formation in small catchments. The relationship between catchment descriptors and flood characteristics has been the subject of recent research which is presented in this paper. The results for different descriptors vary from a tight relationship of an expected shape to a relationship which is opposite to that expected, mainly the case of land use. The parameterisation of the methodology is also presented including the uncertainty analysis and the assessment of its performance. In its present form, the methodology achieves an R^2 value of about 0.64 for both 10 and 100 yr return periods.

1 Introduction

The methodology for the estimations of flood frequency in small catchments is being developed at the Department of Irrigation, Drainage and Landscape Engineering. The purpose of the presented research is mainly the fact that engineers need quick instant flood frequency data for the purposes of different feasibility studies. It usually takes at least one month to obtain such data from the official provider, which is the Czech Hydrological and Meteorological Institute (CHMI), and the data can be relatively expensive. It is also important to take into consideration the fact that the data provided by CHMI have a relatively low level of accuracy. The uncertainty of the data for small catchments which are usually ungauged is ±60 % in the 4th class of accuracy according to Czech standards (Kulasová and Holík, 1997). This means that use of the data should take into consideration its uncertainty and that it is appropriate to apply correction coefficients in cases of higher safety demands.

The approach used for the development of the presented methodology in general applies similarity principles which have been discussed by many authors worldwide (Burn, 1997; Merz and Blöschl, 2005; Wagener et al., 2007; Patil and Stieglitz, 2012). These principles are usually applied in three ways: (i) for the direct estimation of flood quantiles, (ii) for the estimation of probability distribution parameters and (iii) for the estimation of hydrologic model parameters. The proposed methodology adopts the first option in order to be applicable by practical engineers who may be unfamiliar with the application of statistical analysis methods or hydrologic models.

There are different regression based methods which are similar to the method proposed by the authors of this paper. These methods adopt different procedures for parameter estimation, such as ordinary least square regression, weighted least square regression, generalized least square regression, which is discussed by Stedinger and Tasker (1985) and further by Pandey and Nguyen (1999) who involved more parameter estimation methods such as least absolute value regression, robust regression and others. The proposed method uses the power function with shifts in two directions which makes it different from other similar methods. This approach allows choosing more suitable parts of the power function (according to its slope and curvature) but on the other hand it avoids the linearization of the problem by logarithmic transformation.

2 Overview of proposed methodology

The proposed methodology is based on the calculation of flood frequencies using catchment descriptors. The procedure is based on the application of GIS tools and spatial data analysis. The method should be applicable to any small catchment for which the input data are available. The initial list of catchment properties which are considered important for flood forming is as follows:

- catchment area,
- storm rainfall characteristics,
- slope conditions of the catchment,
- catchment shape,
- land use,
- soil properties.

This list corresponds in general to the list used by Sefton and Howarth (1998) for their study and involves both physical-geographic and climate properties as discussed by Berger and Entekhabi (2001). They did an analysis on the long-term basin response but it can be expected that it is even more necessary to involve both types of information in flood response assessment. It also contains types of parameters used for the purpose of maximum possible flood calculation by Reed and Field (1992).

First, the procedure for the calculation of catchment descriptors was defined including the necessary input data layers. The most important input is the digital elevation model (DEM) which is sufficient input for the calculation of the catchment area, the average slope and the catchment shape. This is a relatively easily available data source and the procedures for its processing for purposes of hydrologic analyses have been broadly published. The situation is quite different in the case of the calculation of other descriptors. There are different reasons for the difficulties in the data acquisition and processing. There are many different sources of land use data which differ in many aspects, mainly the resolution, accuracy and information content. Moreover, there are no layers available containing storm rainfall characteristics or gapless soil maps containing sufficient information for the infiltration properties assessment. This is why the analysis on the influence of soil properties could not yet be done and why there was a need to prepare rainfall characteristic maps.

The general construction of the proposed methodology is similar to those published for example by Asquith and Slade (1996) or by Olson (2009) for conditions of regions in the United States. In general, the value is calculated as a product of functions of single catchment descriptors as described by the equation

$$Q_N = a_0 \cdot \prod_i f_i\left(\mathrm{CD}_i\right) + d_0 \tag{1}$$

where Q_N is flood discharge with the return period of N years, a_0 and d_0 are parameters, f_i are mathematical functions and CD_i are catchment descriptors.

The function for the calculation of each component of Eq. (1) is considered as a power function with shifts in both directions in the form of

$$f_i\left(\mathrm{CD}_i\right) = a_i \cdot \left(b_i + \mathrm{CD}_i\right)^{c_i} + d_i \tag{2}$$

where a_i, b_i, c_i and d_i are parameters of mathematical functions. Shifts are driven by parameters b_i and d_i. The methodology itself applies the black-box approach (Dooge and O'Kane, 2003) which means that internal parameters – a, b, c and d – can have conceptual interpretation and thus also be physically meaningful.

3 Assessment of the relationship between catchment descriptors and flood discharges

Discharges with different return periods published by Zítek (1965) were used for the analysis. The data published in this book were derived based on a time series from 250 gauging stations spread over the whole area of the former Czechoslovakia. The shortest length considered for the analysis was 25 yr while the median is 43 yr.

Nearly two hundred catchments with a catchment area up to 150 km^2 for which the flood frequency data are published by Zítek (1965) were chosen for the analysis in the upper Vltava river basin and Dyje river basin (see Fig. 1). Catchments were delineated using a layer containing fourth order catchments available from the Water Research Institute and elevation data to get polygons for calculations of catchment descriptor values.

The calculation procedure was different for each considered catchment descriptor. The simplest one is the calculation of the descriptor related to the catchment slope which is calculated as the average slope from the layer containing slopes calculated based on the analysis of DEM. DEM is also input for the calculation of the catchment descriptor related to catchment shape. For this purpose, Shape Factor – SF was used which is defined as the drainage area divided by the square of the longest flow path. This descriptor was chosen based on previous research (David, 2011). The longest flow path for each catchment was calculated using standard GIS procedures (Flow Direction and Flow Length), while the catchment area was calculated simply from the geometry of each catchment polygon.

For the calculation of the descriptor related to storm rainfall layers containing information on the value of maximum 24 h precipitation, totals for the considered return periods needed to be prepared. They were interpolated from point data digitized based on the information for each gauging station published by Šamaj et al. (1985). The descriptor for each catchment was then calculated as an average value over the catchment area.

Land use was analysed using a curve number parameter (CN) published by, among others, Mishra and Singh (2003). This parameter originally combines the information on land use and soil infiltration properties. However, the spatial distribution was considered only with respect to land use while soil information was considered spatially homogeneous and corresponding to hydrological soil group B, in order to be able to assess land use influence on flood discharges separately.

4 Analyses performed for assessment of the importance of the catchment descriptors considered

The analyses focused on the relationship between catchment descriptors and flood discharges were performed individually for each of the considered catchment descriptors. For this paper, return periods of 10 and 100 yr were selected as in the case of the study published by Pandey and Nguyen (1999). Correlations between dependent and exploratory variables were analysed using parameter optimization for Eq. (2). This was done by the maximization of the coefficient of determination – R^2 using the GRG nonlinear method available in Excel. This option was chosen with respect to the fact that the considered shape of the function which avoids linearization by logarithmic transformation and thus the application of least square solution techniques.

4.1 Analyses on the correlation between catchment descriptors and flood discharges

Basic analyses were performed by relating the value of the catchment descriptor directly to the value of the flood discharge within the given return period. The assumption is that there should be a significant relationship between the catchment area and the peak discharge value and between the precipitation total for a given return period and the peak discharge value related to the same return period.

4.1.1 Catchment area

The catchment area is considered as the most important catchment descriptor. It is assumed that the value of flood discharge increases with an increasing catchment area. However, it is usually also assumed that the relationship between the catchment area and flood discharge is not linear in small catchments due to spatial distribution of storm rainfalls which are the most frequent causes of floods in small catchments in the conditions of the Czech Republic.

Areas of catchments involved in the analyses vary in range from 7.7 km^2 to 146.4 km^2 with a mean value of 58.2 km^2. More than 51 % of catchments are smaller than 50 km^2 and more than 87 % are smaller than 100 km^2.

The results show a relatively clear relationship between the catchment area and the peak discharge value. Figure 2 shows plots of the peak discharge values against the catchment area. Fitted lines are also shown having $R^2 = 0.18$ for $N = 10$ yr and $R^2 = 0.20$ for $N = 100$ yr.

4.1.2 Maximum 24 h precipitation total

The precipitation total, together with the catchment area, is considered the most important factor affecting flood discharge values. The product of the precipitation total and catchment area can be understood as the volume of water available for runoff. Thus, the value of peak discharge is considered increasing with an increasing precipitation total but the relationship is not considered linear as lower values of precipitation totals are in general more affected by losses. Values of maximum 24 h precipitation totals for different return periods are the only data source which is available as a continuous map for the whole area of the Czech Republic and therefore this characteristic was used for the analysis although floods are usually caused by precipitation events with a duration shorter than 24 h.

Interpolated values of maximum 24 h precipitation within the sample vary in range from 51.9 to 92.3 mm in the case of a 10 yr return period and from 75.8 to 146.8 mm in the case of a 100 yr return period. Average values are 61.9 mm and 92.6 mm respectively. However, most catchments have values of a maximum 24 h precipitation total in a very narrow range which is from 55 to 65 mm for more than 72 % in the case of a 10 yr return period and from 80 to 95 mm in the case of a 100 yr return period.

The results show that the relationship between the maximum 24 h precipitation total and peak discharge value for $N = 10$ yr follows almost a straight line (see Fig. 3).

Achieved values of R^2 are higher than for the catchment area, i.e. $R^2 = 0.32$ for $N = 10$ yr and $R^2 = 0.27$ for $N = 100$ yr.

4.1.3 Average slope of the catchment

Catchment slope conditions are considered as important mainly due to their influence on overland flow velocities. A higher slope of the catchment leads to faster concentration and consequently to higher values of peak discharge.

Slope conditions in catchments involved in the analysis vary in a relatively wide range from flat to mountainous areas. The average slope ranges from 1.5 to 18.8 % but 60 % have a value in the range from 4 to 10 %.

Results of performed analyses confirm the assumption of increasing peak discharge values with increasing average slope of the catchment. Results presented in Fig. 4 show the almost straight shape of a fitted curve. Values of the determination coefficient achieved by parameter optimization are $R^2 = 0.15$ for $N = 10$ yr and $R^2 = 0.14$ for $N = 100$ yr.

4.1.4 Catchment shape

Catchment shape affects flood discharges through the runoff concentration. It is assumed that wide catchments (fan-shaped) have higher values of peak discharges than narrow oblong catchments (fern-shaped) which is published, among others, by Murthy (2002). According to the definition of SF the values are higher for fan-shaped catchments than for fern-shaped catchments.

The value of SF can theoretically range from 0 to p but it usually does not exceed the value of about 0.6. This is also the case of the sample used for the analysis where the maximum value is 0.57 while the minimum is 0.10. However, most catchments (75 %) have a value of SF below 0.22.

Results obtained by the basic analyses performed are in opposition to those expected. These results are shown in Fig. 5. Fitted curves have a shape representing a decreasing value of flood discharge with increasing value of SF. However, coefficients of determination are very low: $R^2 = 0.02$ for $N = 10$ yr as well as for $N = 100$ yr.

The results shown do not necessarily refute the mentioned principles. This can be caused by a stronger influence of other factors. Therefore, further analyses had to be performed on the influence of this catchment property.

4.1.5 Land use

Land use affects flood discharges in different ways. Mainly, precipitation losses caused by interception and infiltration and roughness are important. For the purposes of the presented analyses, the CN value was chosen as a catchment descriptor. This parameter was designed to calculate direct runoff which means that it affects flood discharge values through the volume of runoff. It reaches values from 0 to 100. A zero value corresponds to no runoff while a value of 100 corresponds to the maximum runoff. This means that peak discharge should increase with increasing CN value. To avoid the influence of soil properties, spatial distribution of CN values considered the whole analysed area as homogeneously covered by hydrological soil group B.

The value of CN ranges in its definition from 0 to 100. In the sample, the values of this parameter range from 62.1 to 80.9 and there is no significant concentration of these values in this range.

Results of performed basic analyses are again opposite to the meaning of the CN parameter. The trend is decreasing in both cases shown on Fig. 6. The determination is furthermore relatively high, i.e. $R^2 = 0.28$ for $N = 10$ yr and $R^2 = 0.26$ for $N = 100$ yr.

There are several possible reasons for such results. First, the influence of land use can be weaker than the influence of other factors which cannot be avoided in this type of analysis. Second, areas of land use types with low values of CN, such as forests, are usually concentrated in hilly and mountainous areas which typically have high and intense storm rainfall and consequently high values of flood discharges.

4.2 Additional analyses on the correlation between catchment descriptors and flood discharges

Further analyses were performed with the aim to exclude at least partially the influence of the two most important factors affecting flood discharges. These are, according to basic analyses, the catchment area and the maximum 24 h precipitation total. The product of these two values is the volume of water available for runoff. Thus, the assessment was performed on the relationship between selected catchment descriptors and the flood discharge divided by the product of the catchment area and precipitation total.

4.2.1 Catchment shape

Results of the comparison of shape factor and flood discharge divided by the product of catchment area and precipitation total show a growing trend (see Fig. 7). This corresponds to the assumption that flood discharge values increase with increasing value of the shape factor.

The trend obtained by fitting the curve shaped according to the equation is not very significant, having a value of $R^2 = 0.01$ for $N = 10$ yr as well as for $N = 100$ yr. This results in the supposition that this catchment descriptor probably cannot significantly increase the performance of the proposed methodology for estimations of flood discharges.

4.2.2 Land use

In the case of land use represented by the CN value, the results of the comparison with flood discharge divided by the catchment area and precipitation total are similar to those obtained by the basic analysis. It shows an inverted proportion of peak discharge values per unit and unit precipitation to the value of CN in both cases which is again opposite to the definition of the CN parameter.

The trend obtained by fitting the curve shaped according to the equation is relatively significant (see Fig. 8) having the value of $R^2 = 0.30$ for $N = 10$ yr as well as for $N = 100$ yr. This corresponds to the best values of previous analyses. However, it needs to be further analysed due to the obtained results.

4.2.3 Available volume

To make a simple check of the influence of the two parameters providing best performance, the assessment of the relationship between available volumes of the maximum 24 h precipitation total and peak discharge values was performed. The volume was calculated as a product of the precipitation total and the catchment area which were identified as the most important catchment characteristics.

The results of this analysis show that the performance of the calculation based on this parameter does not provide important improvement with respect to the value of the maximum 24 h precipitation total for the given return period. The value of the determination coefficient is a bit higher in the case of the 100 yr return period ($R^2 = 0.33$). In the case of the 10 yr return period, the value of the determination coefficient is lower ($R^2 = 0.30$) than for the application of the 24 h precipitation total alone.

4.3 Methodology parameterisation

The methodology was first parameterised for all tested catchment descriptors including also the land use descriptor which did not provide good results when tested separately. Parameterisation was carried out again by maximizing the R^2 value. The parameterisation was then carried out again without considering the least important descriptors to assess if they can be excluded from the calculation without loss of accuracy. The detailed analysis on the distribution of errors was then carried out to get an overview of the uncertainty.

For all considered catchment descriptors, the results obtained by parameterisation of the methodology can be considered as satisfactory having $R^2 = 0.640$ for $N = 10$

and $R^2 = 0.641$ for $N = 100$. The value of the determination coefficient decreases with the number of dropped catchment descriptors as shown in Fig. 10. Exclusion of land use resulted in the value of R^2 decreased to 0.57 and 0.56 respectively which is much more than in the case of the further exclusion of shape factor. This exclusion resulted in the same value of R^2 for $N = 100$ and in the value of R^2 decreased to 0.54. Further exclusion of average slope resulted in a small decrease of the R^2 value to 0.53 and 0.50 respectively. These results show that the involvement of all considered catchment descriptors improves the performance of the proposed methodology.

The analysis of the uncertainty of the proposed methodology was carried out by the assessment of error values. First, the root mean square error (RMSE) and mean absolute error (MAE) values which are both discussed by Willmott and Matsuura (2005) were used as measures of the uncertainty for each considered combination of catchment descriptors. The values of these measures are shown in Table 1. The results show that in the worst case (only area and precipitations are involved) the relative value of RMSE is about 42 % which is less than the value given by the standard. When all considered catchment descriptors are involved, the relative value of RMSE is 37 and 36 % respectively.

The distribution of errors is shown in Figs. 11 and 12. It shows that more values in the dataset are overestimated than those which are underestimated in both cases which could be understood as an advantage because it is on the side of safety. Furthermore, it shows that more than 80 % of values have an error lower than 50 % and more than 90 % of values have an error lower than 60 % which is a value considered by the Czech standard for hydrological data in the 4th class of accuracy.

5 Conclusions and outcomes

There are several outcomes that can be stated based on the performed analyses. First, the influence of each analysed catchment descriptor is not significant enough to be used as the only one explaining peak discharge values. Best results achieve a value of determination coefficient of about 0.3. This is not a very strong relationship and the uncertainty would be too high in the case of considering one single parameter. This outcome was assumed because of the nature of flood phenomenon. It is a process which is very complex and there are many factors which play an important role. Second, the most important catchment characteristics are the area and the maximum 24 h precipitation total which again confirms the initial assumption. Third, the involvement of land use descriptor (CN) improves the performance of the methodology even though the initial analysis did not confirm its influence on flood discharges with respect to its definition.

The results of parameterisation and first uncertainty assessment show that the concept used for the formulation of the methodology is reasonable and that the methodology provides satisfactory results. Values of optimized method parameters are reported in Table 2. Further research will focus on possible involvement of soil properties as the characteristic which could improve the performance of the methodology.

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Table 1. Values of RMSE and MAE for all considered combinations of involved catchment descriptors.

Return period *N*	10 yr		100 yr	
Considered catchment descriptors	RMSE ($m^3 s^{-1}$)	MAE ($m^3 s^{-1}$)	RMSE ($m^3 s^{-1}$)	MAE ($m^3 s^{-1}$)
A, P	9.63	6.71	17.83	13.23
A, P, S	9.46	6.70	16.73	12.13
A, P, S, SF	9.14	6.26	16.69	12.03
A, P, S, SF, LU	8.41	5.79	15.10	10.59

Table 2. Values of calibrated model parameters.

Return period N	10 yr				100 yr			
Index/parameter	a_i	b_i	c_i	d_i	a_i	b_i	c_i	d_i
0	14.465	–	–	−4.327	17.398	–	–	−2.347
1 (area)	45.142	19.570	−0.522	−8.932	−9.620	75.296	−0.501	1.170
2 (precipitation)	40.804	0.014	−0.575	−5.175	47.366	2.809	−0.567	−5.100
3 (slope)	47.949	3.549	−3.000	−0.818	6.581	2.668	−2.266	−0.514
4 (shape)	8.919	94.128	−8.702	−3.944	8.509	85.437	0.075	4.941
5 (land use)	7.862	0.006	−0.716	−0.257	39.959	0.007	−0.591	−2.549

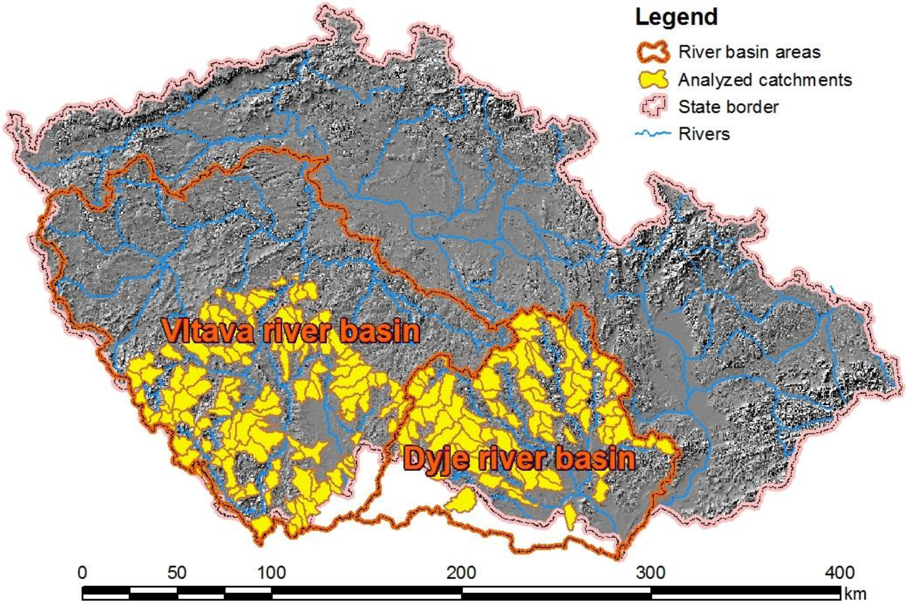

Fig. 1. Catchments up to 150 km^2 selected for the analysis.

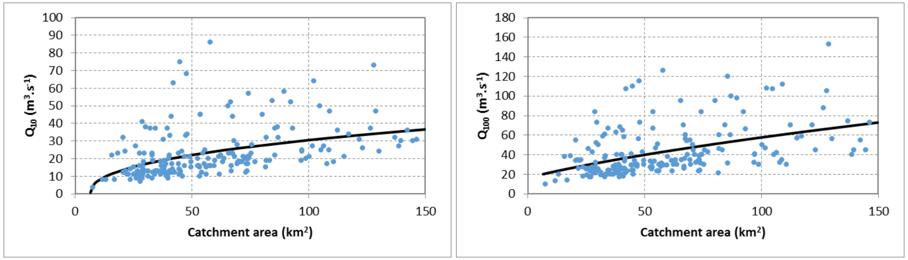

Fig. 2. Relationship between catchment area and peak discharge value for $N = 10$ yr (left) and $N = 100$ yr (right) with fitted lines following Eq. (2).

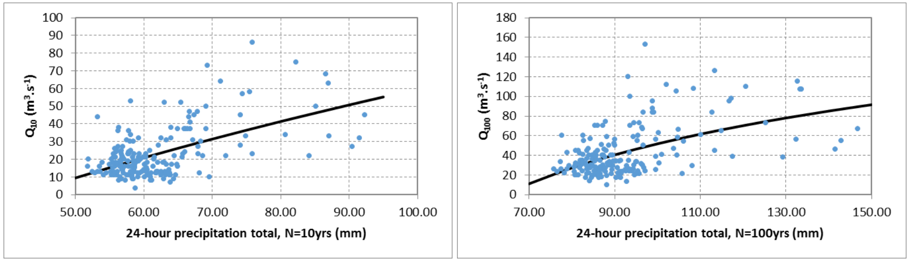

Fig. 3. Relationship between catchment average maximum 24 h precipitation total and peak discharge value for $N = 10$ yr (left) and $N = 100$ yr (right) with fitted lines following Eq. (2).

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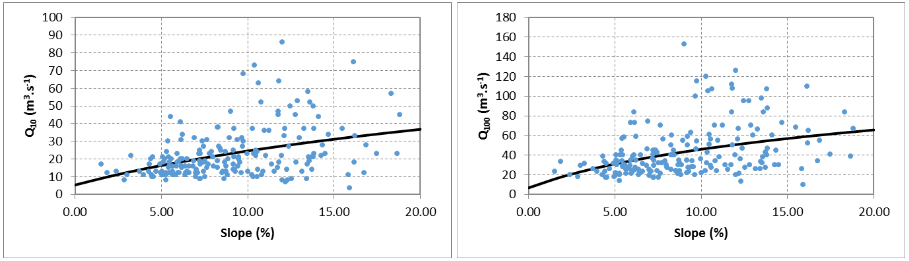

Fig. 4. Relationship between catchment average slope and peak discharge value for $N = 10$ yr (left) and $N = 100$ yr (right) with fitted lines following Eq. (2).

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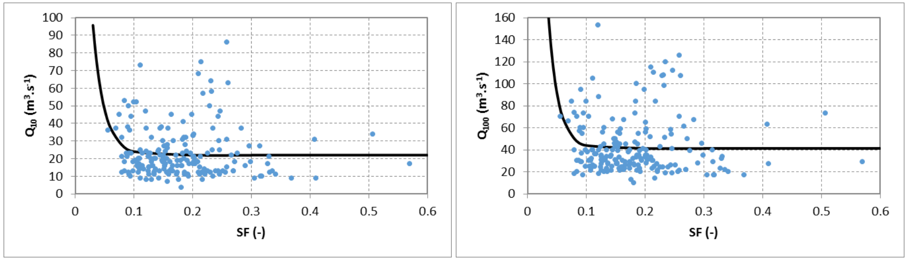

Fig. 5. Relationship between catchment shape factor and peak discharge value for $N = 10$ yr (left) and $N = 100$ yr (right) with fitted lines following Eq. (2).

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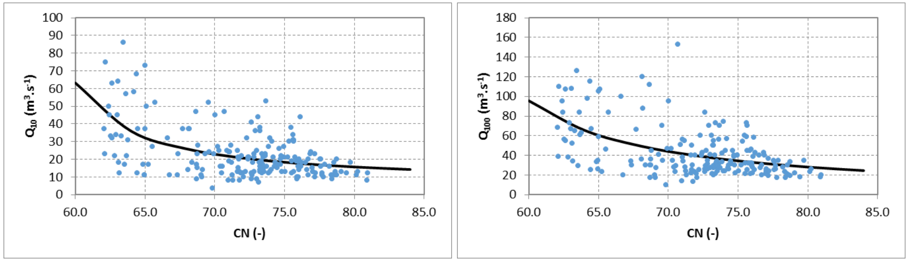

Fig. 6. Relationship between catchment average CN value and peak discharge value for N = 10 yr (left) and N = 100 yr (right) with fitted lines following Eq. (2).

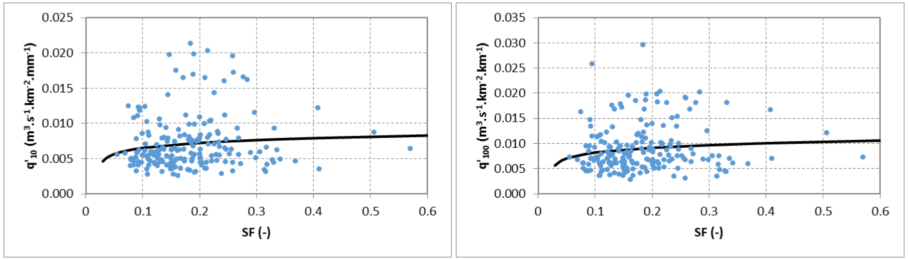

Fig. 7. Relationship between catchment average shape factor and peak discharge value per unit area and unit precipitation total for $N = 10$ yr (left) and $N = 100$ yr (right) with fitted lines following Eq. (2).

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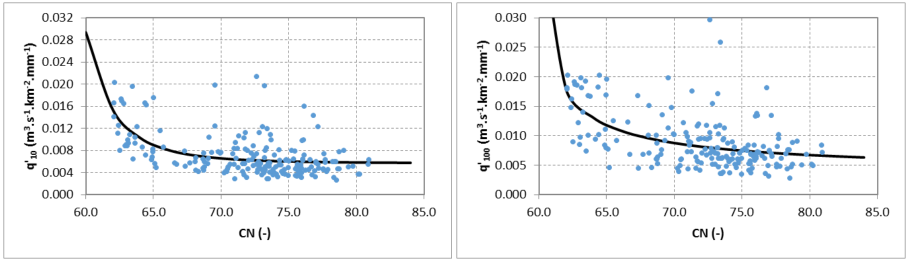

Fig. 8. Relationship between catchment average CN value and peak discharge value per unit area and unit precipitation total for N = 10 yr (left) and N = 100 yr (right) with fitted lines following Eq. (2).

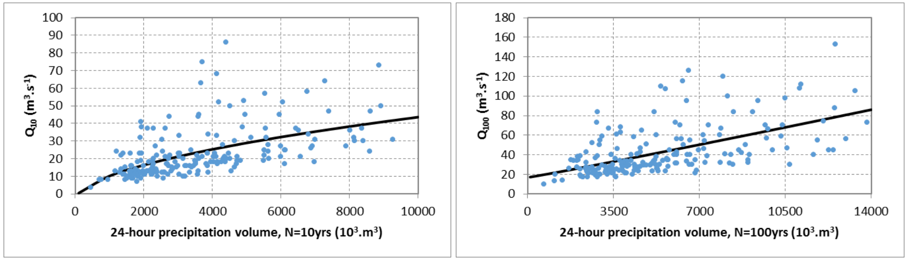

Fig. 9. Relationship between catchment 24 h precipitation volume and peak discharge value for $N = 10$ yr (left) and $N = 100$ yr(right) with fitted lines following Eq. (2).

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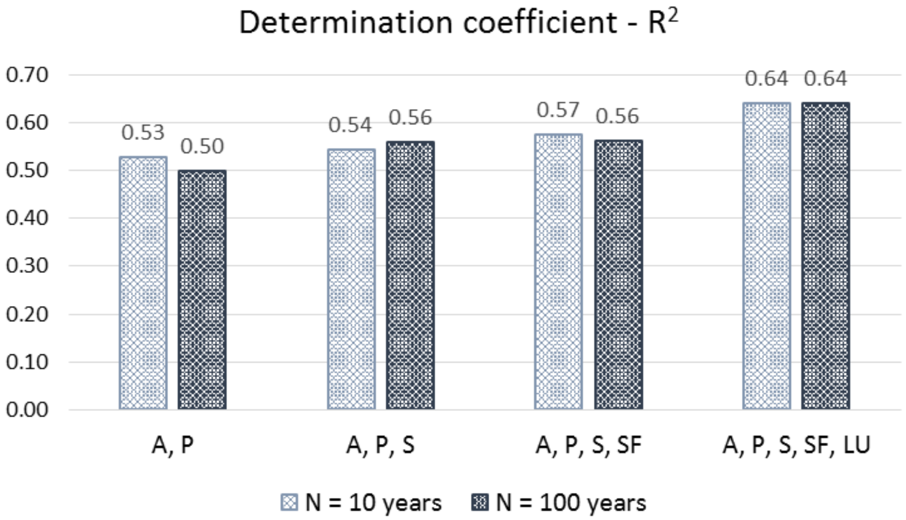

Fig. 10. Values of determination coefficient for optimized parameters for different combinations of considered catchment descriptors (A – area, P – maximum 24 h precipitation total, S – slope, SF – shape factor, LU – land use).

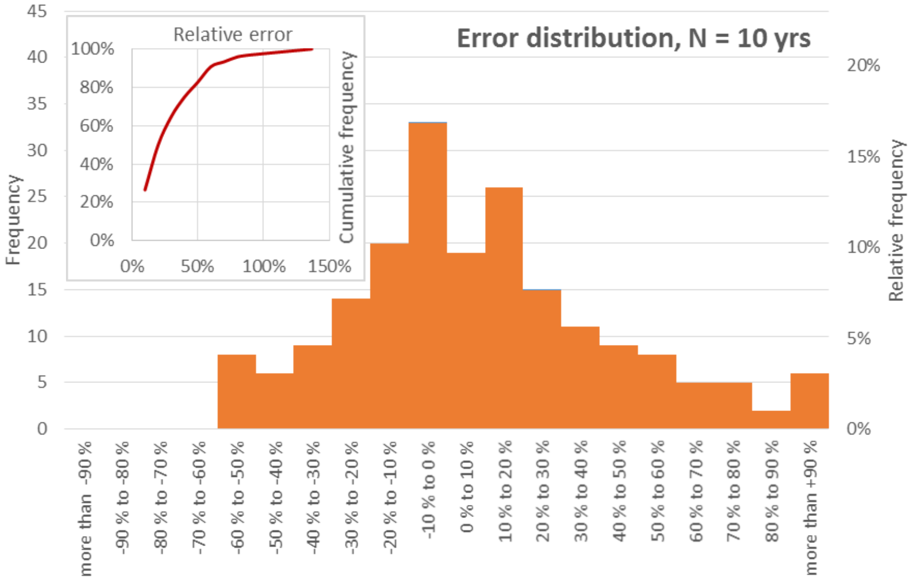

Fig. 11. The distribution of errors for $N = 10$ yr. The graph in the upper left corner shows cumulative frequencies of error absolute values.

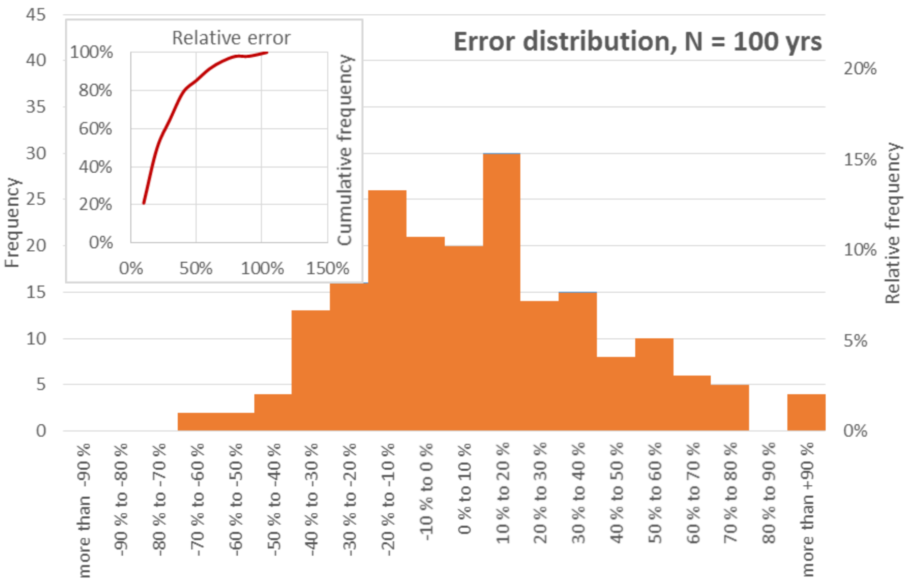

Fig. 12. The distribution of errors for $N = 100$ yr. The graph in the upper left corner shows cumulative frequencies of error absolute values.