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Alternative Approaches to a Calibration of Rainfall-Runoff Models for a Flood Frequency Analysis

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Abstract – One of the tools which are currently being used in flood frequency analysis (FFA) is rainfall-runoff (RR) modelling. Its use in FFA often confronts the problem of how to correctly calibrate RR models to extreme flows. Since FFA only deals with extreme flows, traditional calibration techniques using simple objective functions such as the Nash-Sutcliffe model's efficiency criterion are not sufficient. In this paper we have focused on proposing alternative approaches for calibration techniques of RR models in order to enhance the description of extreme flows. We have selected the HBV type conceptual, lumped model HRON as an RR model. We have suggested two alternative calibration approaches: 1) the use of a new optimization function that compares only values higher than the 95th percentile of observed flows and 2) using two sets of parameters to separately simulate low and high flows. Each of these improvements has enhanced the simulation of extreme flows, which has been demonstrated in the empirical cumulative distribution function calculated for the simulated and observed annual maximum series of flows. The results of this paper show that improvement can be obtained by both approaches, which give good agreement between observed and simulated extreme flows, while preserving a good simulation of low and medium flows.

rainfall-runoff model / calibration / annual maximum series of flows / flood frequency analysis

Kivonat – Gyakoriság-tartóssági vizsgálatra használt csapadék lefolyási modellek kalibrációjának alternatív megközelítései. Az árhullámok gyakoriság-tartóssági vizsgálatára (FFA) a napjainkban használt eszközök egyike a csapadék-lefolyás (RR) modellezés. Ennek használata során gyakran kerülünk szembe avval a problémával, hogy hogyan tudjuk korrekt módon kalibrálni a RR modelleket az extrém vízhozamokra. Mivel az FFA csak az extrém vízhozamokra koncentrál az olyan egyszerű, objektív függvényekkel dolgozó, klasszikus kalibrációs módszerek, mint a Nash-Sutcliffe féle kritérium nem megfelelőek. Jelen tanulmány alternatív megközelítéseket javasol a RR modellek kalibrálására, abból a célból, hogy az extrém vízhozamok elemzését javítsa. A vizsgálatra a HBV típusú koncepcionális, koncentrált paraméterű HRON modellt, mint RR modellt választottuk ki. Két alternatív kalibrációs megközelítést javasoltunk: 1) új optimalizációs függvény használata, amely csak a vizsgált vízhozamok 95. percentilisénél nagyobb értékeket hasonlítja össze és 2) két paraméter készlet használata külön a kis és a nagy vízhozamok szimulációjára. Mindkét új fejlesztési megközelítés javítja az extrém vízhozamok szimulációját, a fejlesztések hatását a szimulált és mért eves maximális vízhozam idősorok empirikus tartóssági görbéinek segítségével mutatjuk be. A tanulmány szerint mindkét megközelítés javulást eredményezhet, amely a vizsgált és szimulált extrém vízhozamok közötti jó egyezéssel igazolható, az alacsony és közepes vízhozamok tartományában való jó szimuláció megtartása mellett.

csapadék lefolyás modell / modellillesztés / évi maximális vízhozam idősorok/ gyakoriság-tartósság vizsgálat

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1 INTRODUCTION

In derived flood frequency analysis (FFA), rainfall-runoff (RR) models are commonly used to continually simulate runoff from a catchment. One of the strongest motivations for the use of RR models in FFA is that, together with stochastic rainfall models, they enable the easy simulation of arbitrarily long series of river flows containing unobserved combinations of extreme values. Such a long series of river flows can be subsequently used to extract various flood characteristics such as peak flow, flood volume or flood duration. One of the advantages of continuous simulation compared to event-based RR models is that these models can also simulate different variables representing the state of the catchment (e.g., soil moisture, evapotranspiration, the amount of water in any snow cover). This enables avoiding the making of estimates about the initial conditions of the catchment's state (see, e.g., Lamb 1999, Boughton – Droop 2003, Hoes – Nelen 2005, Pathiraja et al. 2012). However, the greatest advantage of a continuous simulation is that it can be linked with stochastic weather generators, which enable the generation of various inputs (most often, rainfall amounts and temperatures) of arbitrary lengths. Weather generators preserve the statistical characteristics of observed time series of input variables (see, e.g., Racsko et al. 1991, Chen et al. 2010, Výleta 2013). The RR model can then transform the generated weather data into a time series of generated catchment runoff. Despite the fact that the generated time series preserves the statistical characteristics of the observed time series, they can contain rare combinations of subsequent rainfall events that only occur with a very small degree of probability, thereby causing extreme floods, which are not present in the observed time series of the catchment runoff (Valent 2012a).

In the FFA, which is often used for the estimation of design floods, annual maximum (AM) series of flows or flows above a certain threshold (POT) are used in practise. Therefore, the RR model must be mainly able to satisfactorily simulate extremely high flows. This can be achieved by calibrating the RR model for extreme flows while the proper simulation of low and medium flows is neglected. However, this solution is not suitable, since it does not enable a good simulation of the catchment conditions preceding the flood event. Despite considerable efforts in this area, there is not a united methodology for calibrating RR models to extreme flows. The literature contains several studies dealing with this problem (see, e.g., Paquet et al. 2013, Viney et al. 2009, Tan et al. 2005, Lamb 1999).

This paper presents two new approaches to the calibration of RR models to extreme floods and compares them with traditionally used techniques utilizing the Nash-Sutcliffe criterion. In order to increase the credibility of the presented results, the methodology has been applied to two mountainous catchments situated in the central part of Slovakia (*Figure 1*). The approaches are tested on two nested Slovak mountainous catchments: 1) the Hron at Banská Bystrica (BB) and 2) the Hron at Brezno.

2 DATA

The first catchment is a catchment of the River Hron with an outlet at the Banská Bystrica station. The catchment drains an area of 1768.2 km^2 and flows in a relatively narrow valley with high mountains on each side. The mean altitude of the catchment is 845.1 mASL with the highest peak at 2030.1 mASL. The average annual precipitation amount calculated for the period between 1961 and 2010 from the area precipitation was 846 mm. A high percentage of the catchment is a national park and is covered with coniferous and deciduous forests. The regime of the catchment runoff has a strong seasonal effect with the highest flows in April and the lowest in the winter. The mean annual runoff calculated for the period between 1961 and 2010 is 25.1 m^3/s (447 mm) with minimum and maximum values of 4.9 and 515 m^3/s respectively. The flow data were collected for the period between 1.1.1961 and 31.12.2010.

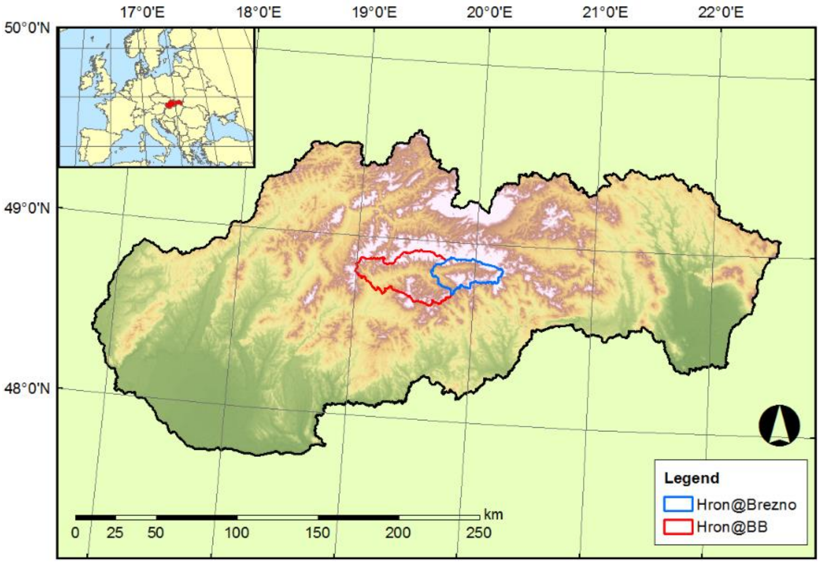


Figure 1. Position of the two catchments:
the Hron at Brezno and the Hron at Banská Bystrica in Slovakia (b)

a)

b)

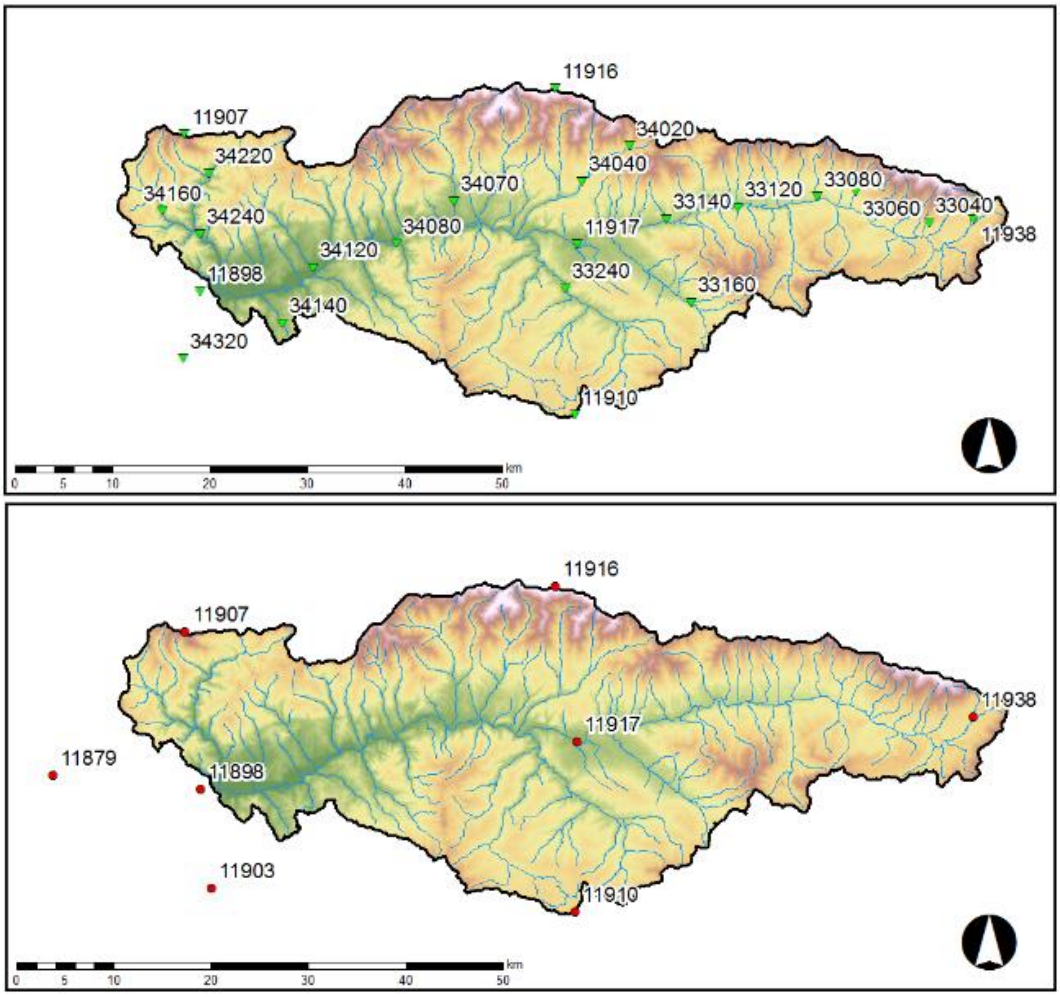


Figure 2. Location of measurement stations in the Hron catchment with the outlet at Banska Bystrica a) 24 rain gauges, b) 7 climatic stations measuring temperatures

The precipitation data were collected from 24 stations (*Figure 2a*) and processed using the inverse distance weighting interpolation method to obtain the catchment's average daily precipitation amounts. The temperature data were collected from 7 climatic stations (*Figure 2b*) and processed using the temperature gradient method to obtain an average daily air temperature for the catchment.

The second catchment is a nested catchment of the River Hron with an outlet at the Brezno station. The catchment drains an area of 578.6 km^2 and is situated in the upper part of the Hron catchment. The mean altitude of the catchment is 916 mASL with the highest peak of Kráľová Hoľa at an altitude of 1946 mASL. The mean annual precipitation amount calculated for the period between 1961 and 2010 from the area precipitation was 830 mm. The flow regime of the catchment is identical to the regime of the first catchment with the highest flows in April and the lowest in January. The mean annual runoff calculated for the period between 1961 and 2010 is 7.6 m^3/s (414 mm) with minimum and maximum values of 1.2 and 178 m^3/s respectively. The flows here were also collected for the period between 1.1.1961 and 31.12.2010.

a)

b)

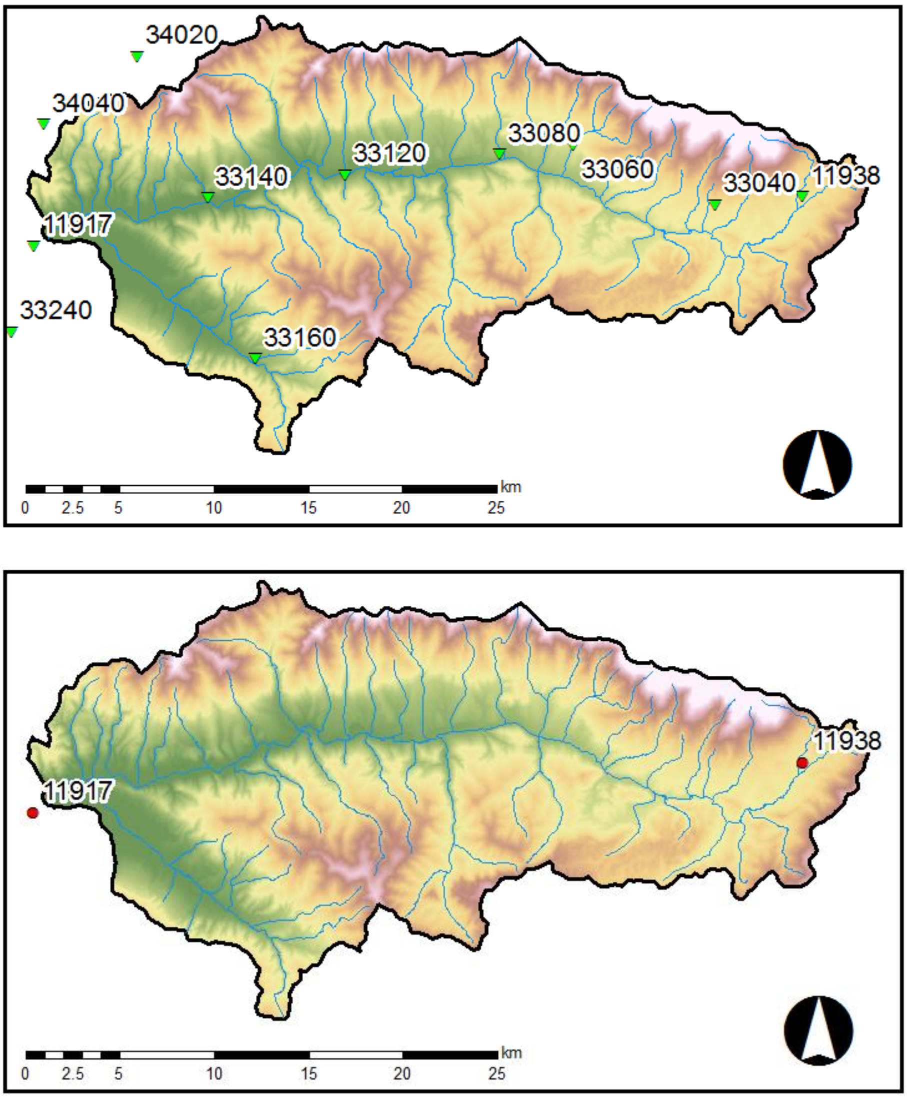


Figure 3. Location of measurement stations in the Hron catchment with the outlet at Brezno a) 11 rain gauges, b) 2 climatic stations measuring temperatures

The precipitation data were collected from 11 stations (*Figure 3a*) and processed in the same way as for the first catchment. The temperature data were collected from 2 climatic stations (*Figure 3b*) and processed using the temperature gradient method to obtain an average temperature for the catchment.

3 METHODOLOGY

This work is focused on the improvement of the calibration procedure of the HRON rainfall-runoff model to better simulate extreme flows. The HRON model is a conceptual lumped model, which works mainly in a daily time-step. It was developed at the Department of Land and Water Resources Management of the Slovak University of Technology and is based on the Swedish HBV model (Bergstrom 1976). The model comprises 3 submodels, each of which represents a different runoff generation process (for the scheme of the model, see *Figure 4*). The model has 14 parameters, which were calibrated using a harmony search algorithm (see, e.g., Valent 2012b or Geem 2009).

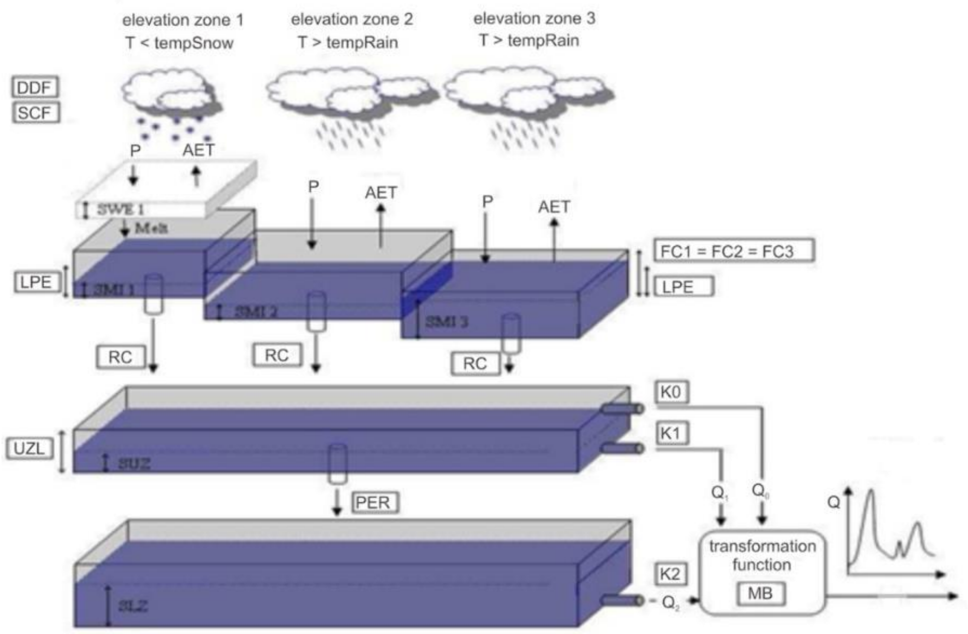


Figure 4. Scheme of the HRON rainfall-runoff model (Valent et al. 2011)

The paper compares the traditionally used calibration technique, utilizing a Nash-Sutcliffe (NS) criterion as the objective function (1) (Nash – Sutcliffe 1970), with two new approaches focused on the calibration to extreme flows. The NS criterion can be written as:

$$NS = 1 - \frac{\sum_{i=1}^{n}\left(Q_{sim,i} - Q_{obs,i}\right)^2}{\sum_{i=1}^{n}\left(Q_{sim,i} - \bar{Q}_{obs}\right)^2} \tag{1}$$

where $Q_{obs,i}$ and $Q_{sim,i}$ are observed and simulated flows in day i and $\bar{Q}_{obs}$ is the average observed flow.

The first approach is based on the selection of a different objective function. In order to improve the simulation of extreme flows, a new objective function has been proposed. The new objective function takes into account only values that are higher than the 95th percentile of the flows observed. The proposed objective function can be written as

$$f(x) = \frac{\left(Q_{obs,p95} - Q_{sim,p95}\right)^2}{\left(Q_{obs,p95} - Q_{p95}\right)^2} \tag{2}$$

where $Q_{obs,p95}$ are all the observed flows that are higher than the 95th percentile calculated from the observed flows; $Q_{sim,p95}$ are simulated flows corresponding to the $Q_{obs,p95}$, and Q_{p95} is the value of the 95th percentile of the flows observed.

The second approach is based on separate simulations of low and high flows. In this approach the HRON RR model utilizes two sets of parameters (the regime switching version of the model). The first set of parameters was used to simulate low flows and was obtained through a traditionally used calibration technique utilizing the NS coefficient (1). The second set of parameters was used to simulate high flows and was estimated by calibrating the model only to the annual maximum floods, where each flood is comprised of the flood peak and two days surrounding it (flood peak ± 2 days). In order to focus the optimization algorithm on the very extreme flows, an optimization function minimizing the NS criterion for both time and rank-ordered flows was used. The function can be written as

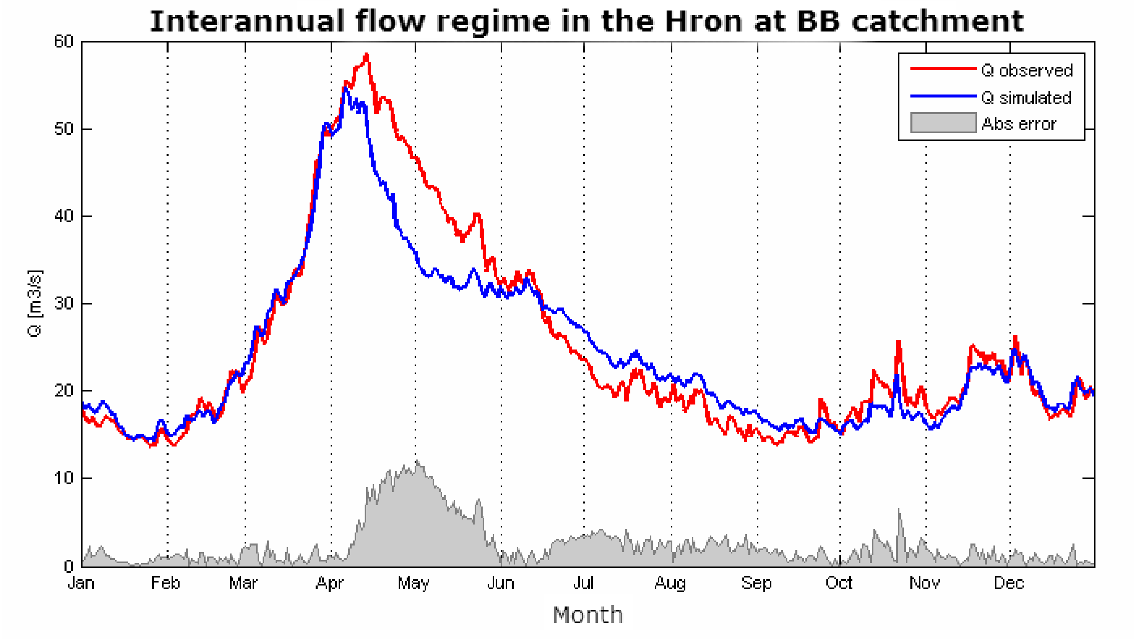
$$f(x) = NS\left(Q_{T,ord}\right) + w \cdot NS\left(Q_{R,ord}\right) \tag{3}$$

where $NS\left(Q_{T,ord}\right)$ and $NS\left(Q_{R,ord}\right)$ are Nash-Sutcliffe criteria calculated for time and rank-ordered flows, and w is a weight (with a value of 2 in this case), which gives the balance between the time (calibration to low and medium flows) and rank-ordered (calibration to high flows) NS criteria (Paquet et al. 2013). Both of the parameter sets were then combined into the switching version of the HRON RR model. The decision as to whether the current flow is considered low or high is taken based on the threshold value of the simulated flow from the previous day (the first flow is calculated as low). The threshold for determining whether the flow is low or high was also calibrated for each catchment individually.

4 RESULTS

In the first step the HRON RR model was calibrated by the traditional approach using the NS criterion as an objective function. In both cases the model was calibrated for the whole period between 1961 and 2010. The overall quality of the simulation was assessed by calculating the NS criterion values (0.744 for the Hron at BB and 0.780 for the Hron at Brezno) and by comparing the observed and simulated interannual flow regimes *(Figure 5).* The quality of the simulation of the extreme flows was assessed by comparing the empirical cumulative distribution functions (ECDF), which were calculated for the observed and simulated series of the annual maximum (AM) flows (*Figure 6*). *Figure 6* shows that both models underestimate extreme flows, which is not acceptable in the FFA. The main reason for this is the NS criterion, which takes into account the flows (low and medium ones) which are the most frequent and thus have the largest impact on the NS value.

a)



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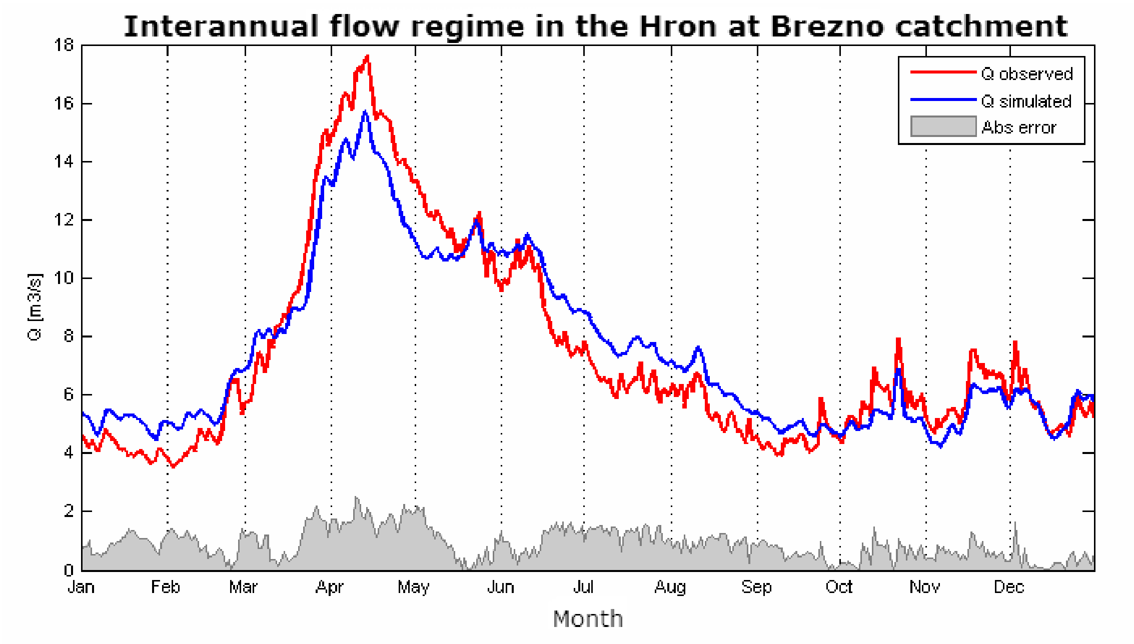
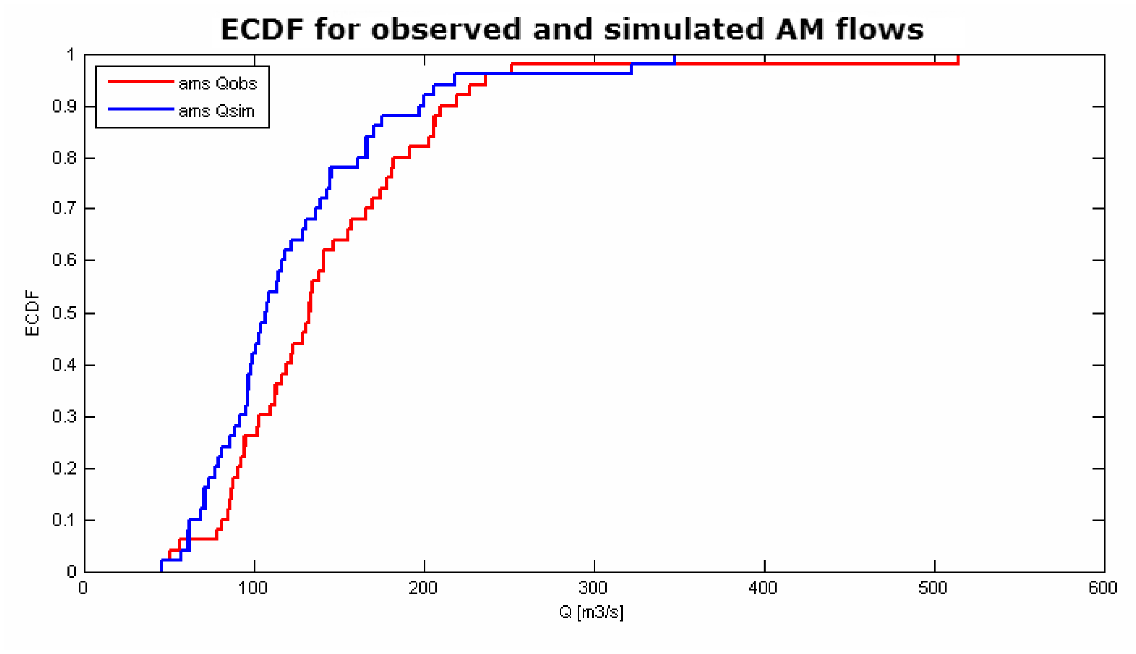


Figure 5. Comparison of observed and simulated interannual flow regimes for the Hron catchments at BB (a) and at Brezno (b). Calculated by the HRON model using the NS criterion (1) as an objective function

a)



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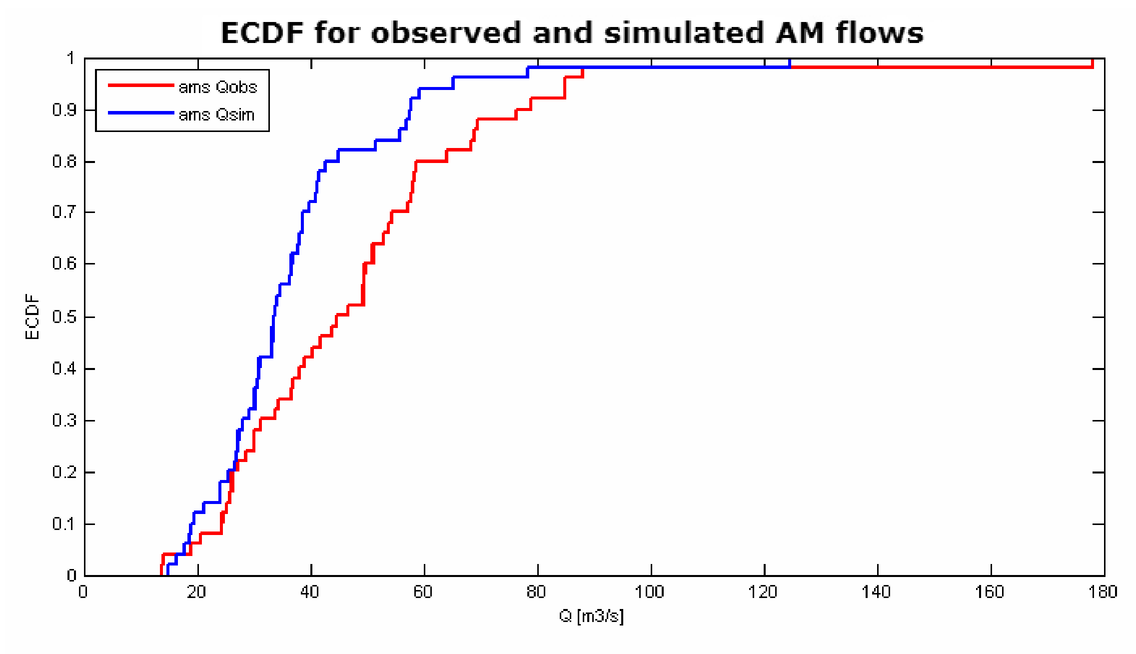
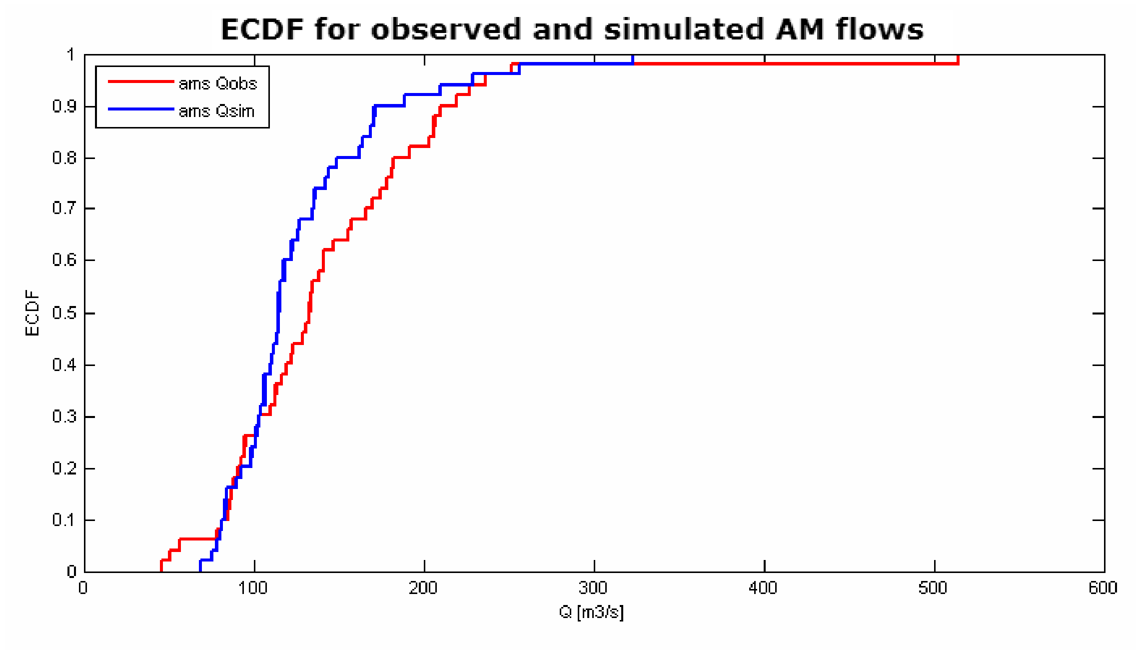


Figure 6. Comparison of the ECDF calculated for the observed and simulated AM flows for the Hron at BB (a) and the Hron at Brezno (b). Calculated by the HRON model using the NS criterion (1) as an objective function

In the next step a new optimization function has been used to improve the simulation of extreme flows. The use of the proposed optimization function (2) had a positive effect on the simulation of extreme flows, especially in the case of the Hron catchment at Brezno (*Figure 7b*). However, the calibration of the model to the values higher than the 95^{th} percentile of the observed flows resulted in the model not being able to reproduce the low and medium flows (*Figure 8*); thus its application is very limited to FFA, when it does not enable correct the simulation of conditions preceding flood events.

a)



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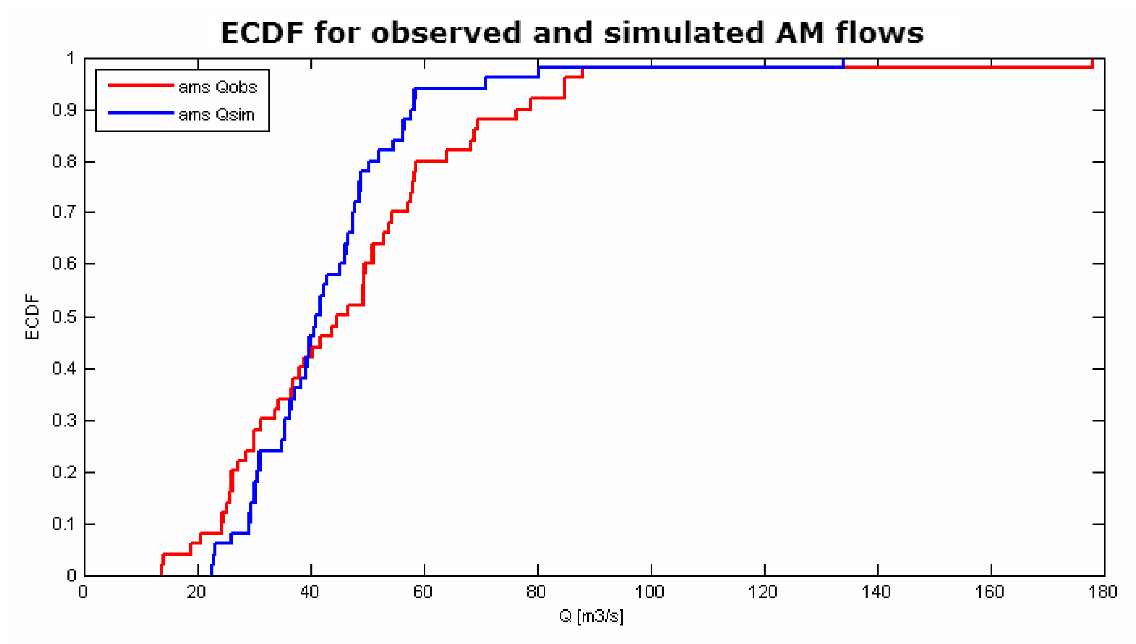


Figure 7. Comparison of the ECDF calculated for the observed and simulated AM flows for the Hron at BB (a) and the Hron at Brezno (b). Calculated by the HRON model using the objective function, which compared only the values higher than the 95th percentile of the observed flows (2)

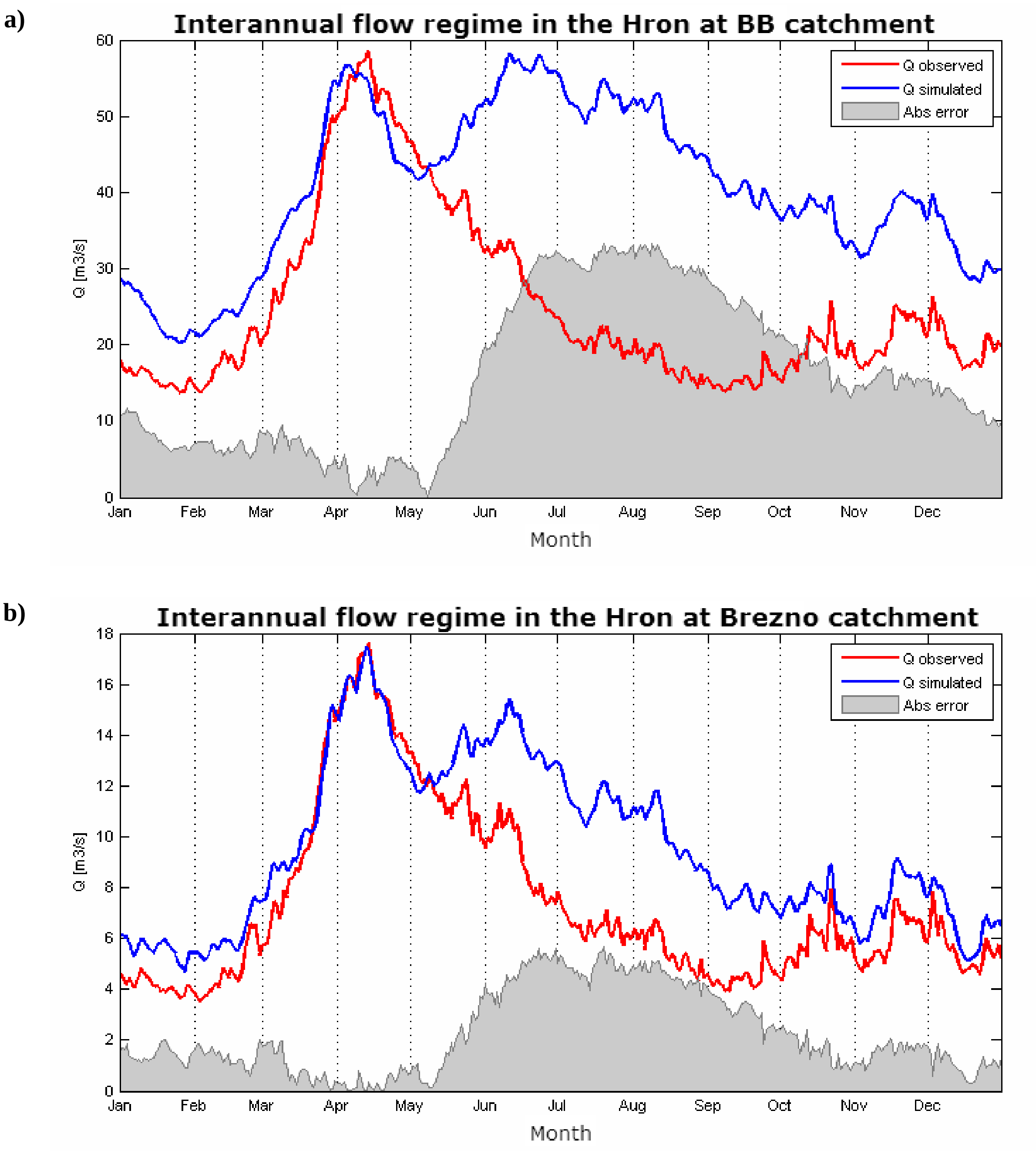
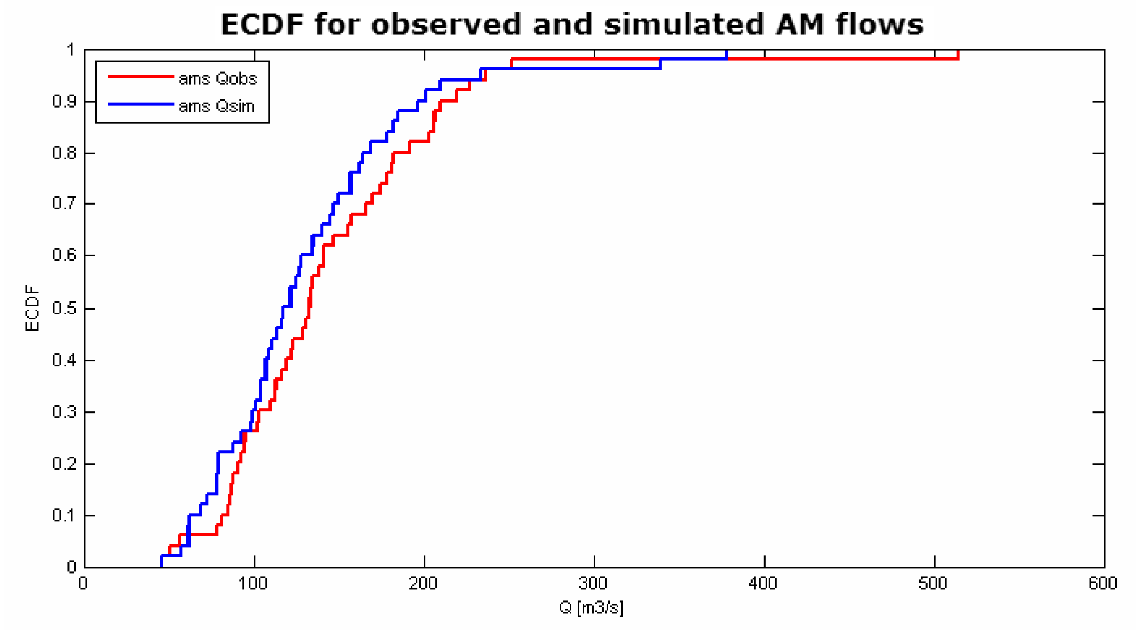


Figure 8. Comparison of the observed and simulated interannual flow regimes for the Hron catchments at BB (a) and at Brezno (b). Calculated by the switching version of the HRON model using the objective function, which compared only the values higher than the 95th percentile of the observed flows (2)

The second approach focuses on improving the simulation of extreme flows while maintaining the good simulation of low and medium flows. It utilizes two sets of parameters to separately simulate low and high flows. The threshold determining whether the flow is low or high was calibrated and was set to be 70.25 and 20.78 m^3/s for the Hron at BB and the Hron at Brezno, respectively. By using separate simulations of the low and high flows, a significant improvement of the simulation of the extreme flows has been observed (*Figure 9*), while preserving the good simulation of the low and medium flows (*Figure 10*).

a)



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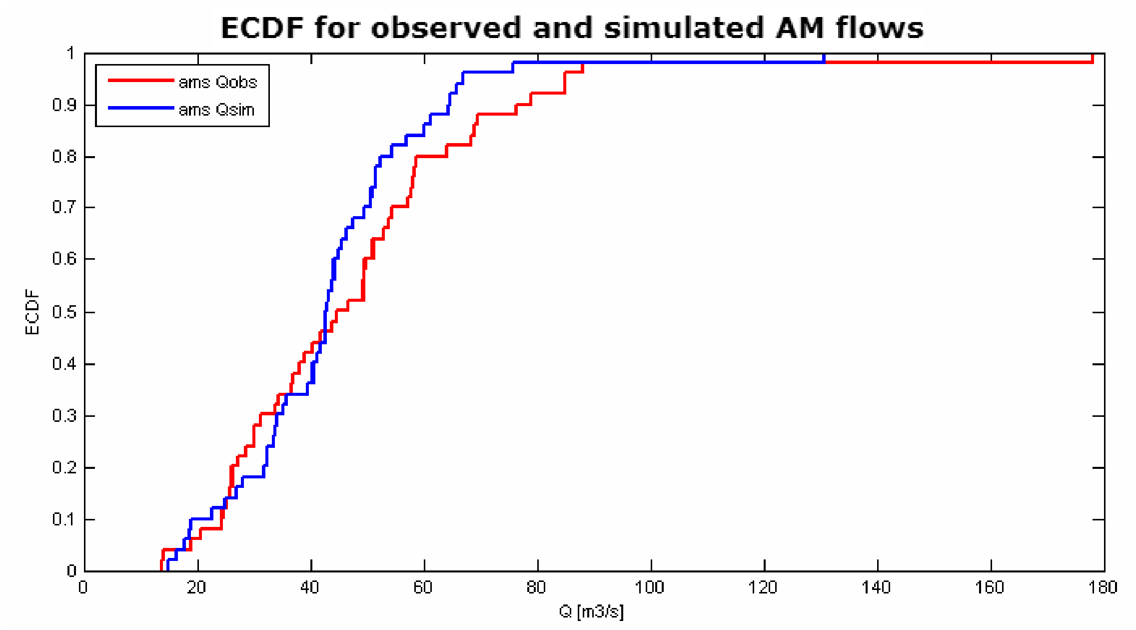
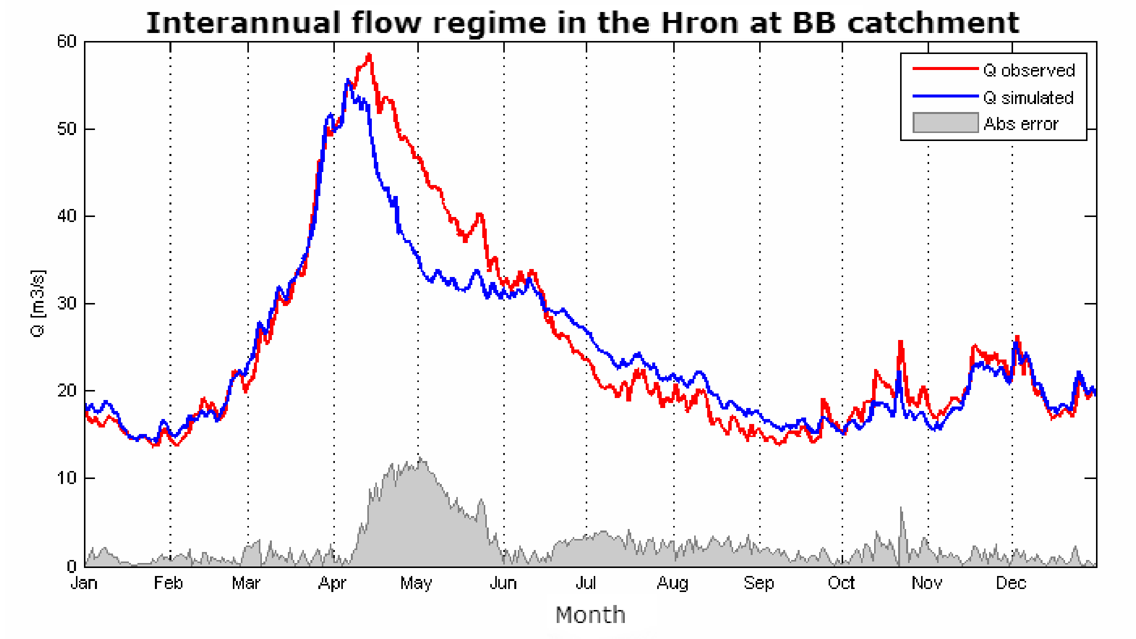


Figure 9. Comparison of the ECDF calculated for the observed and simulated AM flows for the Hron at BB (a) and the Hron at Brezno (b). Calculated by the switching version of the HRON model using the objective function (2) to calibrate parameters for the low flows and (3) for the high flows

a)



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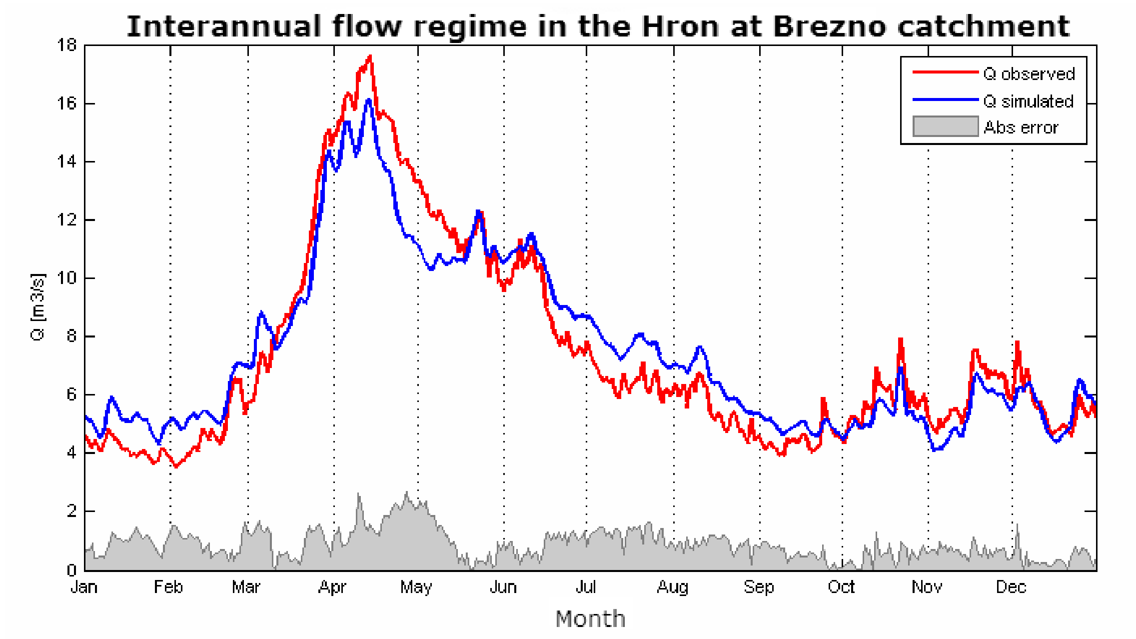

Figure 10. Comparison of the observed and simulated interannual flow regimes for the Hron catchments at BB (a) and at Brezno (b). Calculated by the switching version of the HRON model using the objective function (2) to calibrate parameters for the low flows and (3) for the high flows

5 SUMMARY AND CONCLUSIONS

The main objective of this paper was to improve the traditionally used calibration techniques of the RR models for use in FFA. Traditional approaches for the calibration of RR models are known for not being able to satisfactorily simulate extreme flows, which is caused by using optimization functions such as the Nash-Sutcliffe criterion or mean squared error. The correct simulation of extreme flows is vital in FFA, since only the most extreme flows are used in the analysis (annual maximum series or peaks over threshold).

In the first case study of the paper a traditionally used method for calibrating an RR model was used. The method utilized a NS criterion as an objective function and, for both catchments, it proved to be good in maintaining the overall flow regime (*Figure 5*). The quality of the simulation of extreme flows was assessed by comparing the ECDFs calculated for both the observed and simulated AM flows (*Figure 6*). They proved that the simulation of extreme flows was unsatisfactory and that its use in the FFA is not recommended.

In the next part an alternative approach for calibrating RR models to extreme flows was proposed. The approach utilizes a new objective function, which compares only values higher than the 95th percentile of the observed flows. The improvement of the simulation of the extreme flows was at the expense of the simulation of the low and medium flows. This makes this approach virtually unusable for tasks such as determining flood volumes or durations.

The second approach was comprised of separate simulations of the low and high flows. The low flows were simulated using the same set of parameters calibrated using the traditional approach, while the high flows were simulated using the parameters calibrated to the annual maximum floods (peak ± 2 days) and an objective function minimizing the NS criterion for both the time and rank-ordered flows. The thresholds determining whether a flow is low or high were estimated for each catchment and were set at 70.25 and 20.78 m^3/s for the Hron at BB and the Hron at Brezno, respectively. Using this approach the best simulation of the extreme flows was observed (*Figure 9*), while preserving a good simulation of the low and medium flows (*Figure 10*).

The results of this work show that further work in the calibration of RR models for the needs of FFA should focus not only on the development of new objective functions, but also on investigating the effects and possibilities of using RR models with multiple regimes.

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