

AKADÉMIAI KIADÓ

Pollack Periodica •
An International Journal
for Engineering and
Information Sciences

18 (2023) 2, 72–77

DOI:

[10.1556/606.2023.00538](https://doi.org/10.1556/606.2023.00538)

© 2023 Akadémiai Kiadó, Budapest

ORIGINAL RESEARCH
PAPER



*Corresponding author.

E-mail: viera.rattayova@stuba.sk,
rattayovaviera@gmail.com



AKJournals

Base flow separation method in conditions of the karst catchment

Viera Rattayová*  and Kamila Hlavčová

Department of Land and Water Resources Management, Faculty of Civil Engineering, Slovak
University of Technology, Bratislava, Slovakia

Received: December 20, 2021 • Revised manuscript received: January 27, 2023 • Accepted: March 18, 2023

Published online: April 26, 2023

ABSTRACT

Geological conditions are an important parameter on hydrological modeling that strongly affects runoff generation processes. They are not usually taken into account in the parameters of hydrological models, especially karst catchments, where water transfers through fissures, cavities, caves, and phreatic channels are regularly discarded in studies because of their nonlinear behavior and the variability of their typology. The study compared using of base flow separation methods in the conditions of karst catchments, where the reference base flow values measured are not available. The base flow separation was realized by various methods and the models available, including BFI+ and WHAT

KEYWORDS

base flow separation, Eckhardt recursive digital filter, parameter sensitivity, karst conditions

1. INTRODUCTION

Estimating base flow has an essential role in many hydrology and water engineering issues [1]. The shape, volume, and maximum base flow discharge is the function of a watershed's response to rainfall. The estimation of base flow discharges is necessary for the most accurate description of the characteristics of flood waves (like volume and shape of flood waves), but it is also necessary for the management of water sources in low flow conditions. For hydrological modeling on the watershed is the Base Flow Index (BFI) very important parameter tied to the base flow. It is the portion of water between the long-term base flow and the total long-term discharge. This ratio indirectly describes the amount of water transformed into direct runoff, the target of many hydrological studies.

The primary assumption of accurate base flow modeling is the linear groundwater flow. Considering, that karst aquifers are characteristics to have a non-uniform porosity caused by the karstification process, the consequences of what the nature of the sub-terrain flow in karst aquifers is also not uniform [2]. The underground karst flow can be divided into two mainstream types i.e., conduit flow and diffuse flow [3], but between the two main types of underground flow the conjunctive flow, which is also called the fissure flow [4] exists. Diffuse flow infiltrates through the soil and the fracture and matrix permeability and is characterized by a slow and laminar flow [5]. This diffuse flow is a very important source of water for the karst springs in dry seasons [6].

The complexity of character of the underground flow in a karst watershed is the main reason why the results from the base flow separation method are not capable of credibly describing the real situation in a basin. It is necessary to find a useable method for this type of issue for water management needs. According to Hartmann et al. [7], karst aquifers can be highly influenced by anthropogenic stress (changes in land use and land cover) and changes in meteorological characteristics consequence of climate change. The changes in the rainfall intensities will significantly impact the runoff [8]; it is essential to estimate the possible impact of climate change on water resources and propose some strategic measures [9], especially for drought conditions.

Base flow separation methods were used in many studies to estimate the accuracy of the methods [10–13] and showed the changes in base flow. Results from Shao et al. [10] showed that the base flow separation methods underestimated the baseflow compared to the tracer-based method results. Tenalem et al. [14] used the program HYSEP and available methods for the separation of base flow in seven river gauging stations. His results show that the HYSEP method overestimates base flow in all watersheds. Although it is complicated and inaccurate to estimate base flow in the conditions of a karst catchment with standard methods, it is necessary in some water management projects. The article compares the results from many available and worldwide used base flow separation methods and tries to find the best methods for condition, where continuous conductivity method measurements are not available.

2. METHODS

It is very important to find a suitable model for hydrological modeling in a karst catchment. Standard hydrological models were not constructed for this type of watershed geology, because it is not possible for them to describe the nonlinear flow that occurs in a karst underground. The groundwater flow in subterranean rivers and caves can be turbulent, which significantly complicates base flow estimates. In this research, results from five commonly used base-flow separation methods were compared:

- Base flow separation in the Bilan model;
- Graphic methods;
 - Local minimum method;
 - Fixed interval method;
- Lyne and Hollick digital recursive filter;
- Eckhardt recursive digital filter.

2.1. Graphic methods for base-flow separation

Graphic methods are simple methods for determining base flow separation, based on finding the minimum of stream flow at selected intervals. The main difference between the methods is in identifying the minimum discharge and interval characteristics.

A stream-flow hydrograph is divided into non-intersecting intervals, and the minimum discharge is identified at every interval in the fixed interval method. The length of the interval is calculated according to Eq. (1):

$$N = 0.84 \cdot A^{0.2}, \quad (1)$$

where N is the duration of quick flow; and A is the watershed area (km^2).

The local minimum method uses interval blocks with the fixed length where a local minimum is checked while the lower position of the block slides to the next day. After this process, the points with the local minima values are connected with a straight line.

2.2. Digital recursive filters

Digital recursive filters are the most methods used for the separation of base flow from the measured data. These methods are based on the assumption that long waves are associated more with base flow and that the variability of a more frequent stream flow is caused by direct runoff. This is the reason why is it possible to identify the base flow by low-pass filtering [11]. Two methods were used for research that is preferred by many authors, i.e., the two parameters Eckhardt filter and the one-parameter Lyne and Hollick filters.

2.3. Line and Hollick digital filter

The one-parameter digital filter, which was constructed by Lyne and Hollick [15] is based on the assumption that the storage of the aquifer is linearly proportional with the outflow from the aquifer [11]. Lyne and Hollick proposed the base flow filter equation:

$$f_k = af_{k-1} + \frac{1+a}{2}(y_k - y_{k-1}), \quad (2)$$

where a is the filter parameter. The problem with this filter is in the attenuation of the waves in filtering, because in this method, the $BFI_{\max}$ must be less than 1. The value range of α parameter suggested by the author's equation is from 0.7 to 0.9 [15]. The theoretical framework of the one-parameter filter has been used by many other authors [16–20] and reworked using the various constant values of $BFI_{\max}$. For example, the Chapman and Maxwell [21] used the value of $BFI_{\max} = 0.5$ in their research and the research clearly shows that the one-parameter algorithm can only successfully work, when operate with the restriction that the modeled base flow can never exceed the stream flow (even in the case of a low flow). Although the one-parameter filter uses only the one input parameter α , it has to be seen as a two-parameter filter [11], because the second $BFI_{\max}$ parameter is incorporated hidden in the base equation.

This algorithm separates the runoff signal q_k according to the equation for filtering quick response q_k :

$$q_k = \alpha q_{k-1} + \frac{(1+\alpha)}{2}(h_k - k_{k-1}), q_k \geq 0, \quad (3)$$

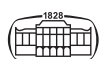
where h is the total stream flow measured; k is the time index; and the α is the filter parameter. The value of the filter parameter α is optionally between 0.90–0.95, but the most recommended value, according to many authors [21, 22] is 0.925.

2.4. Eckhardt's digital recursive filter

Eckhardt's digital recursive filter is widely applied because of its clear physical basis and easy operation [23]. Eckhardt [11] demonstrates that most of the previously published digital filters [18, 19] are based on the equation:

$$b_i = a \cdot b_{i-1} + B \cdot y_i, \quad (4)$$

where y is the total stream flow; b is base flow; i is the time step; and A and B are the filter parameters (a and $BFI_{\max}$),



restricted to $b_i < y_i$. These two parameters are related to the flow recession (α parameter) and the watershed response to rainfall ($BFI_{\max}$). Eckhardt [11] revised this basic equation with the incorporation of his input parameters to the following form:

$$q_{b(i)} = \frac{3\alpha - 1}{3 - \alpha} q_{f(i)} + \frac{2}{3 - \alpha} (q_{(i)} - \alpha q_{(1-i)}). \quad (5)$$

The maximum base flow index ($BFI_{\max}$) describes the response of a watershed to rainfall. The value of $BFI_{\max}$ is a function of watershed's characteristics, especially the hydrogeological characteristics, which can be very complex and variable.

The Eckhardt derived the values of $BFI_{\max}$ according to the hydrogeological characteristics of a watershed:

- For perennial streams with a porous aquifer 0.80;
- For ephemeral streams with a porous aquifer 0.50;
- For perennial streams with a hard rock aquifer 0.25.

However, it is very difficult in some cases to estimate the value of the $BFI_{\max}$ parameter because of the complexity of watershed's geology. Smakhtin [23] mentions that the amount between a 50-day and 90-day discharge can be interpreted as an index representing the portion of groundwater stream flow storage in a total discharge, excluding the effects of the catchment area. Collischonn and Fan [24] proposed using this ratio to estimate the base flow index. Using the daily stream-flow data from 15 gauging stations, they proposed an equation for the $BFI_{\max}$ estimating:

$$BFI_{\max} = 0.8344 \frac{Q_{90}}{Q_{50}} + 0.2146. \quad (6)$$

The results of Collischonn and Fan [23] show that the $BFI_{\max}$ values estimated by the proposed method well correlate with the $BFI_{\max}$ values predefined by Eckhardt [11].

It is possible to obtain parameter α from the observed stream flow data like value equal to recession constant. Parameter α describes the characteristics of the recession behavior of the watershed. Parameter α can be determined by two main procedures i.e., by the master recession curve and by performing separate calculations of the parameter of the individual recession segments [25]. Master recession curve was used to calculate this parameter. In the first step, the length of the duration of the recession must be determined by the histogram of the duration of the flood wave recession. The characteristics length of the duration of recession was selected as a value, where the frequency of the length of the recession on the histogram has a marked reduction. The correlation was constructed between the stream-flows Q_i and Q_{i-1} for the recession belonging to the estimated length of recession duration. The resulting value of parameter α is recession constant equal to the slope of a regression line determined using the correlation method.

3. DESCRIPTION OF THE STUDY AREA

The case study was realized on a small watershed situated in Little Carpathians, up to the Horne Oresany hydrological

measuring station on the Parna Stream. The Parna stream has a multi-branched structure in this basin with many small tributaries.

According to the hydrogeological maps, the watershed has predominantly mixed karst and fracture permeability with inter-grain permeability in the northern part [26, 27]. The area of the watershed is 42 km². The watershed has mostly forested land cover with small areas of dispersed settlements. The input data consists of a 24-years long time series of daily discharges from the Horne Oresany water gauge, and the daily precipitation and mean daily temperature from the nearest climatic station - Dolne Oresany. The difference in altitude is 468 m, while the highest point of the watershed is 700 m.a.s.l. The maximum discharges from the Parna are concentrated in the spring season. The maximum measured discharge was 0.999 m³ s⁻¹, the minimum discharge 0.002 m³ s⁻¹ with a median value of 0.175 m³ s⁻¹.

This watershed was selected despite its karst character, because it is located above to the Horne Oresany water dam. The results from the base flow separation from this watershed was necessary for designing the control flood waves characteristics, which are important for assessing of the water structure.

4. RESULTS

The BFI + program was used to calculate the base flow with the selected filtering methods. The input data necessary for the hydrograph analysis are the daily discharge data. The input parameters for selected methods were set at:

- for local minimum method $F = 0.9$, $N = 2$;
- for fixed interval method $N = 2$.

The daily time series was processed by the program to the base flow values, and the base flow index was calculated. The graphic methods do not provide the smooth behavior of the separated base flow. While the local minimum method does not react to any changes in the total discharge all the stream flow changes are identifiable, including small changes, in the results of the fixed interval method (Fig. 1).

The base flow estimated by the Lyne and Hollick one-parameter digital filter was processed in the Web-based Hydrograph Analysis Tool (WHAT). The value of the input parameter α was selected as 0.925, which is the predefined value in the tool and this value is recommended by many authors (like the ones mentioned above).

The results show that the filter reacts sharply to changes in the discharge. Every increase in the stream flow discharge appears on the base flow discharge; the filtered base flow represents the expected behavior of the base flow in the low flows.

For estimating the base flow by the Eckhardt recursive digital filter, three alternative input parameters were used:

- The predefined value of parameter $\alpha = 0.98$ and the alternatives of the $BFI_{\max}$ value;



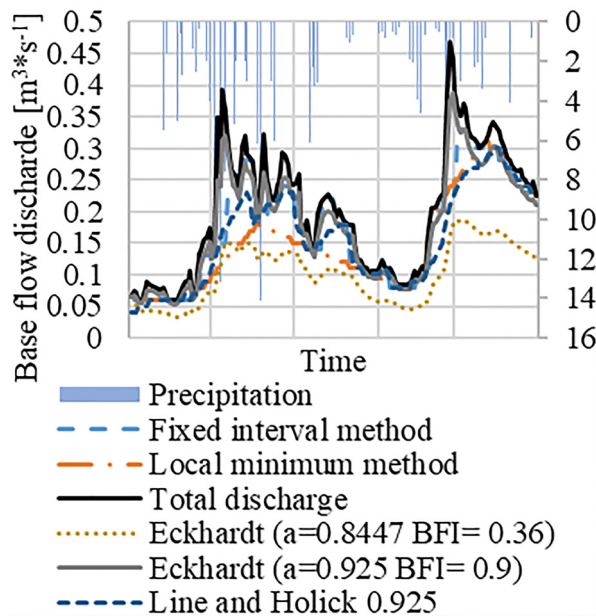


Fig. 1. Base-flow separated from total discharge by two graphic base flow separation methods

- The calculated value of parameter $\alpha = 0.8447$ and the estimated value of $BFI_{\max} = 0.518$;
- The calculated value of parameter $\alpha = 0.8447$ and the alternatives of the $BFI_{\max}$ value.

For the first alternative of the input parameter, the range of $BFI_{\max}$ values 0.4–0.9 was applied. The expected behavior of the base flow in low flow conditions is that the base flow line will be very close or the same to the line of the total discharge. This assumption follows from the knowledge, that the main part (or the whole) of the stream flow in a longer lasting drought is composed of the base flow (the slow part of a runoff). The results from the first alternative show, that the separated base flow with the predefined parameter of α does not represent the expected manner of base flow and that the course of the base flow curves does not correspond with the total discharge in low flow conditions (Fig. 2).

In the next step the value of parameter α was calculated according to the approach mentioned in the methodology. A histogram of the recession duration was created, and the representative length of the duration was set at 4 days. The regression analysis was realized by applying the threshold level of the Q_{70} -predefined number in the “ifstat” R package, which was used for this analysis. The value of the maximum base flow index was estimated from the calculated values of the 50 and 90-day discharge with the value $BFI_{\max} = 0.518$. This estimated value is very close to the Eckhardt $BFI_{\max}$ for ephemeral streams with a porous aquifer (0.50), which absolutely do not correspond to the characteristics of watershed hydrogeology. The results from the base flow separation show a relatively smooth reaction to changes in the stream flow, but the course of the base flow is visibly mismatched to the expected course of the base flow in the low flow condition.

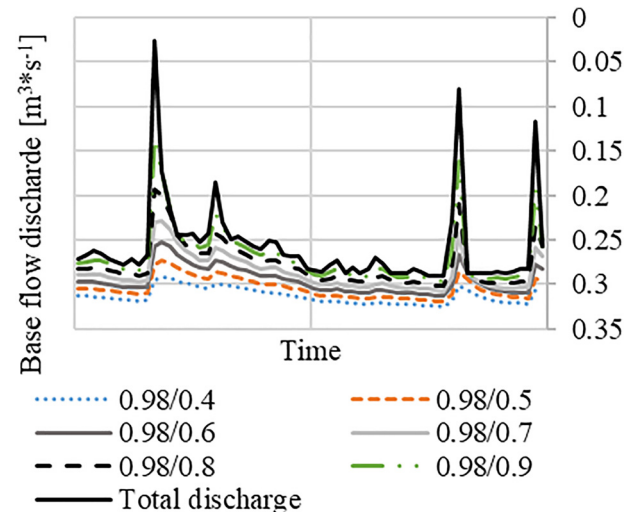


Fig. 2. Base-flow separated from total discharge by Eckhardt recursive filter, with using predefined input parameter $\alpha = 0.98$ and 6 alternatives of maximum base flow index (0.4–0.9)

The results from the separation process with the last alternative of the input parameters show that the best matched results of the base flow separation in the low flows are in the greatest values of $BFI_{\max}$. The base flow increased rapidly with the increased stream flow, and the line of the base flow recession very quickly started to correspond with the recession curve of the total discharge. The course of the base flow curve becomes smoother with the lower values of the $BFI_{\max}$ parameter.

The base flow indexes were provided from every output of the previous methods and then estimated by the BILAN water balance model (Fig. 3). Although there is no reference values of the base flow index for karst (from the method for

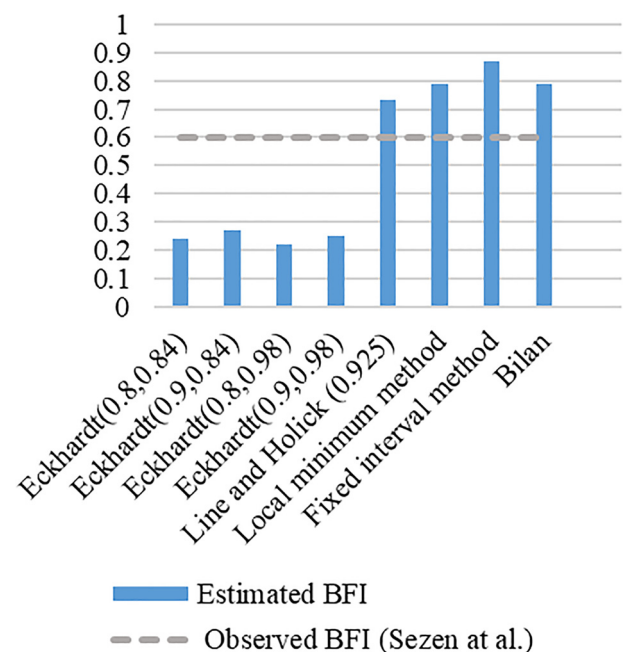
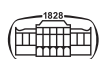


Fig. 3. Base flow indices estimated by selected methods



measuring conductivity), the results were compared with the results from karst aquifer in Slovenia [22]. This output was selected as a reference value according to the studied watershed's similar geological and climatic conditions. The results show that the value of BFI most corresponding with reference value was calculated by Line and Hollick, local minimum method, and Bilan model. The results of the base flow index from each alternative input parameter of the Eckhardt digital filters have very low values. These phenomena are caused by the lower values of the separated base flow compared with the total stream flow in the medium and low flow conditions.

5. CONCLUSION

The results from the base flow separation with Eckhardt's recursive filter confirm the assumption that the diffuse flow, which is part of the base flow behaves similarly to the base flow in other rocky and small permeable watersheds. The character of the flow of this portion of the base flow has a mostly linear character. It corresponds with the three setting values of BFI max parameter where the most porous and water collecting aquifer has the lowest value of BFI_{max} while the rocky aquifer, which are the lowest collectors of groundwater, has the highest value of BFI_{max} . It is still not possible to estimate the behavior of the conduit segment of the base flow because of its nonlinear character. The Lyne and Hollick one-parameter filter provide relatively smooth results for the separated base flow curve, the base flow values in the low flow condition are the close to total discharge values, and the base flow index value calculated with this method is relatively close to the reference value. These results need to be verified on more karst river basins, but they provide information about the complexity of choosing the most appropriate base flow separation method and about the importance of choosing proper input parameter values. The trends in base flow volume are expected to be influenced by climate change, mainly the consequence of changes in the precipitation amount; this assumption can be a task for the following research.

REFERENCES

- [1] M. Zhang, N. Liu, R. Harper, Q. Li, K. Liu, X. Wei, D. Ning, Y. Hou, and S. Liu, "A global review on hydrological responses to forest change across multiple spatial scales: Importance of scale, climate, forest type and hydrological regime," *J. Hydrol.*, vol. 546, pp. 44–59, 2017.
- [2] N. Goldscheider and D. Drew, Eds, *Methods in karst hydrogeology*. International contributions to hydrogeology, vol. 26, Taylor and Francis Group, 2014.
- [3] I. Douglas, F. Joly, M. Marcus, and B. Messerli, *Processes in Karst Systems, Physics, Chemistry, and Geology*, Springer, 1989.
- [4] O. Bonacci, "Regionalization in karst regions," in *Proceedings of the Ljubljana Symposium*, Ljubljana, Slovenia, April 5, 1990, pp. 135–145.
- [5] W. B. White, "Karst hydrology: Recent developments and open questions," *Eng. Geol.*, vol. 65, nos 2–3, pp. 85–105, 2002.
- [6] T. N. Adji, E. Haryono, H. Fatchurohman, and R. Oktama, "Diffuse flow characteristics and their relation to hydrochemistry conditions in the Petoyan Spring, Gunungsewu Karst, Java, Indonesia," *Geosci. J.*, vol. 20, no. 3, pp. 381–390, 2016.
- [7] A. Hartmann, Y. Liu, T. Olanoye, T. R. Berthelin, and V. Max, "Integrating field work and large-scale modeling to improve assessment of karst water resources," *Hydrogeol. J.*, vol. 29, pp. 315–329, 2021.
- [8] G. Foldes, S. Kohnová, M. M. Labat, and K. Hlavčová, "Predicted changes in short-term rainfall intensities and runoff at the Ipolitca River basin," *Pollack Period.*, vol. 15, no. 3, pp. 172–183, 2020.
- [9] M. Aleksić, P. Sleziać, and K. Hlavčová, "Parameterization of the rainfall-runoff model in changing climate," *Pollack Period.*, vol. 16, no. 3, pp. 64–69, 2021.
- [10] G. Shao, D. Zhang, Y. Guan, M. A. Sadat, and F. Huang, "Application of different separation methods to investigate the base-flow characteristics of a semi-arid sandy area, Northwestern China," *Water*, vol. 12, no. 2, 2020. Paper no. 434.
- [11] K. Eckhardt, "How to construct recursive digital filters for base-flow separation," *Hydrol. Process.*, vol. 19, no. 2, pp. 507–515, 2005.
- [12] T. Vasileva, T. Orehova, and K. Kroumova, "Groundwater contribution to the river flow for the upper course of the Osam River based on two base-flow separation methods," *Gelologica Balcanica*, vol. 46, no. 2, pp. 73–82, 2017.
- [13] S. R. H. Duki, S. M. Seyedian, H. Rouhani, and M. Farasati, "Evaluation of base flow separation methods for determining water extraction (Case study: Gorganroud River Basin)," *Water Harvesting Res.*, vol. 2, no. 2, pp. 54–70, 2017.
- [14] A. Tenalem, E. Assefa, and A. Tilahun, "Comparison of different base flow separation methods and drought vulnerability in a Rift Valley area," *J. Spat. Hydrol.*, vol. 15, no. 2, 2019. Paper no. 2.
- [15] V. D. Lyne and M. Hollick, "Stochastic time-variable rainfall-runoff modeling," in *Institute of Engineers, Australia National Conference, Perth, Australia*, January 15–16, 1979, pp. 89–92.
- [16] A. R. Ladson, R. Brown, B. Neal, and R. Nathan, "A standard approach to base-flow separation using the Lyne and Hollick filter," *Aust. J. Water Resour.*, vol. 17, no. 1, pp. 25–34, 2013.
- [17] L. Li, H. R. Maier, D. Partington, M. F. Lambert, and C. T. Simmons, "Performance assessment and improvement of recursive digital base-flow filters for catchments with different physical characteristics and hydrological inputs," *Environ. Model. Softw.*, vol. 54, pp. 39–52, 2014.
- [18] T. Chapman, "A comparison of algorithms for stream flow recession and base-flow separation," *Hydrol. Process.*, vol. 13, pp. 701–714, 1999.
- [19] R. J. Nathan and T. A. McMahon, "Evaluation of automated techniques for base flow and recession analyses," *Water Resour. Res.*, vol. 26, no. 7, pp. 1465–1473, 1990.
- [20] J. G. Arnold, P. M. Allen, R. Muttiah, and G. Bernhardt, "Automated base flow separation and recession analysis techniques," *Groundwater*, vol. 33, no. 6, pp. 1010–1018, 1995.
- [21] T. Chapman and A. Maxwell, "Base-flow separation - Comparison of numerical methods with tracer experiments," in *Hydrology and Water Resources Symposium*, Barton, Australia, January 1, 1961, pp. 539–545.



- [22] P. Guzmán, O. Batelaan, M. Huysmans, and G. Wyseure, “Comparative analysis of base-flow characteristics of two Andean catchments, Ecuador,” *Hydrol. Process.*, vol. 29, no. 14, pp. 3051–3064, 2015.
- [23] V. U. Smakhtin, “Low flow hydrology: A review,” *J. Hydrol.*, vol. 240, nos 3–4, pp. 147–186, 2001.
- [24] W. Collischonn and F. M. Fan, “Defining parameters for Eckhardt’s digital base-flow filter,” *Hydrol. Process.*, vol. 27, no. 18, pp. 2614–2622, 2013.
- [25] Manual on low-flow estimation and prediction, Operational hydrology report, no. 50, 2008.
- [26] Geological maps from the landscape atlas of the Slovak Republic (in Slovak), 2021. [Online]. Available: <http://apl.geology.sk/atlaskrajiny/>. Accessed: Jan. 5, 2021.
- [27] C. Sezen, N. Bezak, and M. Šraj, “Hydrological modeling of the karst Ljubljana river catchment using lumped conceptual model,” *Acta Hydrotech.*, vol. 31, no. 55, pp. 87–100, 2018.

