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Baseflow Ratio in Catchments with Regolith-Dominated Groundwater Circulation of Different Lithology—Comparison of Kille's, Rambert's and Hydrograph Separation Methods

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Abstract

Baseflow separation was performed for 42 small catchments completely built up of either crystalline rocks or folded/unfolded Paleogene flysch rocks. Three different methods were applied—Local minimum (BFI), Kille's and Rambert's. Mean total annual runoff in individual catchments varied from 179 to 1132 mm, with an average of 498 mm. Taking into account results for the whole dataset, baseflow participated in 45% ± 15% ratio of the total runoff. Local minimum and Kille's method results were quite similar: both showed average baseflow participating on 39%/40% of total runoff in unfolded Paleogene catchments, on 29%/29% in folded flysch and 44%/45% in catchments with crystalline basement. Rambert's method results were 10% to 12% higher from the previous two, reaching 50% in unfolded flysch Paleogene catchments, 41% in folded flysch and 56% in crystalline catchments. Differences might be caused by the nature of Rambert's method, which is based on recession curves analyses, while the previous two result from discharge statistics. Still, usually only less than 50% of unevaporated precipitation is able to infiltrate and recharge groundwater resources in crystalline rocks and flysch sediments, and folded flysch rocks are sometimes able to absorb only 10–20% of unevaporated precipitation.

Keywords: runoff; baseflow; Kille; local minimum; Rambert; West Carpathian Mts. catchments

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1. Introduction

Determination of the share of groundwater runoff in streamflow in terms of the relationship between precipitation and runoff from catchments has been one of the main subjects of research in the field of hydrology and hydrogeology for many decades. Statistical separation methods, baseflow separation methods based on mathematical models and digital filters, and methods based on recession curves analysis are some of the many known tools used in this research topic.

Statistical procedures were developed to estimate the proportion of groundwater from a long-term series of minimum discharges. Pioneering work in this area included studies by Wundt [1,2], who used low discharges as a measure of usable groundwater quantities. Castany et al. [3] proposed determining the proportion of baseflow as the arithmetic mean of the 30 consecutive days with the lowest flows in the year. A significant milestone was

Kille's method [4], known as MoMNQ, which eliminates the influence of direct runoff using monthly minima arranged in ascending order. Fendeková and Fendek pointed out the specifics and risks of incorrect application of this method [5]. The problem of accurately interpreting the termination point of direct runoff in relation to the onset of the flow wave was also discussed in detail by Ineson and Downing [6], Ward [7], Appleby [8], and Balek [9]. The overall theoretical framework for low-flow hydrology was summarized by Smakhtin [10].

The rise in computer technology enabled the automation of processes and the development of recursive digital filters. The basic algorithm was proposed by Lyne and Hollick [11], and its effectiveness was later evaluated by Nathan and McMahon and Chapman [12,13]. The widely used HYSEP software, developed under the USGS by Sloto and Crouse [14], implemented fixed interval, sliding interval, and Local minimum methods based on the principles of Pettyjohn and Henning [15]. Further improvements in filter parameterization were introduced by Eckhardt [16,17], Arnold et al. [18], Collischonn and Fan [19], and most recently by Pelletier and Andréassian [20], who sought to achieve an unbiased choice of separation constants. Tallaksen and Van Lanen gave an overview of the hydrograph separation methods used using recession curves [21].

The central tool of integrated reservoir analysis is the master recession curve (MRC), which forms a theoretical envelope for individual recession segments. The methodological foundation for its practical application was laid by Rambert through the manual separation of outflow components using exponential templates [22]. Tallaksen analyzed the weaknesses of visual segment matching ("matching strip method") in relation to the loss of information about the variability of discharge processes [23], while Fiorillo summarized the physical foundations of analytical recession models [24]. A fundamental innovation was brought about by the digital transformation of Rambert's principles by Malík [25], based on the assumption that an identical flow rate (Q) reflects the same state of water saturation in the system. The method utilizes the superposition of laminar and turbulent sub-regimes and an iterative search for the representative time (t_r). The MRC construction process was gradually automated by the interactive tools of Lamb and Keith [26], the spreadsheet macros of Posavec et al. [27], and the specialized RC 4.0 software by Gregor [28]. The application of hybrid genetic algorithms by Gregor and Malík subsequently enabled the objective construction of MRCs even in cases of fragmented data or complex flow regimes [29]. Current research is shifting toward a stochastic understanding of discharge processes, with Fiorotto and Caroni introducing a statistical framework to account for measurement uncertainty [30]. The importance of including natural variability in MRC models is emphasized by McMahon and Nathan [31].

Most research in the area of the Western Carpathians devoted to the assessment of groundwater runoff is of a partial nature. Among the oldest is the work of Dovina [32], which evaluates the minimum specific groundwater runoff from the crystalline rock catchments of the Western Carpathians using the graphical method of Foster [33], Kille and Castany. Foster's method was also used by Zakovic [34], where the specific groundwater outflow as part of the evaluation of the hydrogeological conditions of sandstone formations was determined. One of the first more extensive works from this area is the work of Krasny et al., who used Kille's method as a standard for the assessment of groundwater runoff in the territory of the former Czechoslovakia to form a baseflow map for the whole country [35]. Kessl and Knezek documented a good correlation of baseflow runoff values obtained by Kille's and Kliner–Knezek methods used on the example of several watersheds in the Czech Republic [36]. Machlica and Fendekova compared the determination of groundwater runoff using Kille's method and a watershed balance model in a small flysch catchment [37]. The work of Stojkovova can be considered the first comparative

analysis [38], determining the groundwater runoff in various lithological environments of the Western Carpathians by several methods-Kille and Local minimum method. Other comparative works were smaller-local character and were dedicated to description of runoff conditions of specific watersheds with different lithologies. They compared the results of baseflow separation using Kille's method, the Local minimum method, but also Castany's method. Among the more recent works from the region of the Western Carpathians are the works of Dugovic and Malik [39,40], who compared the determination of groundwater runoff using Kille's method and the Local minimum method for catchments characterized by different rock types.

Comparative analysis approach was also applied on baseflow separation techniques in other regions of the world. Chapman and Maxwell compared numerical recursive digital filters for baseflow separation against measured tracer experiment data in a foundational hydrology paper [41]. Later Chapman evaluated and compared one-, two-, and three-parameter digital filtering and recession algorithms for estimating baseflow and surface runoff [13]. Gonzales et al. evaluated and compared various baseflow separation techniques in a highly controlled temperate lowland catchment by focusing on the tracer versus non-tracer methods approach [42]. By using different types of methods (hydrochemical), Igawami et al. evaluated the role of bedrock on rainfall–runoff processes of a small headwater catchment characterized by fissure-type permeability [43]. In a case-study, Nejadhashemi presented the results of a verification of the accuracy of five mathematical methods of baseflow separation [44]. In a broad comprehensive study by Stoelze et al., the authors compared nine different two-parameter conceptual groundwater models for baseflow separation from streamflow data in catchments with different types of aquifer [45], concluding that there is no universally superior conceptual groundwater model structure and that the simulation of baseflow runoff depends directly on the specific hydrogeological type of the aquifer. Vogel and Kroll introduced a model to estimate stream low-flow statistics at an ungauged site by relating a simple linear conceptual storage model to the geomorphologic properties of a catchment [46], showing that traditional regression techniques usually relate low flows directly to catchment attributes. And more recently, Latuamury et al. compared seven different recession models in paired watersheds [47], using the RC 4.0 module [48] of the HydroOffice 2015 software pack [49].

This study presents the results of a multi-method determination of the parameters of baseflow focused on comparing and highlighting the differences obtained by individual methods. The methods used for this study were the classical statistical method of Kille, baseflow separation method of Local minimum (BFI) and a master recession curve analysis method modified with Rambert's iterative solution. At the same time, it aims to compare the obtained results of runoff parameters for geological environments with different lithological and morphologic settings, but with similar groundwater circulation in the uppermost few tens of metres of the disconnected and weathered regolith zone on examples from 42 catchments in the Western Carpathians region in the territory of the Slovak Republic. The selected catchments represent three types of bedrock: crystalline base rock, folded flysch Paleogene sediments and unfolded flysch Paleogene sediments.

Differences in resulting baseflow determination can be seen between methods used in this study and it is obvious that the geological structure of the studied catchments, as a factor affecting the formation of groundwater or base runoff, weighs mainly on a regional scale within the differences in the investigated hydrogeological units. Meanwhile, in the smaller, more individual extent, it is the local morphologic characteristics, such as mean elevation, area, ruggedness of terrain and their specific combinations, that seem to be the primary factors affecting the runoff components ratio of catchments, along other natural

conditions such as land cover, precipitation and evaporation, which were not directly considered in this study.

2. Materials and Methods

For the purpose of this study, 42 catchments from the region of the Western Carpathians Mts. were selected to be analyzed (Figure 1). When selecting catchments, several factors affecting the quality of the achieved results were taken into account; in particular, the lithological homogeneity of the rock environment in terms of the basic division of the hydrogeological units of Western Carpathians, and similarities in lithology and/or contrasting lithological properties of rocks/sediments forming the area of catchment were considered. According to this, another selection condition was the area of the catchment. Given the fact that the larger the catchment is the more pronounced the differences in lithology may be, the area of individual catchments did not exceed 100 square kilometres at the time of the selection. The concept for selecting small headwater catchments which enclose homogenous lithologies is that the morphologic catchment divide line (boundary) corresponds with the hydrogeological boundaries and to a large extent eliminate any lateral cross-boundary flow. Considering this, it can be assumed that the values of the obtained runoff parameters represent the infiltration capacity of the individual studied hydrogeological units.

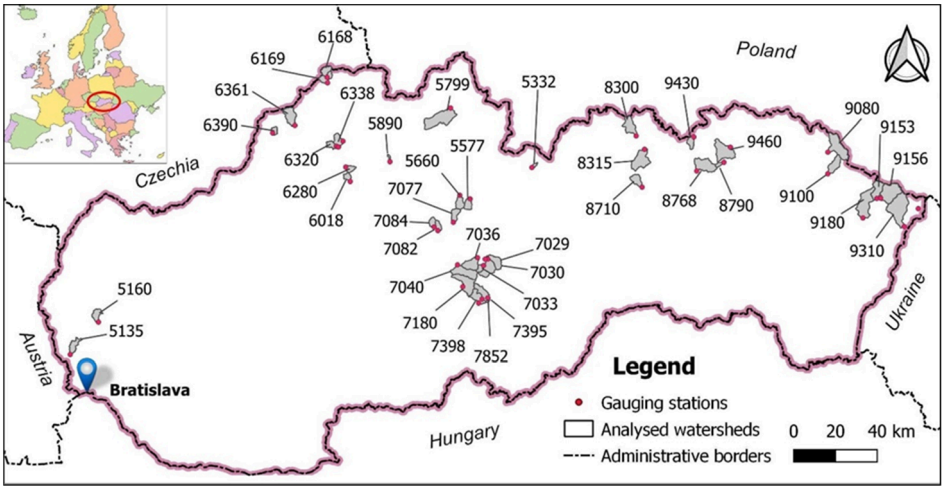


Figure 1. Map of 42 evaluated catchments in the territory of the Slovak Republic; see Tables 1–3 for explanations.

Availability of surface flow observation in a sufficient time span was the final condition. In a previous study [40], 42 catchments in three hydrogeological units were selected according to these conditions, specifically, 19 catchments representing the crystalline rock hydrogeological unit, 16 catchments representing the folded flysch Paleogene hydrogeological unit and 7 catchments representing the unfolded Inner Carpathian Paleogene hydrogeological unit. Still, similar hydrogeological environments were analyzed: in all three types, regolith-dominated groundwater circulation is present. In all three units, the majority of groundwater circulation is bound to the cracked and weathered near-surface zone (regolith) although lithology and tectonic history might be different [50]. The basic information about the surface water gauging stations on rivers/creeks as seen in Tables 1–3 is based on the available yearbooks of the Slovak Hydro-Meteorological Institute (SHMI) [51].

The groundwater divide lines for the catchments were determined by the position of surface water gauging stations. In this case, SHMI's data on areas of the evaluated catchments, presented in yearbooks, were not used. In the past, the original values were

determined by planimetry on paper maps which were often intentionally deformed (for military-tactical reasons in the cold-war period in the second half of the 20th century); the current digital form of the relief data enables more accurate delineation of areas. Having in mind the geological background of the data, in this study the manual procedure of catchment delineation was preferred. For the needs of our study, the priority was to determine the catchment area as accurately as possible; however, we do not claim to definitively determine it accurately [40].

Table 1. Selected characteristics of the evaluated catchments representing the crystalline rock hydrogeological unit.

ID	Catalogue Number [1]	River/ Creek	Gauging Station	Evaluated Period	Area (km^2)	Stationing [km]	Mean Elevation [m a.s.l.]	Mean TRI [2]
2	5135	Vydrica	Červený most	1965–2012	21.38	3.30	350	13.52
3	5160	Blatina	Pezinok	1962–2009	18.96	8.75	482	18.84
4	5332	Beliansky p.	Tri Studničky	1975–1991	3.40	15.20	1632	39.07
13	5577	Zadná voda	Kožiarka	1972–2003	15.79	1.20	1422	32.27
14	5660	Palúdžanka	Horáreň Hluché	1970–2011	19.72	10.20	1376	36.20
22	6018	Valčiansky p.	Valča	1987–2000	10.04	7.90	852	32.94
38	6280	Bystrička	Kunerad	1968–2012	11.44	8.00	1009	15.76
51	7029	Šaling	Čierny Balog	1987–2012	25.21	0.90	849	22.64
52	7030	Čierny Hron	Čierny Balog	1969–2012	66.17	15.50	853	21.22
53	7033	Brôtovo	Čierny Balog	1981–2012	9.47	3.30	846	19.31
54	7036	Vydrovo	Čierny Balog	1981–2012	34.08	1.10	782	14.91
55	7040	Kamenistý p.	Hrončok	1970–2012	47.60	11.40	915	38.87
57	7077	Lomnistá	Jasenie	1984–2002	18.79	4.90	1368	34.79
58	7082	Bukovec	Pohronský Bukovec	1984–1992	10.19	4.60	1038	34.54
59	7084	Sopotnica	Brusno	1984–1997	11.73	7.60	1308	16.71
60	7180	Slatina	Hriňová nad VN	1971–2012	52.92	50.80	848	19.13
61	7395	Ipeľ	Ipeľský potok	1990–2012	26.63	200.10	836	19.66
62	7398	Ipeľ	Málinec-nad VN	1995–2012	53.14	197.60	803	10.82
78	7852	Kokavka	Ďubákovo	1990–2003	2.84	11.50	882	44.79

[1] as listed in the SHMI yearbooks [51]; [2] mean value of the terrain ruggedness index [52].

The geological characteristics of the three studied hydrogeological units included in this paper (crystalline rock, folded flysch zone of the Outer Carpathians Paleogene and unfolded Inner Carpathian Paleogene hydrogeological units) are based on the description of the basic Alpine tectonic units in the territory of the Western Carpathians, which are divided into External and Internal Western Carpathians and their present form is a result of the Alpine orogenic stage, with remnants of earlier Hercynian (Variscan) evolution. A tectonic unit is characterized as three-dimensional rock body with its own defined borders, lithostratigraphic and structural content as well as defined tectonic evolution. The boundary between the External and Internal Western Carpathians is represented by the "Pieniny Klippen Belt" which is a narrow and intensively deformed belt consisting of steep cliffs, or klippen, composed of Jurassic and Early Cretaceous limestones which are more resistant to erosion than the surrounding Upper Cretaceous and Paleogene marlstones and clayey sediments [53].

Table 2. Selected characteristics of the evaluated catchments representing the folded flysch Paleogene hydrogeological unit.

ID	Catalogue Number [1]	River/Creek	Gauging Station	Evaluated Period	Area (km^2)	Stationing [km]	Mean Elevation [m a.s.l.]	Mean TRI [2]
16	5799	Hruštínka	Lokca	1979–1999	78.67	0.90	858	14.25
26	6168	Predmieranka	Klokočov-Klin	1982–2012	15.99	8.00	783	17.80
27	6169	Predmieranka	Klokočov	1985–1997	35.18	5.00	722	17.31
46	6361	Papradianka	Papradno	1983–1993	36.53	13.80	735	24.30
47	6390	Petrinovec	Vydrná	1961–2012	8.49	2.20	596	21.94
102	8768	Ľutinka	Ľutina	1992–2011	50.02	5.10	775	28.31
103	8790	Pastovník	Hertník	1969–1983	5.48	4.80	784	12.94
110	9080	Vydranka	Medzilaborce	2001–2010	64.73	0.54	556	16.42
111	9100	Olšava	Čabiny	1973–1992	30.93	0.65	446	19.27
112	9153	Stružnica	Starina	2001–2011	33.30	0.10	577	20.43
113	9156	Cirocha	Starina-nad VN	2001–2011	66.57	43.40	618	14.57
114	9180	Pčolinka	Snina	2001–2010	71.11	1.00	384	21.92
118	9300	Zbojský p.	Nová Sedlica	1972–1988	35.20	12.40	675	21.97
119	9310	Ulička	Ulič	2001–2011	96.57	2.50	573	22.42
122	9430	Večný p.	Lenartov	1982–1992	14.88	4.50	742	22.24
124	9460	Šibská voda	Kľušov	1992–2010	59.91	4.30	472	12.01

[1] as listed in the SHMI yearbooks [51]; [2] mean value of the terrain ruggedness [52].

Table 3. Selected characteristics of the evaluated catchments representing the unfolded Inner Carpathian Paleogene hydrogeological unit.

ID	Catalogue Number [1]	River/Creek	Gauging Station	Evaluated Period	Area (km^2)	Stationing [km]	Mean Elevation [m a.s.l.]	Mean TRI [2]
19	5890	Čiernik	Turany	1969–2003	2.69	0.50	564	10.57
42	6320	Lietava	Lietava-obec	1969–1979	11.47	3.75	529	16.06
43	6330	Lietava	Lietava-Majer	1969–2010	13.57	2.70	521	9.33
44	6338	Bitarovský p.	Bánová	1991–2009	18.59	1.03	416	26.23
85	8300	Kamienka	Hniezdne	1980–2008	34.46	0.70	716	23.55
86	8315	Jakubianka	Jakubany	1987–1997	54.16	8.00	941	16.94
100	8710	Torysa	Nižné Repaše	2001–2011	21.07	123.90	1003	20.51

[1] as listed in the SHMI yearbooks [51]; [2] mean value of the terrain ruggedness index [52].

The catchments within the crystalline rock hydrogeological unit are represented by the "core mountains belt" and "Vepor belt" tectonic units, which are characterized by the central part of the mountain range (core) formed by early Paleozoic crystalline basement rock (mostly granites, and granodiorites), which is partly or completely covered by Mesozoic sediments [53]. The studied catchments were selected within the crystalline basement rock parts of these units, trying to avoid any presence of Mesozoic sediments that might be karstified and potentially cause some parts of runoff to be diverted to other catchments as seen on Figure 2.

The basic lithostratigraphic profile representing the "core mountains belt" tectonic unit is shown in Figure 3. This unit's bedrock is composed by a complex of late Paleozoic metabasites and metasediments, as well as Devonian and Carboniferous granitoid magmatites, with complexes of metamorphic rocks consisting of mainly amphibolites, schists, phyllites and metagreywackes [54].

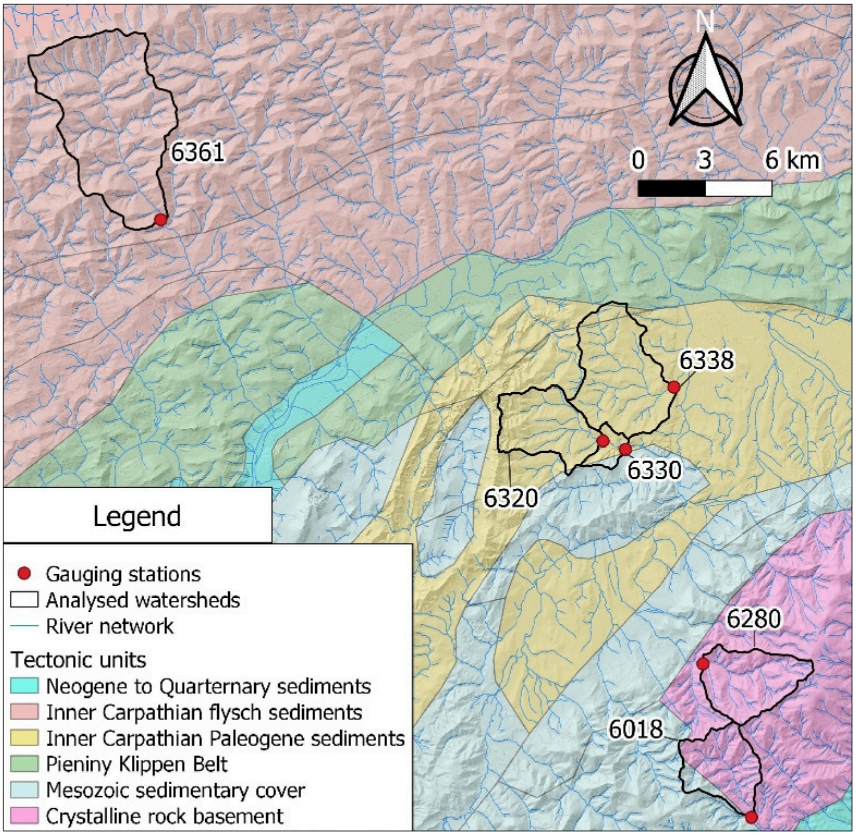


Figure 2. Example of geological settings of analyzed catchments within the tectonic units of the Western Carpathians Mts.

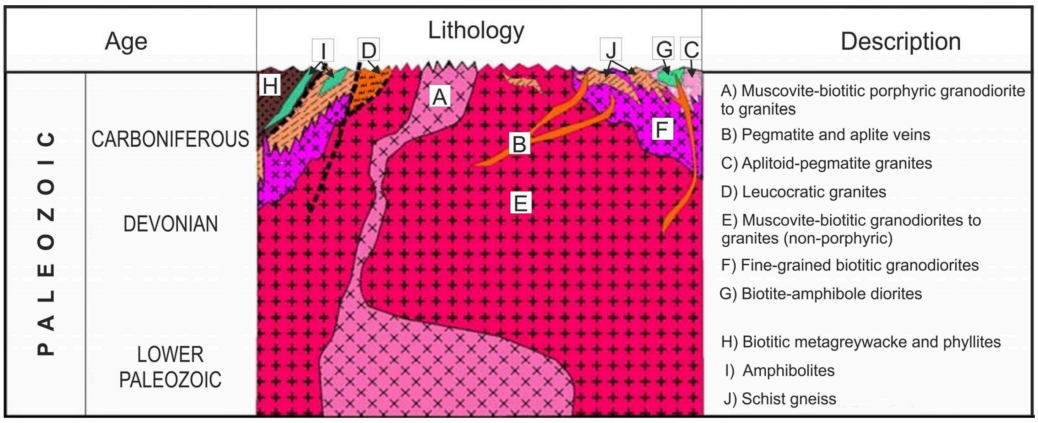


Figure 3. Litostratigraphical profile of the crystalline basement of the core mountains belt (based on Polák et al.) [54].

Research including pumping tests on 187 boreholes in granitic and metamorphic rocks of this hydrogeological unit was summarized by Malík et al. [55]. In it, they addressed its hydrodynamic properties in terms of determining the transmissivity coefficient (T) with the mean value of 6.51×10^{-5}–3.97×10^{-5} $m^2 \cdot s^{-1}$ and hydraulic conductivity coefficient (k) with the mean value of 2.15×10^{-6}–1.96×10^{-6} $m \cdot s^{-1}$ [55].

The flysch zone hydrogeological unit is represented, from a lithological point of view, by the Flysch zone, which is a massive accretionary wedge (a nappe stack) composed by Cretaceous and Paleogene formations in typical "flysch" development with alternating clayey shales and sandstones, deposited in deep-water environment by gravity flows and turbidity currents [53]. The Flysch zone consists of several nappe systems: the outer under-

lying "Krosno" nappe system, which is generally characterized by variegated claystones, and the internal overlaying "Magura" nappe system, formed by prevailing sandstones (majority of studied catchments). Catchments located in the outer Krosno nappe system (6168, 6169, 9080, 9100, 9153, 9156, 9180, 9300 and 9310) can be characterized by lithological units of the Silesian nappe [Figure 4], which ranges from the late Cretaceous to late Oligocene Paleogene period. The oldest formation of this group—the Istebna Formation—belongs in the Santonian to Paleocene stage and are characterized by quartz sandstones to conglomerates with positions of dark clays and claystones. Overlaying is a lithologically diverse sequence of the Sub-Menilite Formation, characterized by the predominance of pelitic or sandstone facies with distinctive green claystone positions. Next there is the Menilite Formation, which is represented by dark black-brown claystones with fine to medium grained quartz sandstone positions. The upper most Krosno Formation (approx. 80 m thick) is characterized by grey fine-grained sandstones and grey calcareous clays [56].

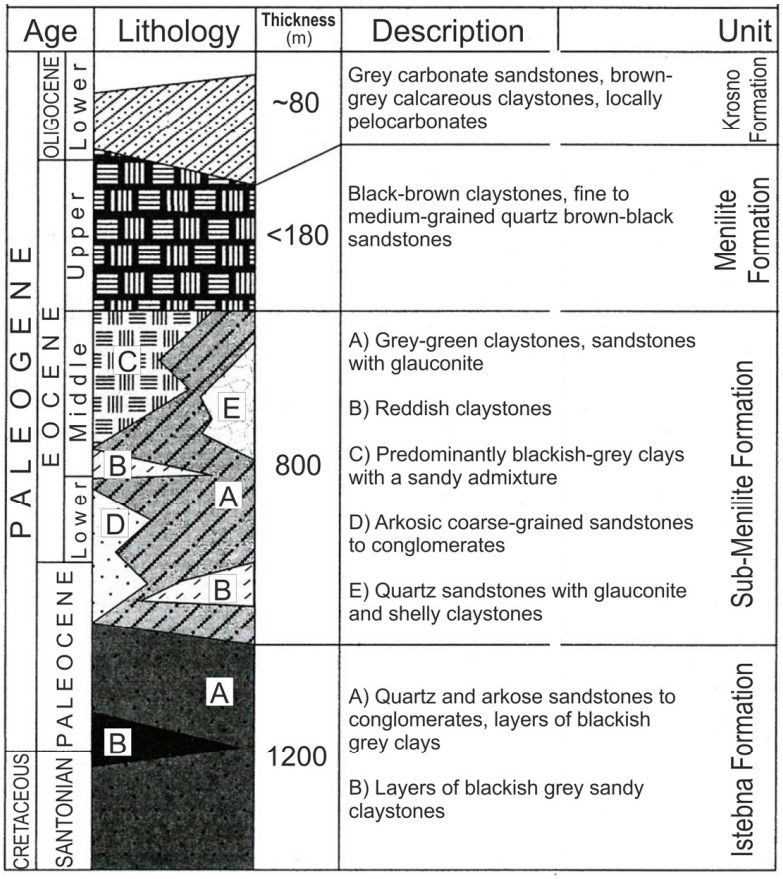


Figure 4. Litostratigraphical profile of the Silesian Nappe in the Krosno Nappe system (based on Potfaj et al.) [56].

The rest of the flysch zone catchments (5799, 6361, 6390, 8768, 8790, 9430 and 9460) belong to the inner Magura Nappe system which can be described by the Paleogene Rača unit, whose litostratigraphical profile is shown on Figure 5. Stratigraphically, this unit ranges from the upper Paleocene to late Oligocene period and covers four formations. Beloveža Formation is the oldest and is characterized by thin-layered monotonous clays and fine-grained sandstones (fine-rhythmic flysch). The overlaying Zlín Formation has two distinctive lithologic evolutions—claystone and sandstone evolution. The sequence ends with Malcov Formation, which is characterized by calcareous claystones and siltstones with positions of sandstones [57].

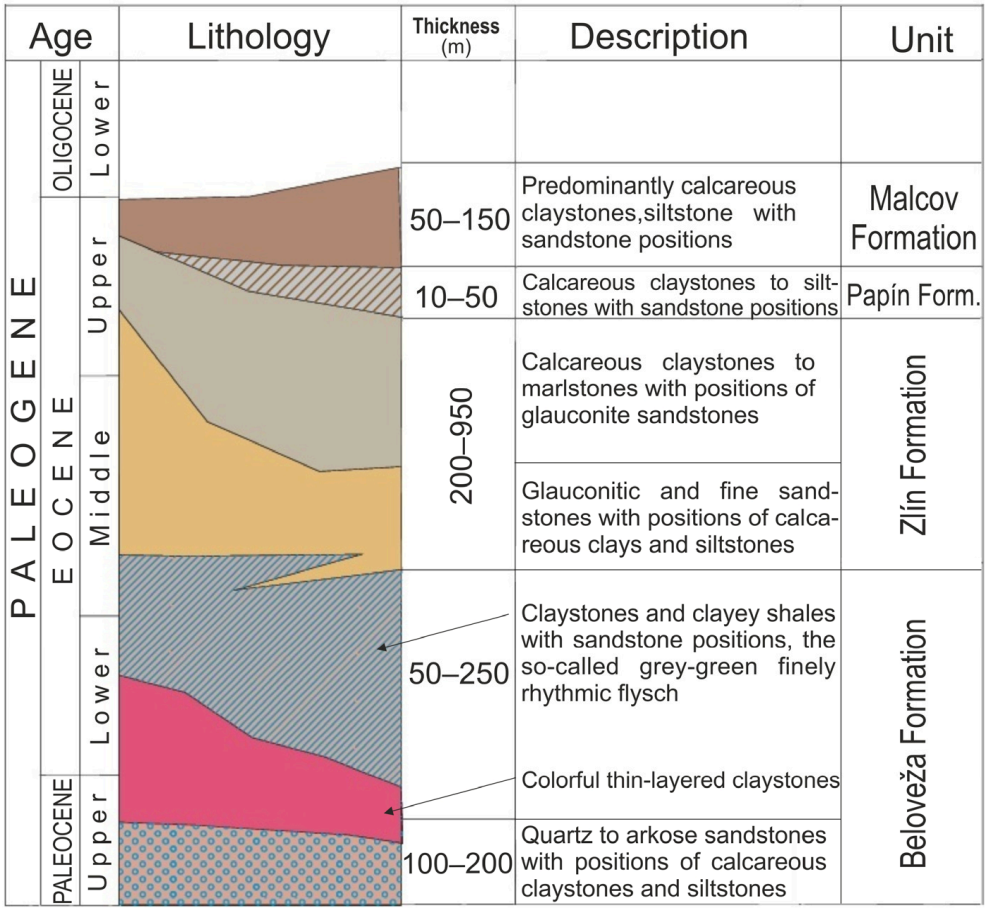


Figure 5. Litostratigraphical profile of the Rača unit in the Magura Nappe system (based on Žec et al.) [57].

After studying pumping tests results from several hundred wells in the flysch zone, Jetel published the opinion that the lithological representation of sandstones and claystones does not play an important role in the circulation of groundwater, because it takes place in the weathered near-surface zone [58]. At that time, he published the results of the transmissivity coefficient (T) for the near-surface Krosnian formation with a value of 4×10^{-5}–6×10^{-4} $m^2 \cdot s^{-1}$ and the hydraulic conductivity coefficient (k) with a value of 4×10^{-6}–4×10^{-5} $m \cdot s^{-1}$, while for the near-surface zone of the Rača unit he determined the coefficients with values of $T = 5 \times 10^{-6}$–6×10^{-4} $m^2 \cdot s^{-1}$ and $k = 4 \times 10^{-7}$–2×10^{-5} $m \cdot s^{-1}$ [58]. Later, Malík and Švasta processed the results of pumping tests from all available boreholes of the flysch zone of the Western Carpathians (database of 335 boreholes), while determining the transmissivity coefficient (T) with an average value of 4.31×10^{-5}–2.22×10^{-4} $m^2 \cdot s^{-1}$ [59].

Paleogene sediments, which form the Inner Carpathian Palegoene hydrogeological unit are divided into several lithostratigraphic (litofacial) groups while the studied catchments are represented by the so-called Central Carpathian Paleogene Basin (or Subtatric Group). The stratigraphic range of this group is from Eocene to Oligocene, with the sequence starting with Eocene Borové formation—Bartonian transgressive basal carbonate breccias and conglomerates—overlain by Eocene to Oligocene Huty formation—Priabonian to Rupelian claystones with limestone and sandstone positions—as well as by typical mass transport deposits ("flysch" sandstones and claystones), and terminated by Rupelian deposition of predominantly sandy gravity flow deposits [53]. A more detailed lithostratigraphic description is showed in Figure 6.

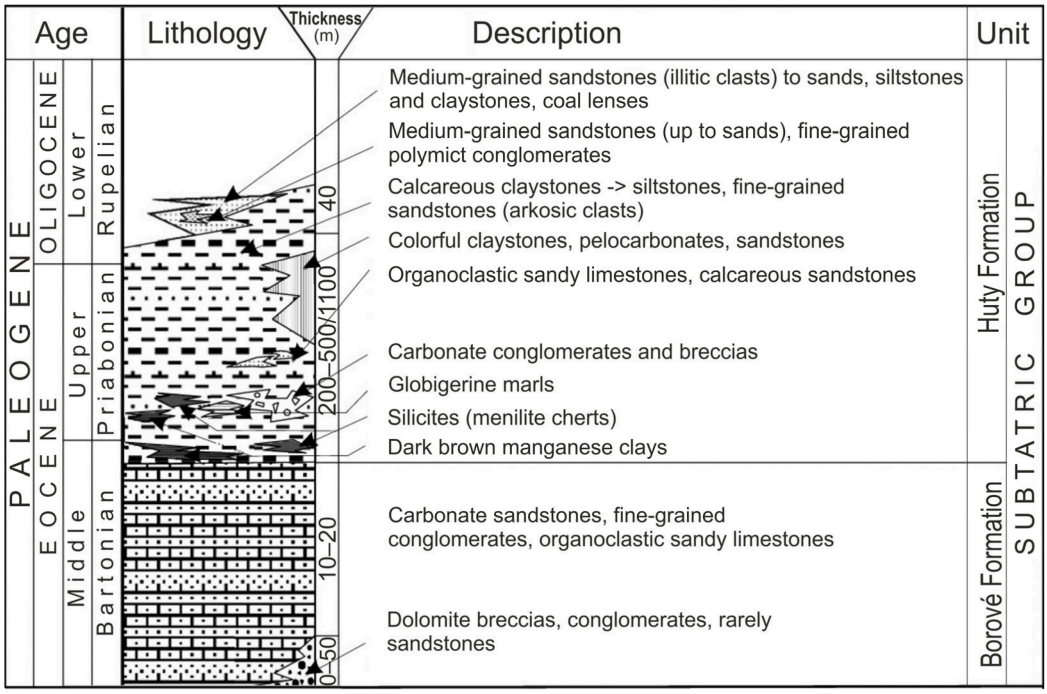


Figure 6. Lithostratigraphic profile of the Subtatric group (or Inner Carpathian Paleogene) (based on Mello et al.) [60].

In the above-mentioned study [59], Malík and Švasta also studied sediments of the Inner Carpathian Paleogene. From the results of pumping tests on 330 boreholes in the monitored formations, they determined the hydraulic parameter of transmissivity coefficient with an average value of 2.02×10^{-4}–1.49×10^{-4} $m^2 \cdot s^{-1}$.

The main difference between the two Paleogene sedimentary hydrogeological units is that the Inner Paleogene unit was not affected by the final stages of Alpine orogeny and remained in a subhorizontal position with vertical movement of individual blocks; meanwhile, Flysch zone nappes of the Outer Carpathians, as a result of subduction of the basement, were set in motion during the Oligocene to Miocene periods, forming an extensive fold-and-thrust complex composed mainly of claystones and sandstones, while crystalline rocks formed the catchments' bedrock in the core Mt. units of the Inner Carpathians, being predominantly granitoids/granodiorites and gneisses in their lithology. All the listed hydraulic characteristics of the investigated environments represent the parameters of the near-surface weathered regolith zone for each studied hydrogeological unit, presuming that the morphologic boundaries of catchments represent the hydrogeologic boundaries as well.

The studied data consists of average daily surface water flow or discharge in $m^3 \cdot s^{-1}$ from 42 gauging stations. The values were provided from SHMI as a part of the "Integrated System for the Simulation of Runoff Processes" (ISSOP) [61], in which they were used by the State Geological Institute of Dionýz Štúr (SGIDS) in the past period. The time series include stream flow monitoring data for the period from 1961 to 2012. Although the data for many catchments in this range concern different time periods—which could possibly influence the resulting estimated groundwater runoff values—the evaluated time series are as long as possible for the use of statistical methods of determining groundwater runoff (minimum of 10 years). If only overlapping time series were used, it would not be possible to cover as many catchments and the scope of this study would be considerably smaller.

From the data, the average annual values of the total runoff (Q_c) in $m^3 \cdot s^{-1}$ for the monitored period available for individual catchments were determined, which were later, using catchments' areas, converted to millimetres (mm) to show also specific runoff values.

Furthermore, the groundwater runoff parameters, namely the average annual groundwater runoff (Q_{gw} in mm) and subsequently the ratio of groundwater runoff to total runoff (Q_{gw}/Q_{tot} in %) from catchments were determined using three different methods (Tables 4–6). These three methods are incorporated (or partly) in the software modules of the HydroOffice 2015 software pack [48], which were used to help process the statistical determination (HydroOffice, Milos Gregor, Mojtin, Slovakia).

The methods described below were selected mainly for their successful previous use in similar conditions and environments of the Western Carpathian Mts, as well as their accessibility. The statistical method of Kille and the Local minimum baseflow separation method were used in Western Carpathians in the past, but mostly in partial small-scale studies. Motivation for use of these specific methods was to expand on this research to a larger overall extent for the territory of the Western Carpathians. Furthermore, it is well known, that baseflow indices are generally highly correlatable to hydrological properties of soils, geological properties and other storage-related parameters [21]. Therefore, it is of great interest to examine the results of using a comparative analysis of these methods in real conditions, where, for example, such characteristics are not available from geological surveys, etc.

Table 4. Average annual values of total runoff, groundwater runoff and ratio of groundwater to total runoff in the crystalline rock hydrogeological unit. Q_{tot} represents total annual runoff; Q_{gw} represents baseflow/groundwater runoff.

ID	Catalogue Number	Q_{tot} [mm]	Kille's Method		Local Minimum Method		Rambert's Method	
			Q_{gw} [mm]	Q_{gw}/Q_{tot} [%]	Q_{gw} [mm]	Q_{gw}/Q_{tot} [%]	Q_{gw} [mm]	Q_{gw}/Q_{tot} [%]
2	5135	193	83	43	75	39	108	56
3	5160	361	109	30	105	29	289	80
4	5332	621	252	41	250	40	376	60
13	5577	1132	457	40	467	41	683	60
14	5660	969	492	51	456	47	674	70
22	6018	474	233	49	223	47	421	89
38	6280	824	418	51	402	49	393	48
51	7029	310	132	42	126	41	176	57
52	7030	339	128	38	125	37	185	55
53	7033	290	120	41	120	41	114	39
54	7036	284	131	46	126	44	125	44
55	7040	445	188	42	186	42	280	63
57	7077	948	527	56	527	56	413	44
58	7082	603	308	51	337	56	240	40
59	7084	836	442	53	441	53	407	49
60	7180	369	163	44	161	44	129	35
61	7395	338	155	46	147	44	233	69
62	7398	311	136	44	132	42	141	45
78	7852	389	174	45	167	43	240	62

Regarding Rambert's method, it was firstly developed locally in France [22] and given the existence of other baseflow separation methods at that time, which were already more well known in the field, like Foster's or Kille's methods [4,33], Rambert's method never really made such an impact. It was only later that this method was proposed in Czechoslovakia (at that time) by Kullmann to be used alongside Kille's method [62], but again, it never really gained any momentum as a baseflow separation method (to our knowledge), mainly because of its technical difficulties and limitations at that time. Only after the advances in information technologies after the end of 20th century was it

revived again [25], and therefore it was decided to also use this method for comparison and evaluation. The used methods themselves are described further.

Table 5. Average yearly values of total runoff, groundwater runoff and ratio of groundwater to total runoff in the folded flysch Paleogene hydrogeological unit. Q_{tot} represents total annual runoff; Q_{gw} represents baseflow/groundwater runoff.

ID	Catalogue Number	Q_{tot} [mm]	Kille's Method		Local Minimum Method		Rambert's Method	
			Q_{gw} [mm]	Q_{gw}/Q_{tot} [%]	Q_{gw} [mm]	Q_{gw}/Q_{tot} [%]	Q_{gw} [mm]	Q_{gw}/Q_{tot} [%]
16	5799	495	206	42	206	42	281	57
26	6168	676	191	28	185	27	204	30
27	6169	649	147	23	138	21	239	37
46	6361	519	125	24	121	23	131	25
47	6390	401	120	30	126	31	278	69
102	8768	338	121	36	115	34	138	41
103	8790	449	205	46	230	51	177	40
110	9080	546	109	20	102	19	177	32
111	9100	410	100	24	94	23	205	50
112	9153	512	129	25	129	25	271	53
113	9156	559	129	23	127	23	54	10
114	9180	267	64	24	63	23	72	27
118	9300	787	194	25	177	23	204	26
119	9310	542	109	20	104	19	125	23
122	9430	473	149	32	184	39	166	35
124	9460	179	77	43	68	38	80	45

Table 6. Average yearly values of total runoff, groundwater runoff and ratio of groundwater to total runoff in the Inner Carpathian Paleogene hydrogeological unit. Q_{tot} represents total annual runoff; Q_{gw} represents baseflow/groundwater runoff.

ID	Catalogue Number	Q_{tot} [mm]	Kille's Method		Local Minimum Method		Rambert's Method	
			Q_{gw} [mm]	Q_{gw}/Q_{tot} [%]	Q_{gw} [mm]	Q_{gw}/Q_{tot} [%]	Q_{gw} [mm]	Q_{gw}/Q_{tot} [%]
19	5890	1043	478	46	469	45	460	44
42	6320	203	99	49	99	49	164	81
43	6330	365	210	58	207	57	151	41
44	6338	261	79	30	78	30	148	57
85	8300	377	107	28	102	27	138	37
86	8315	310	104	34	100	32	89	29
100	8710	513	197	38	183	36	303	59

Firstly, this study used the classic statistical method of Kille [4], which was previously described and evaluated specifically for the region of the Western Carpathians Mts. [5]. For determining the value of long-term average groundwater runoff from a catchment with this method, at least a 10-year-long period of daily flow observations is required. The method is based on an analysis of minimum monthly surface stream flows. By plotting the values of minimum monthly flows in ascending order on the graph with linear distribution of coordinates, an image similar to the duration line of non-attained flows is obtained. The lower part of the set of ordered points can be translated by a straight line, representing, in terms of Schroeder [63], the dividing line of "pure groundwater drainage". From the area under this straight line, the average groundwater runoff can then be calculated, the value of which corresponds to the central guideline of the balancing straight line. However, in reality, most sets of minimum monthly flows have an asymmetric distribution

of abundance. Therefore, Kille further proposed transforming the distribution by plotting the same ascending ordered values in a semi-logarithmic plot, with the *x*-axis having a linear scale and the *y*-axis having a logarithmic scale. In such coordinates, it was possible to translate again, with a set of points, an equalizing straight line approximately in the range of values $5 \leq n \leq 50$. This straight line, just like in the previous case, can be considered the line separating the groundwater runoff. If the logarithms of the y-coordinate of the equalizing line are converted to their natural values and plotted in the original linear graph, an exponential curve is obtained, which in the upper part of the set of points lies between the original measured values and an exaggerated equalization line led by the lower part of the set of ordered values of minimum monthly flows (Figure 7).

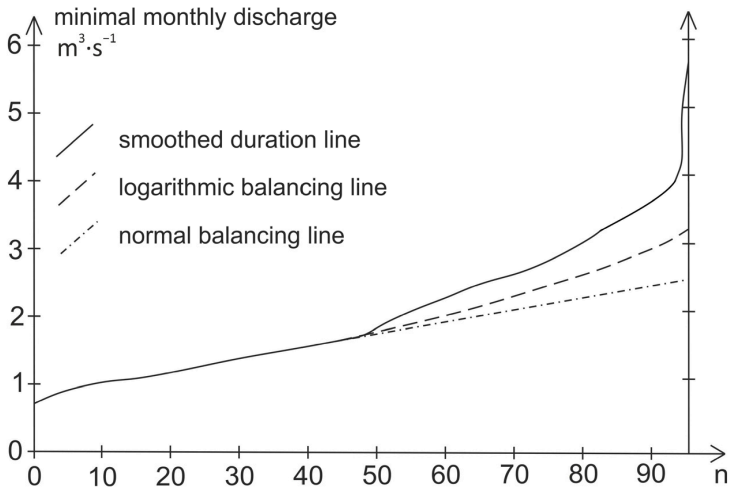


Figure 7. Representation of original method of Kille [4].

From the sum of the minimum monthly flows in the lower part of the dataset and the reduced values of the minimum monthly flows in the area of the exponential curve (in the upper part of the dataset), it is then possible, according to Kille, to calculate the most probable value of the average long-term groundwater runoff [4]. To calculate the values of groundwater runoff by this method, the Kille 3.1 module [64] from the HydroOffice 2015 software pack [48] was used (Figure 8).

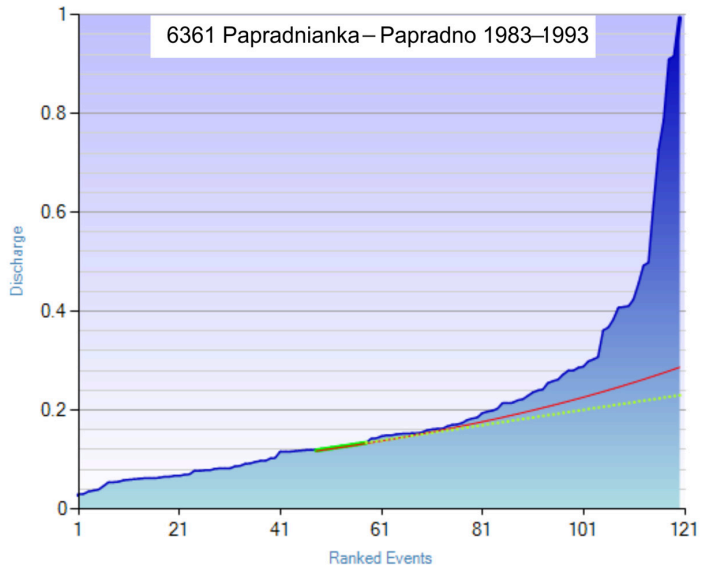


Figure 8. Example of groundwater runoff analysis using Kille's method in the Kille 3.1 module in the case of the Papradnianka catchment in the Papradno No. 6361 gauging object.

As the second alternative method, Local minimum method (BFI) was applied at the same set of discharge time series. This method represents one of the three basic continuous baseflow separation methods as standardized by Sloto & Crouse [14]: fixed interval, sliding interval and Local minimum methods. Methods for continuous separation generally divide streamflow into a quick and a delayed component using an automated time-based separation. The delayed component is thought to represent the portion of total streamflow, that originates in groundwater drainage, defined by Hall as baseflow (Q_b) [65]. The Local minimum method (BFI), as stated before, is based on an automated time-based algorithm which checks each day for discharge observations to determine if it has the lowest value of discharge in ½ of the selected interval minus 1 day before and after the day which is being checked. If the check is positive, then the checked value is a Local minimum and is subsequently connected by a straight line to adjacent Local minimums in the dataset (Figure 9). The baseflow values in between each Local minimum are estimated by linear interpolations. For baseflow separation using this method, a specific value of the time interval or times step length of $N = 20$ days was used, which was established as best for local hydrological and meteorological conditions of the studied region of Western Carpathian Mts by the work by Stojkovova and Fendekova [66], who used this method to determine runoff characteristics in similar catchments of the studied region. The average values of baseflow (groundwater) runoff were determined by the BFI+ 3.0 [67] module of the HydroOffice 2015 software pack [48] (Figure 10).

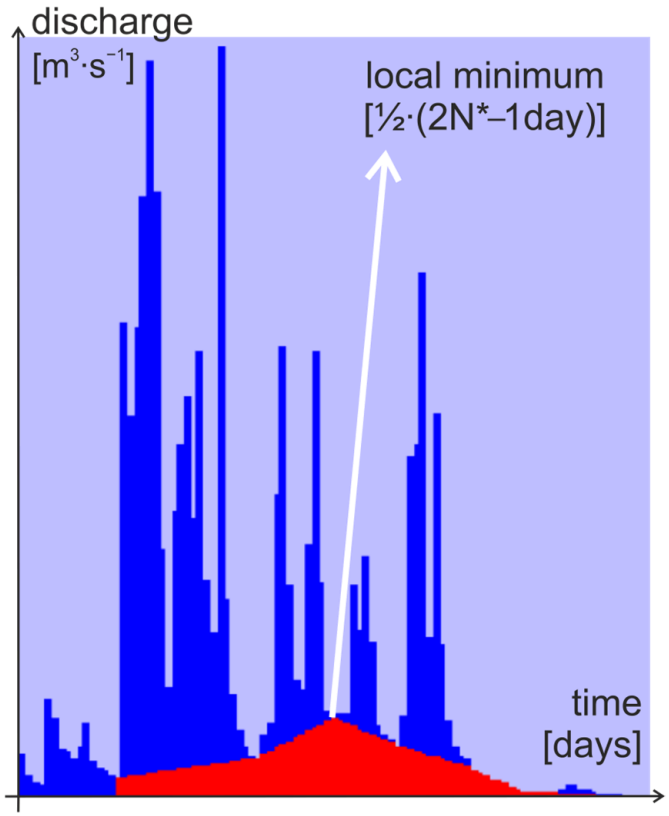


Figure 9. Visualization of Local minimum baseflow separation method [67]. Blue color represents daily discharge rates; red color represents baseflow values. The interval 2*N** used for hydrograph separation is the odd integer between 3 and 11 nearest to *N* (the number of days after which surface runoff ceases) [15].

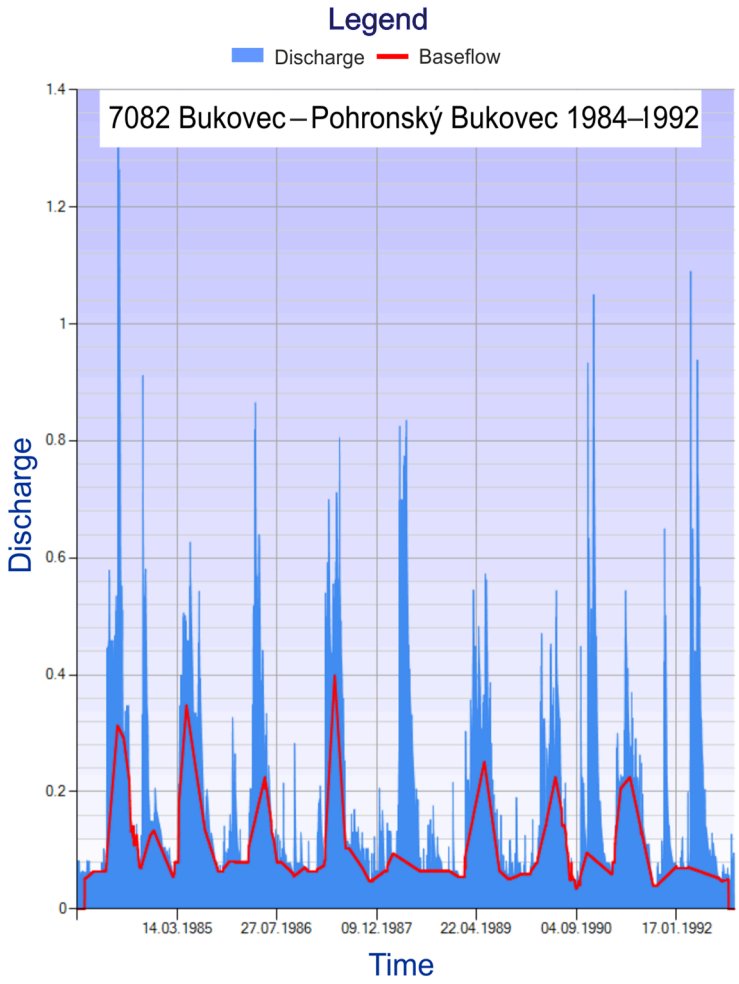


Figure 10. Example of groundwater runoff analysis using the Local minimum method in the BFI+ 3.0 module in the case of Bukovec catchment in the Pohronský Bukovec No. 7082 gauging object. Blue color represents daily discharge rates; red color represents baseflow values.

Rambert applied exponential recession curve to delineate baseflow in stream hydrograph in his method [22]. In this pre-digital era, the baseflow master recession curve had to be manually created (in corresponding scale) in the form of a paper or plastic template. In later work, a digital conversion of this method described the supposed delineation of the baseflow recession curve as an exponential formula defining one of the flow components, the "slowest one" with the lowest recession coefficient value [25]. This flow component is then inherently included in the whole master recession curve of the watershed, which can be composed as a set of several linear and exponential equations [25]. Such a solution was then incorporated into the RC 4.0 module [48] of the HydroOffice 2015 software pack (Figure 11) [48], which uses artificial intelligence, and acts as a combination of a highly hybridized genetic algorithm and an artificial immune system method, together with another 14 conceptual models of recession functions. In the process of hydrograph separation into individual flow components, every measured discharge value $\boldsymbol{Q_t}$ and also relevant portions of $Q_{t01} \ldots Q_{t0n}$ discharge values of individual flow components ($Q_{t01} + Q_{t01} + Q_{t0n} = Q_t$) are considered to be represented just by a time t value—theoretical elapsed time from the overall maximum discharge value Q_{max}. Using iteration procedures, proportional amounts of different flow components (including baseflow) can be calculated, both for every moment of evaluated period or for the whole evaluated period [25].

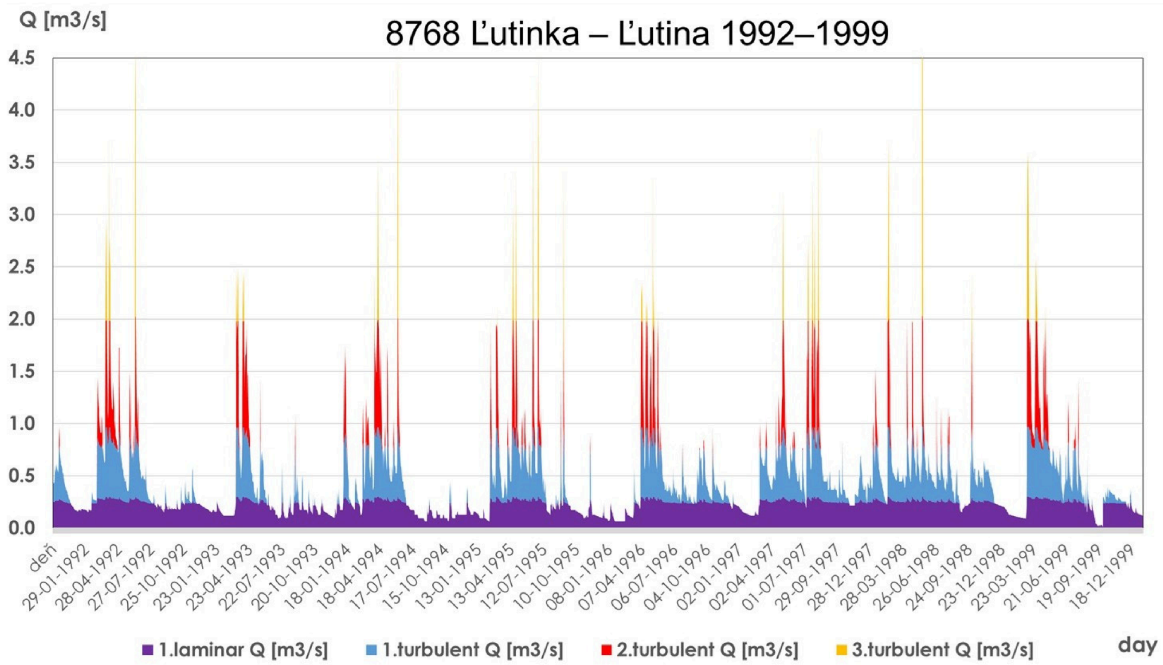


Figure 11. Example of groundwater runoff analysis using Rambert's method in the RC 4.0 module in the case of the Ľutinka catchment in the Ľutina No. 8768 gauging object.

3. Results

The main results of this study are the average yearly values of baseflow/groundwater runoff from catchments for the three studied hydrogeological units determined by the three described methods as well as the ratio or percentage share of the groundwater runoff component to the total runoff from catchments. The crystalline rock hydrogeological unit represents a fissure hard rock environment consisting of granitoids and gneisses, while the Outer flysch Paleogene hydrogeological unit and the unfolded Inner Carpathian Paleogene hydrogeological unit represent a consolidated sedimentary geological environment consisting of either folded or unfolded claystones and sandstones. In the meantime, all three hydrogeological units exhibit similar groundwater circulation features, where an overwhelming majority of groundwater circulates in the regolith zone, the several tens of metres thick weathered and loosened zone. Each hydrogeological unit is described in terms of a basic statistical overview in its own subsection.

3.1. Crystalline Rock Hydrogeological Unit

The average annual value of total runoff from catchments representing the crystalline hydrogeological unit was determined from 193 mm to 1132 mm. The average annual value of groundwater runoff determined by the method of Kille ranged from 83 mm to 527 mm, while the Local minimum method provided values of 75–527 mm, and determined by Rambert's method, the values varied from 108 mm to 683 mm. The percentage share of the groundwater runoff component to the total runoff determined by the method of Kille varied from 30% to 56%; by the Local minimum method from 29% to 56%; and determined by the Rambert's method, the values ranged from 35% to 89% (Table 4).

The lowest values of groundwater runoff as well as the share of groundwater runoff in the total runoff were determined by both Kille's method and the Local minimum method in the Blatina creek catchment, which represents a relatively less elevated catchment (482 m a.sl.) with less rugged terrain (TRI = 18.84) among the studied catchments. On the other hand, the highest values of groundwater runoff and the groundwater runoff to total runoff ratio were determined by both above-mentioned methods in the Lomnistá creek

catchment. Although the area of this catchment (18.79 km^2) is more or less the same as in the Blatina creek catchment (18.96 km^2), the mean elevation of this catchment is much higher (1369 m a.s.l.) and also the terrain is much more rugged (TRI = 34.79) with steeper slopes (Table 1).

With the use of the Rambert's method, the catchments with lowest and highest values of determined runoff parameters are different, though the pattern of their morphologic characteristics is similar to the above-mentioned catchments determined using the other two methods. The lowest groundwater runoff and groundwater to total runoff ratio was determined by Rambert's method in the Slatina river catchment, which is a relatively large catchment with an area of 52.92 km^2, moderate mean elevation (848 m a.s.l.) and relatively less rugged terrain (TRI = 19.13). The highest values of groundwater runoff parameters using this method were determined in the catchment of the Zadná voda creek, with an area of 15.79 km^2. The mean elevation of this catchment is the second highest from all catchments in this unit (1422 m a.s.l.) and the terrain is relatively rugged (TRI = 32.27) with steep slopes (Table 1).

3.2. Folded Flysch Paleogene Hydrogeological Unit

The values of average annual total runoff from catchments in the folded flysch Paleogene hydrogeological unit were determined in the range of 179–787 mm. Using the method of Kille, the average yearly values of groundwater runoff varied from 64 mm to 206 mm; meanwhile, with the Local minimum method, the values ranged from 63 mm to 230 mm and finally with the use of Rambert's method the values determined ranged from 54 mm to 281 mm. The ratio, in which the groundwater runoff forms the total runoff from catchments in this hydrogeological unit ranged from 20% to 46, or from 19% to 51%, while using Kille's method and the Local minimum method, respectively. Additionally, when Rambert's method was applied, the values were determined in the range of 10–69% (Table 5).

In this hydrogeological unit, the catchment with lowest value of groundwater runoff determined by both the method of Kille and the Local minimum method was the Pčolinka creek catchment. This catchment is fairly large with an area of 71.11 km^2 but is also the catchment with the lowest mean elevation (384 m a.s.l.) among other catchments in this unit. The highest value of groundwater runoff determined by Kille's method was in a catchment of Hruštínka creek, which is also one of the larger (second largest; area = 78.67 km^2) catchments in this unit. In comparison with the Pčolinka catchment, it has the highest mean elevation in this group (858 m a.s.l.). On the other hand, when the Local minimum method was used, the highest value of groundwater runoff was established in the Pastovník creek catchment. Compared to the above-mentioned catchments, this is the smallest of all with an area of only 5.48 km^2, but with the second highest mean elevation (784 m a.s.l.). Also, using both Kille's method and the Local minimum method, the highest value of groundwater runoff to total runoff ratio was determined in this catchment. On the other hand, the lowest value of this ratio was calculated by both methods in the Vydranka catchment and Uličká catchment, with the same values (Table 5). Both of these catchments are fairly large (Uličká catchment being the largest with an area of 96.57 km^2) and have less than average mean elevation among the studied catchments in this unit (556 and 573 m a.s.l., respectively), while none of the catchments have a significantly rugged relief, with maximum TRI value of 28.31 (Table 2).

The results for catchments with the lowest and highest parameters of groundwater runoff vary with the use of Rambert's method, although the similarities of results obtained by the other two methods in the catchments morphologic characteristics are noticeable. The lowest values of groundwater runoff as well as groundwater runoff to total runoff ratio were determined in the Cirocha river catchment using this method, which is one

of the relatively larger (66.57 km^2), less rugged (TRI = 14.57) catchments with lower mean elevation (618 m a.s.l.) among other catchments in this unit (Table 2). The highest values of the above-mentioned groundwater runoff parameters were determined, using Rambert's method, in catchments of Hruštínka and Petrinovec creeks (Table 5). These catchments morphologic characteristics are fairly different. While the Hruštínka catchment (as described previously) is one of the larger, more elevated catchments, the Petrinovec catchment is the second smallest of the group (8.49 km^2), but has a relatively more rugged terrain (TRI = 21.94) with steeper slopes.

3.3. Unfolded Inner Carpathian Paleogene Hydrogeological Unit

The catchments representing the unfolded Inner Carpathian Paleogene unit were characterized by the average yearly total runoff determined in the range of 203–1043 mm. The average annual value of groundwater runoff for catchments in this unit determined by Kille's method ranged from 79 mm to 478 mm, by the Local minimum method it was determined from 78 mm to 469 mm and, determined by the Rambert's method, it varied from 89 mm to 460 mm. The values of groundwater runoff to total runoff ratio ranged from 28% to 58% when the method of Kille was used, from 27% to 57% while using the Local minimum method and by the Rambert's method it was determined in the range of values of 29–81% (Table 6).

The lowest value of groundwater runoff was determined in the catchment of the Bitarovský potok creek (less than average size and mean elevation; highest TRI) by both Kille's and the Local minimum method, while the highest value was determined by both said methods in the Čiernik creek catchment, which is the smallest catchment in this group with an area of only 2.69 km^2. The catchment with the lowest value of the groundwater runoff to total runoff ratio, determined by both above-mentioned methods was the Kamienka creek catchment, which is the second largest among other catchments in this unit (34.46 km^2), with relatively high mean elevation and terrain ruggedness index (Table 3). On the other hand, the highest value of this ratio was determined in the Lietava (6330) creek catchment by both said methods. This is one of the smaller catchments with less than average elevation (521 m a.s.l.) and the lowest rate of terrain ruggedness index (TRI = 9.33).

When the Rambert's method was used, the lowest values of groundwater runoff parameters (groundwater runoff; groundwater to total runoff ratio) were determined in the Jakubianka creek catchment, which is the largest catchment (54.16 km^2) in this unit with a mean elevation of 941 m a.s.l. The highest value of groundwater runoff was, on the other hand, determined by this method in the Čiernik creek catchment, which was already described previously and which corresponds with results obtained by the other two methods. Additionally, the highest value of the share in which groundwater runoff forms the total runoff of a catchment was determined by this method in the Lietava (6320) creek catchment.

3.4. Overall Overview of the Results in Studied Hydrogeological Units

Based on the values of groundwater runoff (baseflow) to total runoff ratio for individual catchments, average and median values were calculated for all three hydrogeological units determined by all three methods. Standard deviation was also determined for resulting values of each unit and method (Table 7).

Using Kille's method, it was determined that in the crystalline unit, groundwater runoff contributes an average of 44% to the total runoff, with the median value basically the same. For the folded flysch unit it was on average 29% with a median value of 25%, while for the unfolded sediments of the Inner Carpathian Paleogene it was on average 40%, or 38% for the median value.

Table 7. Overall statistical values of the groundwater to total runoff ratio for studied hydrogeological units. Q_{tot} represents total annual runoff, Q_{gw} represents baseflow/groundwater runoff.

HG Unit		Crystalline Rock	Folded Flysch Paleogene	Unfolded Inner Carpathian Paleogene
Count		19	16	7
Q_{gw}/Q_{tot} [%] Kille's method	Average	44.9	29.0	40.4
	Median	44.3	25.0	38.4
	St. Dev. [1]	6.0	8.3	10.8
Q_{gw}/Q_{tot} [%] Local minimum method	Average	43.9	28.9	39.3
	Median	42.9	24.3	35.6
	St. Dev.	6.4	9.4	11.0
Q_{gw}/Q_{tot} [%] Rambert's method	Average	55.8	37.4	49.6
	Median	56.0	36.0	44.1
	St. Dev.	14.2	14.8	17.3

[1] variation/dispersion of dataset.

The Local minimum method showed that the average share of groundwater runoff in the total runoff was determined at 45% in the catchments of the crystalline rock hydrogeological unit with a median value of 44%. For the hydrogeological unit of the folded flysch Paleogene sediments, it was 29% on average and the median was 24%, while for the unit of unfolded Inner Carpathian Paleogene sediments, the average value was 39% and the median was 36%.

The average and median share of groundwater runoff in the total runoff determined by the Rambert's method was 56% for the crystalline hydrogeological unit, 37% and 36% for the folded flysch Paleogene hydrogeological unit and 49% and 44% for the unfolded Inner Carpathian Paleogene unit.

As for the standard deviation calculated for the given groundwater to total runoff ratio datasets, the value for the crystalline hydrogeological unit was 6% for the Kille and Local minimum methods, while for the Rambert's method it was 14%. The deviation in the folded flysch Paleogene unit was determined at 8% by Kille's method, 9% by the Local minimum method and at 15% determined by Rambert's method. For the unfolded Inner Carpathian Paleogene hydrogeological unit, the value of standard deviation was 11% when determined by the Kille and Local minimum methods, while when determined by Rambert's method it was 17%.

4. Discussion

When discussing the hydrogeological properties of individual hydrogeological units, it should be considered that the study compares regolith zones—loosened and weathered near-surface zones of units several tens of metres (10–50 m) thick. However, it seems that the granitoids have apparently more massive (thicker) loosened zones, with fissure type of permeability, originally. Although, we assume that this is an intergranular type of aquifer type, as the fissures and cracks in the exposed part are filled with secondary filling formed by loose rock, or sediment, which is then associated with a higher rate of storativity. In this case, fissures and tectonics affect the circulation of groundwater in the deeper bedrock; however, much less groundwater circulates there.

Jetel already reported in the past [58] the exponential decrease in hydraulic conductivity with increasing depth. Geological history—the length of exposure to exogenous processes—could have played a more significant role in the development of the loosened zone in comparison to tectonic development of mostly closed fissure systems.

The main result of this study, from a hydrogeological point of view, is the share of groundwater runoff in total runoff from catchments. From these values, we observed that on average, the highest ratio of groundwater runoff to total runoff was determined in catchments of the crystalline rock hydrogeological unit by all three methods. The second highest share was determined in the unfolded Inner Carpathian Paleogene catchments and the lowest average value of this ratio was determined in the folded flysch Paleogene hydrogeological unit (Figure 12). In comparison to the Kille and the Local minimum methods, Rambert's method provided 10% higher values for all units, on average. The difference between Kille's method and the Local minimum method was relatively negligible—1% higher results on average, determined by the method of Kille (Table 7).

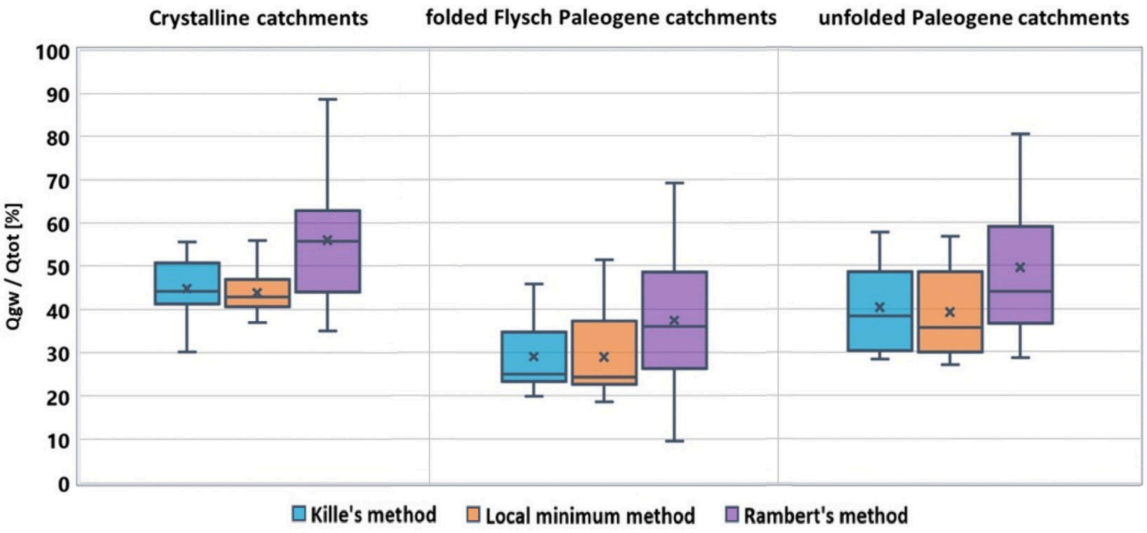


Figure 12. Visualization of statistical characteristics of the obtained results. Skewness, dispersion, and median of groundwater to total runoff values for each hydrogeological unit determined by each method used.

The spread of the data for the Kille and the Local minimum methods was generally smaller, compared to Rambert's method. The smallest overall spread was observed for catchments in crystalline rock hydrogeological unit, and specifically for Local minimum method baseflow determination, meaning that the most precise results for baseflow determination in crystalline rock catchments were achieved by this method. For folded flysch Paleogene catchments, we observed the smallest spread (highest precision) of results with the use of Kille's method. In the unfolded Paleogene hydrogeological unit, the spread was quite wide and quite similar for all three methods (Figure 12).

For every method and every hydrogeological unit, the data had a positive skewness, meaning that the average value was always higher than median value. The only exception was Rambert's method determination in the crystalline rock unit, where it was negative (Figure 12).

Overall, Kille's method and the Local minimum method showed very strong linear dependency, when the values of groundwater to total runoff ratio for individual catchments were correlated (Figure 13). The coefficient of determination R^2 showed a strong fit of 0.91 for crystalline and folded flysch Paleogene catchments and even stronger at 0.99 for unfolded Paleogene catchments, having in mind the different count of catchments in the studied hydrogeological units.

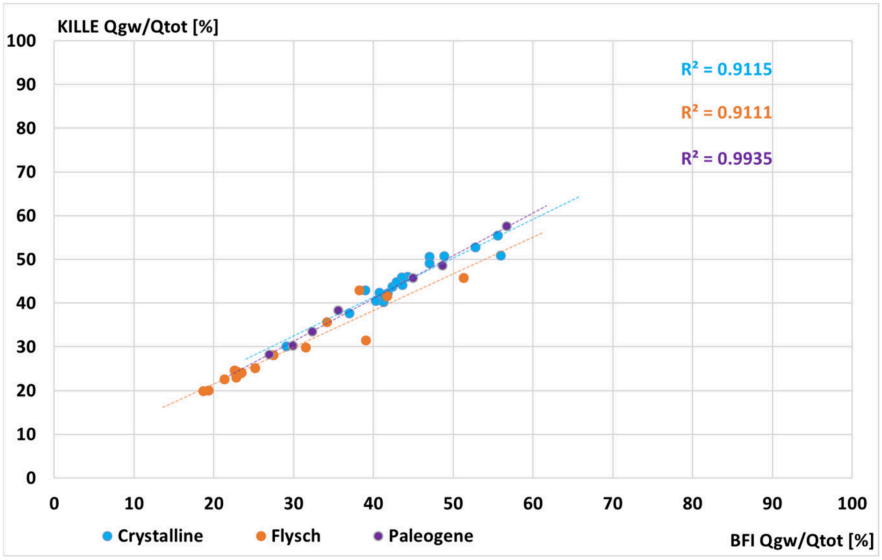


Figure 13. Comparison of results obtained by Kille's method (KILLE) and Local minimum (BFI) method for all studied catchments. Q_{tot} represents total annual runoff, Q_{gw} represents baseflow/groundwater runoff.

This was not the case when any of the two methods were correlated this way with Rambert's method (Figures 14 and 15). When compared to the individual values of baseflow to total runoff ratio determined by Kille's method for catchments of the crystalline hydrogeological unit, the coefficient of determination R^2 was only 0.08; for the folded flysch unit 0.20 and for the unfolded Paleogene it was only 0.07. The R^2 of the correlation between results determined by Rambert's method and Local minimum method was also quite low, at R^2 = 0.15, 0.17 and 0.08 for crystalline, folded flysch and unfolded Paleogene units, respectively. The comparison between Rambert's method and any of the other two methods was doubtlessly very similar, due to the good correlation between Kille's method and the Local minimum method.

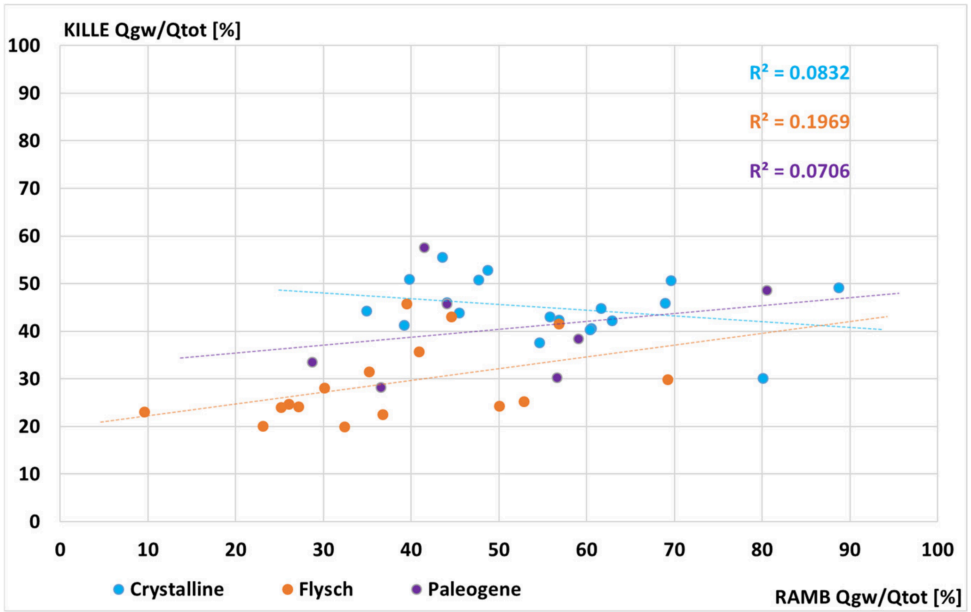


Figure 14. Comparison of results obtained by Kille's method (KILLE) and Rambert's method (RAMB) for all studied catchments. Q_{tot} represents total annual runoff, Q_{gw} represents baseflow/groundwater runoff.

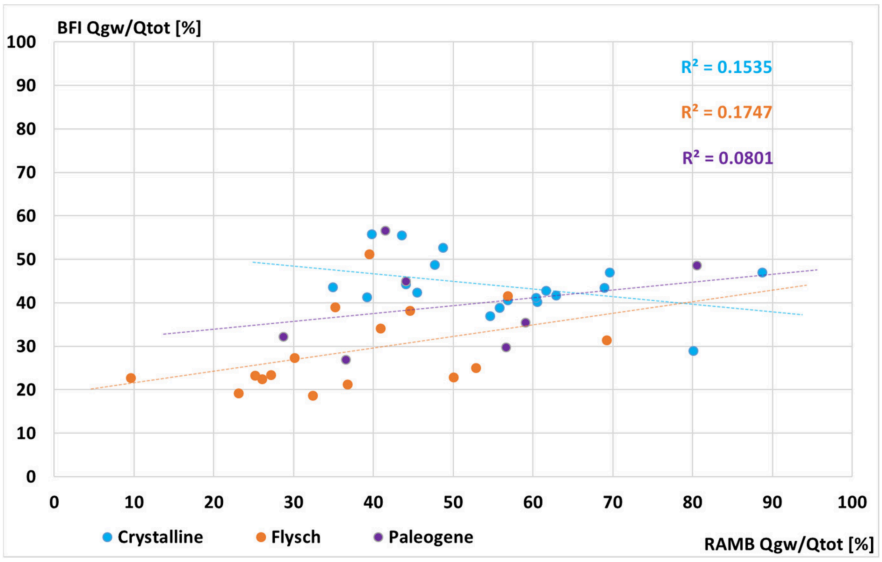


Figure 15. Comparison of results obtained by Local minimum (BFI) method and Rambert's method (RAMB) for all studied catchments. Q_{tot} represents total annual runoff, Q_{gw} represents baseflow/groundwater runoff.

While determining the baseflow with Rambert's method, the highly hybridized genetic algorithm was implemented for creation of the MRCs or master recession curves for individual catchments of each hydrogeological unit. The algorithm works with the cloud of data and tries to select one recession line, representing the data cluster of the most representative recession curve. Apparently, there could be an opportunity for the subjectivity of the algorithm during interpretation, in which the baseflow can be increased by inclusions of non-baseflow components (e.g., interflow), or on the other hand, decreased when low values arise from excessively rapid recession leading to underestimation of the baseflow component.

5. Conclusions

On the territory of Slovak part of the West Carpathian Mts., hydrographs of 42 catchments of uniform geological settings were analyzed for baseflow. Three different methods were applied—Local minimum (BFI), Kille's and Rambert's. Although the bedrock of the individual catchments was homogeneous, three bedrock groups of catchments could be distinguished: crystalline, folded flysch and unfolded flysch Paleogene sediments. Due to differences in mean catchments' altitudes ranging from 350 to 1632 m a.s.l., with an average of 796 m a.s.l., mean total annual runoff also varied from 179 to 1132 mm (average of 498 mm). The highest mean elevations were found in crystalline catchments (350–1632 m a.s.l.; 971 m a.s.l. in average); in the case of the two Paleogene catchments types, the altitudes were similar: 384–858 m a.s.l./644 m a.s.l. in average for folded Flysch and 416–1003 m a.s.l./670 m a.s.l. in average for unfolded Paleogene basement. Precipitation total in the area strongly depended on altitudes, which therefore means that the values of total annual runoff were in the range 193–1132 mm (average of 528 mm) in catchments with crystalline basement, 179–787 mm/488 mm in folded and 203–1043 mm/439 mm in unfolded Paleogene basement catchments.

In absolute values, highest baseflow in average was found also in 19 crystalline catchments (Local minimum method: 245 mm/Kille's method: 241 mm/Rambert's method: 296 mm) and the two Paleogene basement catchments were quite comparable, as there was slightly higher baseflow in 16 unfolded Paleogene claystone/sandstone catchments (182/177/207 mm) than in 7 catchments of folded Flysch basement (136/136/192 mm). In

general, baseflow values showed even higher correlation with the altitude than the total runoff values. Just like total runoff values, baseflow was ranging a lot within individual catchments both in the groups of detection methods as well as in the groups by basement rock types. For Kille's method it was 83–527 mm in crystalline, 64–206 mm in folded Flysch and 79–478 mm in unfolded Paleogene. For Local minimum method, baseflow results were in range of 75–527 mm in crystalline, 63–230 mm in folded Flysch and 78–469 mm in unfolded Paleogene. Rambert's method resulted generally in higher values, but in similar ranges: 108–683 mm in crystalline, 54–446 mm in folded Flysch and 89–460 mm in unfolded Paleogene. The whole catchments' dataset yielded ranges of 64–527 mm for Kille's method baseflow, 63–527 mm for Local minimum (BFI) method baseflow and 54–683 mm for Rambert's method baseflow.

For hydrogeological studies the most important parameter should be the ratio of baseflow in total runoff from the catchment, in other words, baseflow share shown in (%) values. Local minimum and Kille's method results were quite similar: in average baseflow was participating on 39%/40% of total runoff in unfolded flysch Paleogene catchments, on 29% according to both methods in folded flysch, and in the case of catchments with crystalline basement, baseflow represented 44%/45% of total runoff. Rambert's method results were different both in variability of individual baseflow ratio values (standard deviation of 19% in comparison to 11% in previous two methods) as well as in their difference from Local minimum and Kille's method results which were from 16% to 51% for the whole dataset. In general, baseflow ratio was 10% to 12% higher, reaching 50% in unfolded flysch Paleogene catchments, 41% in folded flysch and 56% in crystalline catchments.

In general, usually less than one half of unevaporated precipitation is able to infiltrate and recharge groundwater resources in crystalline rocks and flysch sediments, while especially folded flysch rocks are sometimes able to absorb only 10–20% of unevaporated precipitation.

We assume the differences between the used methods to be caused by nature of Rambert's method based on hydrograph recession curves analyses, while the previous two resulted from discharge statistics. Contrary to statistical methods or digital filters, the Rambert's baseflow separation method requires discharge curves analysis to be performed prior to baseflow separation to determine initial discharge rate and the recessional exponent at least for the baseflow component. In this way, its use might be affected by subjectivity of interpretation, even when automatic recession curve assemblages are applied.

Considering this, we concluded after the extensive assessment of the three methods used that the Kille's statistical method and the Local minimum baseflow separation method seem to be the most suitable, overall. Due to the negligible differences in the determination of groundwater runoff by these two methods, both methods are essentially interchangeable with very similar results achieved while using them. However, the difference between the applicability of both methods is the condition of a sufficient time series of streamflow observations. At least 10 hydrological years of observations are required to determine the baseflow by Kille's method, which is not always possible for time/funding-limited short-term research and the like. Unlike Kille's method, baseflow separation using the Local minimum method is possible on a much smaller dataset with comparable results. Therefore, we recommend the use of this method in the case of a lack of observations; otherwise, both methods can be used simultaneously, or independently. Also, regarding the differences between methods used in terms of distinct regolith zone assessment, the use of the Local minimum method seems to be more suitable for runoff analysis in crystalline rock environments characterized by fissure permeability and a more pronounced quick-flow part of the total runoff, on which this method showed the smallest spread in determination of baseflow. On the other hand, Kille's method showed the smallest spread of values in the

porous sedimentary environments of the Paleogene sedimentary catchments. Rambert's method showed a relatively high spread of determination of groundwater runoff in all three studied regolith environments. Although the overall mean difference in results compared to the other two methods was not that high (around 10%), the variability and standard deviation for individual catchments was significant.; therefore, we conclude that this method is not optimal for large-scale studies such as this one, if there are other, more precise methods available.

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Abbreviations

The following abbreviations are used in this manuscript:

SHMI	Slovak Hydro-Meteorological Institute
ISSOP	Integrated System for the Simulation of Runoff Processes
SGIDS	State Geological Institute of Dionýz Štúr
TRI	Terrain Ruggedness Index
BFI	Baseflow index
MRC	Master Recession Curve
HYSEP	Hydrograph Separation Program

References

1. Wundt, W. Die Niedrigwasserführung in Baden-Würtemberg als Maß für verfügbaren Grundwassermengen. *Gas-Wasserfach* **1953**, *24*, 719–722.
2. Wundt, W. Die Kleinstwasserführung der Flüsse als Maß für die verfügbaren Grundwassermengen. In *Die Grundwässer in der Bundesrepublik Deutschland und Ihre Nutzung*; Grahmann, R., Ed.; Forschungen zur Deutschen Landeskunde: Bonn, Germany, 1958; Volume 104, pp. 47–54.
3. Castany, G.; Margat, J.; Albinet, M.; Mellatoziére-Bouillin, O. *Evaluation Rapide et Cartographique des Ressources en L'eaux Souterraines D'une Grande Region (Aplication au Venezuela)*; Bureau de Recherches Géologiques et Minière: Orléans, France, 1972; pp. 2–26.
4. Kille, K. Das Verfahren MoMNQ, ein Beitrag zur Berechnung der mittleren langjährigen Grundwasserneubildung mit Hilfe der monatlichen Niedrigwasserabflüsse. *Z. Dtsch. Geol. Ges.* **1970**, *120*, 89–95. [CrossRef]
5. Fendeková, M.; Fendek, M. Killeho metóda—Teória a prax. *Podz. Voda* **1999**, *5*, 77–87.

6. Ineson, J.; Downing, R.A. The ground-water component of river discharge and its relationship in hydrogeology. *J. Inst. Water Eng.* **1964**, *18*, 519–541.
7. Ward, R.C. *Principles of Hydrology*; McGraw-Hill: London, UK, 1967; 403p.
8. Appleby, F.V. Recession and the baseflow problem. *Water Resour. Res.* **1970**, *6*, 1398–1403. [CrossRef]
9. Balek, J. *Groundwater Resources Assessment*; Developments in Water Science, 38; Elsevier Science B.V.: Amsterdam, The Netherlands, 1989; 245p.
10. Smakhtin, V.U. Low flow hydrology: A review. *J. Hydrol.* **2001**, *240*, 147–186. [CrossRef]
11. Lyne, V.; Hollick, M. *Stochastic Time-Variable Rainfall-Runoff Modeling*; Hydrology and Water Resources Symposium: Perth, Australia, 1979; pp. 89–93.
12. Nathan, R.J.; McMahon, T.A. Evaluation of Automated Techniques for Base Flow and Recession Analyses. *Water Resour. Res.* **1990**, *26*, 1465–1473. [CrossRef]
13. Chapman, T.G. A comparison of algorithms for streamflow recession and baseflow separation. *Hydrol. Process.* **1999**, *13*, 701–714. [CrossRef]
14. Sloto, R.A.; Crouse, M.Y. *HYSEP: A Computer Program for Streamflow Hydrograph Separation and Analysis*; USGS WRI Report; USGS: Lemoyne, PA, USA, 1996; 46p.
15. Pettyjohn, W.A.; Henning, R. *Preliminary Estimate of Ground-Water Recharge Rates, Related Streamflow and Water Quality in Ohio*; OSU Water Resources Centre Report 552; Ohio State University: Columbus, OH, USA, 1979; 323p.
16. Eckhardt, K. How to construct recursive digital filters for baseflow separation. *Hydrol. Process.* **2005**, *19*, 507–515. [CrossRef]
17. Eckhardt, K. A comparison of baseflow indices, which were calculated with seven different baseflow separation methods. *J. Hydrol.* **2008**, *352*, 168–173. [CrossRef]
18. Arnold, J.G.; Allen, P.M.; Muttiah, R.; Bernhardt, G. Automated baseflow separation and recession analysis techniques. *Ground Water* **1995**, *33*, 1010–1018. [CrossRef]
19. Collischonn, W.; Fan, F.M. Defining parameters for Eckhardt's digital baseflow filter. *Hydrol. Process.* **2013**, *27*, 2614–2622. [CrossRef]
20. Pelletier, A.; Andréassian, V. Hydrograph separation: An impartial parametrization for an imperfect method. *Hydrol. Earth Syst. Sci.* **2020**, *24*, 1171–1187. [CrossRef]
21. Tallaksen, L.M.; Van Lanen, A.J. (Eds.) Hydrological drought. In *Processes and Estimation Methods for Streamflow and Groundwater*; Development in Water Science 48; Elsevier: Amsterdam, The Netherlands, 2004; 579p.
22. Rambert, R. *Aplication de L'analyse des Hydrogrammes des Cours D'eau á L'évaluation de L'écoulement Souterrain*; Bureau de Recherches Géologiques et Miniéres: Orléans, France, 1971; 34p.
23. Tallaksen, L.M. Review of baseflow recession analysis. *J. Hydrol.* **1995**, *165*, 349–370. [CrossRef]
24. Fiorillo, F. The Recession of Spring Hydrographs, Focused on Karst Aquifers. *Water Resour. Manag.* **2014**, *28*, 1781–1805. [CrossRef]
25. Malík, M. Hydrograph separation into flow components using parameters of the master recession curve. *Podz. Voda* **2010**, *6*, 113–124.
26. Lamb, R.; Keith, B. Using interactive recession curve analyses to specify a general catchment storage model. *Hydrol. Earth Syst. Sci.* **1997**, *1*, 101–113. [CrossRef]
27. Posavec, K.; Bačani, A.; Nakić, Z. A visual basic spreadsheet macro for recession curve analysis. *Ground Water* **2006**, *44*, 764–767. [CrossRef] [PubMed]
28. Gregor, M. Software development for time-series analysis of springs yields and river discharges. *Podz. Voda* **2008**, *14*, 191–200.
29. Gregor, M.; Malík, P. Construction of master recession curve using genetic algorithms. *J. Hydrol. Hydromech.* **2012**, *60*, 3–15. [CrossRef]
30. Fiorotto, V.; Caroni, E. A new approach to master recession curve analysis. *Hydrol. Sci. J.* **2013**, *58*, 966–975. [CrossRef]
31. McMahon, T.A.; Nathan, R.J.; George, R. Incorporating natural variability in master recession curves. *Hydrol. Earth Syst. Sci.* **2026**, *30*, 893–903. [CrossRef]
32. Dovina, V. *Underground Runoff from Crystalline Complexes of Western Carpathians—Results of Evaluation and Their Possible Application on Solutions of Basic Hydrogeological Problems*; Western Carpathians, Hydrogeology and Engineering Geology Series 8; SGIDS: Bratislava, Slovakia, 1989; pp. 105–125.
33. Foster, E.E. Rainfall and Runoff. *Geogr. J.* **1949**, *114*, 215. [CrossRef]
34. Zakovič, M. *Hydrogeological Conditions in the Paleogene of the Levočské Vrchy Mountains*; Western Carpathians, Hydrogeology and Engineering Geology Series 2; SGIDS: Bratislava, Slovakia, 1980; pp. 231–272.
35. Krásný, J.; Hanzel, V.; Daňková, H.; Hanzel, V.; Kněžek, M.; Matuška, M.; Šuba, J.; Krásná, E.; Krásný, J.; Kullman, E.; et al. (Eds.) *Mapa Odtoku Podzemní Vody ČSSR 1:1,000,000*; Kartografie Praha, Czech Hydro-Meteorological Institute: Prague, Czech Republic, 1981.
36. Kessl, J.; Kněžek, M. Methods of baseflow calculations. *Podz. Voda* **2000**, *6*, 52–58.
37. Machlica, A.; Fendeková, M. Separation of runoff components using BILAN model in the Chvojnica river catchment. *Podz. Voda* **2006**, *12*, 135–147.

38. Stojkovová, M. Groundwater runoff of Slovakia. *Podz. Voda* **2007**, *8*, 146–152.
39. Dugovič, R.; Malík, P. Comparison of the groundwater runoff in different geological conditions of selected Western Carpathian watersheds using the method of Kille and BFI model. *Podz. Voda* **2021**, *27*, 51–60.
40. Dugovič, R.; Malík, P. Comparison of groundwater runoff of three different hydrogeological units in the Western Carpathians determined by Kille's and hydrograph separation methods. *Acta Geol. Slov.* **2024**, *16*, 99–106.
41. Chapman, T.G.; Maxwell, A.I. Baseflow separation—Comparison of numerical methods with tracer experiments. In Proceedings of the 23rd Hydrology and Water Resources Symposium, Hobart, Australia, 1 January 1996; pp. 539–545.
42. Gonzales, A.L.; Nonner, J.; Heijkers, J.; Uhlenbrook, S. Comparison of different base flow separation methods in a lowland catchment. *Hydrol. Earth Syst. Sci.* **2009**, *13*, 2055–2068. [CrossRef]
43. Igawami, S.; Tsujimura, M.; Onda, Y.; Shimada, J.; Tanaka, T. Role of bedrock groundwater in the rainfall–runoff process in a small headwater catchment underlain by volcanic rock. *Hydrol. Process.* **2010**, *24*, 2771–2783. [CrossRef]
44. Nejadhashemi, A.P.; Shirmohammadi, A.; Montas, H.J. Evaluation of streamflow partitioning methods. In *Proceedings of the ASAE Annual International Meeting, Las Vegas, NV, USA, 27–30 July 2003*; Pap. No. 032183; ASAE: St. Joseph, MI, USA, 2003.
45. Stoelzle, M.; Weiler, M.; Stahl, K.; Morhard, A.; Schuetz, T. Is there a superior conceptual groundwater model structure for baseflow simulation? *Hydrol. Process.* **2015**, *29*, 1301–1313. [CrossRef]
46. Vogel, R.; Kroll, C. Regional geohydrogeologic-geomorphic relationships for the estimation of low-flow statistics. *Water Resour. Res.* **1992**, *28*, 2451–2458. [CrossRef]
47. Latuamury, B.; Mardiatmoko, G.; Kastanya, A. Master recession curve visualization using seven baseflow recession models in paired watersheds. *J. Teknosains* **2024**, *14*, 1–17. [CrossRef]
48. Gregor, M.; Malík, M. *RC 4.0 User's Manual*; HydroOffice Software Pack for Water Sciences: Bratislava, Slovakia, 2010; 21p. Available online: http://www.hydrooffice.org (accessed on 21 October 2025).
49. Gregor, M. The usage possibilities of HydroOffice 2010 software for hydrologists and hydrogeologists. *Acta Geol. Slov.* **2011**, *3*, 95–104.
50. Jetel, J. *Methods for Regional Evaluation of Hydraulic Parameters of Rocks*; Metod. Příruč., sv. 1.; Ústřední Ústav Geologický: Prague, Czechoslovakia, 1985; 147p.
51. Nejedlík, P.; Poórová, J.; Škoda, P.; Blaškovičová, L.; Borodajkevyčová, M.; Podolinská, J.; Liová, S.; Lovásová, Ľ.; Fabišíková, M.; Pospíšilová, I.; et al. *Hydrological Yearbook of Surface Water 2010*; Hydrometeorological Institute: Bratislava, Slovakia, 2010; 227p.
52. Riley, S.J.; De Gloria, S.D.; Elliot, R. A Terrain Ruggedness Index That Quantifies Topographic Heterogeneity. *Int. J. Sci.* **1999**, *5*, 23–27.
53. Hók, J.; Pelech, O.; Teťák, F.; Németh, Z.; Nagy, A. Outline of the geology of Slovakia (W. Carpathians). *Miner. Slov.* **2019**, *51*, 31–60. [CrossRef]
54. Polák, M.; Plašienka, D.; Kohút, M.; Putiš, M.; Bezák, V.; Maglay, J.; Olšavský, M.; Filo, I.; Havrila, M.; Buček, S.; et al. (Eds.) *Vysvetlivky ku Geologickej Mape Regiónu Malé Karpaty 1:50,000*; SGIDS: Bratislava, Slovakia, 2012; 287p.
55. Malík, P.; Černák, R.; Švasta, J. Comparison of Resistive Hydraulic Properties of Granitoids, Metamorphic and Carbonate Rocks from Specific Discharge Data. In *Engineering Geology for Society and Territory—Volume 3: River Basins, Reservoir Sedimentation and Water Resources*; Lollino, G., Arattano, M., Rinaldi, M., Giustolisi, O., Marechal, J.C.H., Grant, G.E., Eds.; Springer: Berlin/Heidelberg, Germany, 2015; pp. 549–556. [CrossRef]
56. Potfaj, M.; Šlepecký, T.; Maglay, J.; Hanzel, V.; Boorová, D.; Žecová, K.; Kohút, M.; Nagy, A.; Teťák, F.; Vass, B.; et al. (Eds.) *Vysvetlivky ku Geologickej Mape Regiónu Kysuce 1:50,000*; SGIDS: Bratislava, Slovakia, 2003; 193p.
57. Žec, B.; Gazdačko, Ľ.; Kobulský, J.; Bóna, J.; Potfaj, M.; Pristaš, J.; Žecová, K.; Derco, J.; Kucharič, Ľ.; Marcin, D.; et al. (Eds.) *Vysvetlivky ku Geologickej Mape Nízke Beskydy—Stredná Časť 1:50,000*; SGIDS: Bratislava, Slovakia, 2011; 188p.
58. Jetel, J. *Permeability and Transmissivity of Near-Surface Rock Zone in the Western Tract of the West Carpathian Flysch Belt*; Western Carpathians, Hydrogeology and Engineering Geology Series 2; SGIDS: Bratislava, Slovakia, 1994; Volume 12, pp. 7–62.
59. Malík, P.; Švasta, J. Regional Values of Transmissivity Coefficient in Pre-Quaternary Rocks of Slovakia. *Eur. Geol.* **2013**, *35*, 46–53.
60. Mello, J.; Boorová, D.; Buček, S.; Filo, I.; Fordinál, K.; Havrila, M.; Iglárová, Ľ.; Kubeš, P.; Liščák, P.; Maglay, J.; et al. (Eds.) *Vysvetlivky ku Geologickej Mape Stredného Považia 1:50,000*; SGIDS: Bratislava, Slovakia, 2011; 378p.
61. Bajtoš, P.; Malík, P.; Černák, R.; Gavurík, J. Baseflow simulation using the recession coefficent in a spatially distributed hydrologic model—ISSOP project application in Slovakia. *Podz. Voda* **2016**, *22*, 51–60.
62. Kullmann, E. *Karst-Fissure Waters*; SGIDS: Bratislava, Slovakia, 1990; 184p.
63. Schroeder, G. *Die Grundwasserreserven der Flussgebiete*; *Bes. Mitt. Deutsch. Gewasserk. Jb., 13*; Bundesanstalt für Gewässerkunde (BfG): Koblenz, Germany, 1955; 30p.
64. Gregor, M.; Fendek, M. *Kille 3.1 User's Manual*; HydroOffice Software Pack for Water Sciences: Bratislava, Slovakia, 2012; 11p. Available online: http://www.hydrooffice.org (accessed on 21 February 2023).
65. Hall, F.R. Base-flow recessions—A review. *Water Resour. Res.* **1968**, *4*, 975–983. [CrossRef]

66. Stojkovová, D.; Fendeková, M. Temporal and spatial changes of groundwater runoff in Flysch belt area catchments in the northeastern part of Slovakia. *Podz. Voda* **2010**, *16*, 142–151.
67. Gregor, M. *BFI+ 3.0 User's Manual*; HydroOffice Software Pack for Water Sciences: Bratislava, Slovakia, 2010; 21p. Available online: http://www.hydrooffice.org (accessed on 1 March 2023).

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