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RESEARCH

The response of forested upland micro-watersheds to extreme precipitation in a precipitation abundant year

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Abstract
We performed a comparative paired catchment study of three headwater upland forest micro-catchments with different forest types in the precipitation-abundant year 2020. The analysis was based on baseflow separation and resulting baseflow index (BFI). The year 2020 was intentionally chosen as a way to reflect the expected effects of climate change in the region where more extreme hydroclimatic events are expected. Our team demonstrated that in case of hydroclimatic extremes, there are significant differences in the runoff response from these catchments, depending especially on the tree species composition in the forest stands. Three forest types with the predominance of European beech (*Fagus sylvatica*), Norway spruce (*Picea abies*), and mixed forest were analyzed. The observed different values of BFI were interpreted in relation to the ability of forest stands to retain water and slow runoff in extreme runoff events determined by the stormflow component as an indication of their flood control efficiency. A significantly worse flood control efficiency and an overreaction of runoff response to precipitation events were observed in the spruce catchment. This also suggests that the spruce catchment is more prone to suffer from drought since twice as much water was lost from the system during extreme hydroclimatic events as opposed to the other two with less spruce in the stands and less water is thus available for groundwater recharge.

1 Introduction

One of the fundamental impacts of global climate change (GCC) is its effect on forests. Forest stands in Europe are an important factor in the water cycle of the landscape; they significantly influence the parameters of the precipitation-runoff process and the water balance. The influence of forest vegetation on catchment runoff characteristics is well described in past and current literature, both in general terms (Winkler et al. 2021; Wang et al. 2019; Zhang et al. 2017) as well as during periods of low flows (Deutscher and Kupec 2014) and peak flows (Černohous et al. 2017). Streamflow characteristics are dominantly influenced by climatic factors (Miller et al. 2021; McMillan 2019; Woodhouse et al. 2016), geology, and land cover (Kuentz et al. 2017). In landscape water management, the influence of forest vegetation on flow quantities is more important than the annual volumes of water bound in vegetation (Hrachowitz et al. 2013). This all leads to forests being a key agent in mitigating the negative effects of GCC on the landscape scale. Since 2010, the drying out of forests in the region has been occurring due to the increase in temperature and associated increase of the evapotranspiration fraction (Kupec et al. 2021), manifested in decreasing ratio of runoff from the system (Bloomfield et al. 2019). It seems that with the changing conditions, the stressed forest stands are losing some of its ability to control the water balance parameters and that their role in the landscape is changing (Kupec et al. 2021). To sustain European forests, it is important to understand why and how these changes are propagated.

In Europe, there are two main groups of forest tree species — evergreen and deciduous, which both affect the water balance differently. The basic influence of evergreen and deciduous tree species on the hydrological cycle under normal weather conditions can be summarized as follows (Brinkmann et al. 2016; Rötzer et al. 2017): deciduous trees reach higher transpiration rates for a shorter part of the year (short growing season), evergreen trees exhibit lower transpiration but for a longer part of the year (longer growing season), and evergreen trees have higher interception all year long. In monocultures of Norway spruce (*Picea abies*) (the main evergreen species in the region), the shallow rooting trees, low quality litter, and dense rooted floor limit the infiltration

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into soils (Juřička et al. 2022), especially in periods of high precipitation (Du et al. 2019). One of the expected manifestations of GCC is the increasing extremity of weather (Ummenhofer and Meehl 2017), notably more frequent and more extreme precipitation and heat waves and droughts (McMillan et al. 2018). The influence of healthy forest vegetation on hydrological extremes in hydrologically standard years is described in the literature (Filoso et al. 2017; Krejčová 1994). However, in recent years in Europe, forests are subject to long-term stress due to the increasing lack of available water (Senf et al. 2020). While the forest stands consisting of tree species that are found in their ecologically optimal conditions are relatively resistant to these impacts or capable of adaptation, stands of tree species occurring on the border of their ecological optimum are recently showing signs of damage and degradation as a result of the impacts of GCC, e.g., the current bark beetle calamity in the Czech Republic (Zahradník and Zahradníková 2019). What would be the reaction of current forest stand types already negatively affected by the effects of GCC to extreme weather during extreme years is less well understood.

In 2020, the Křtiny catchment received the highest precipitation during the last 70 years (1950–2020) while Kanice and Útěchov catchments received the 2nd highest precipitation recorded during this period. For both catchments, this year was the 5th warmest in the 1950–2020 period (Cornes et al. 2018). We intentionally used this year only for the analysis of runoff response to extreme hydroclimatic events in three experimental headwater catchments with different tree species composition in the forest stands. The year 2020 was the most recent year where a high number of extreme precipitation events happened. Thus, the results can be a good indication of what can be expected in the future. We dealt with evaluation of the influence of forest vegetation on the transformation of hydrological extremes mainly by baseflow separation and baseflow index (BFI). The definition of baseflow is perceived differently by different authors (Smakhtin 2001; McMillan 2019). The basic idea of separating baseflow (the part of streamflow affected mainly by the water supply in the basin) and stormflow (the part affected by precipitation) has been studied for over a hundred years (Boussinesq 1904; Maillet 1905; Horton 1933); its use has not lost its importance even in recent studies (Xie et al. 2020; Taormina et al. 2015). In forested catchments, baseflow can be understood as runoff of surplus water that the forest stands (plant-soil system) did not physiologically use under standard hydroclimatic conditions (Filoso et al. 2017). Stormflow on the other refers to the fraction of runoff that leaves the catchment in a rapid manner without being able to be used by the trees. In forested headwater catchments under conditions when the runoff is predominated by baseflow, streamflow is primarily influenced by the forest stand type and its predominating tree species (Kupec et al. 2018).

There are a number of methods of baseflow separation with different levels of complexity (Mohammadlou and Zeinivand 2019). Baseflow can also be measured by direct methods such as chemical and radioactive tracers (Chapman 1999). However, these methods are time-consuming, expensive, and complex. No matter what baseflow separation technique is used, the results are usually quite similar, and it is a widely used approach, even though there is lack of presentation of the physical processes (Lu et al. 2022). Here we used the local minimum method (Gregor 2010) as a fast and efficient way to quantitatively estimate the baseflow and to estimate the importance of groundwater influence in the experimental catchments (Wrede et al. 2015). The so-called baseflow index (BFI) then indicates the proportion of baseflow to the total runoff. The value of this parameter is influenced by a number of factors — geological, morphological, climatic, vegetation, etc., and it is indicative of the baseflow proportion and its residence time (Hrachowitz et al. 2014). In a situation where all the above-mentioned factors are very similar or identical, we assume that the nature of the vegetation cover of the catchment has the highest influence on this parameter (Ledesma et al. 2019).

The presented article uses the paired catchment experiment design to compare the runoff response of three headwater forested catchments with different predominant tree species in the forest stands in the uplands of Central Europe to hydroclimatic extreme events in a precipitation abundant year. It strives to showcase how current forest stands react to these extremes in a time when the extremity of weather is predicted to become the new normal.

2 Material and methods

2.1 Experimental catchments

The research area is in the uplands of the Czech Republic in South Moravian Region in the territory of the TFE (Fig. 1). There are three experimental micro-watersheds designed as paired catchments of relatively similar size, natural conditions, shape, and morphology (Table 1) with different tree species composition: Kanice (KA) with a predominance of mixed spruce-beech stands, Křtiny (KR) with mainly spruce stands, and Útěchov (UT) with a predominance of beech stands (Table 2). The analysis of the current species composition was carried out by remote sensing using data from the Sentinel-2 satellite (Fernandez-Carrillo et al. 2020). All the forest stands are fully stocked with the exception of clearings after harvest. Forest stand units older than 50 years are represented by 57%, 35%, and 56% in Kanice, Křtiny, and Útěchov, respectively (Lesprojekt Brno corp 2013).

All three catchments are located close to each other (less than 10 km) in the Brno massif, which is mainly made up of

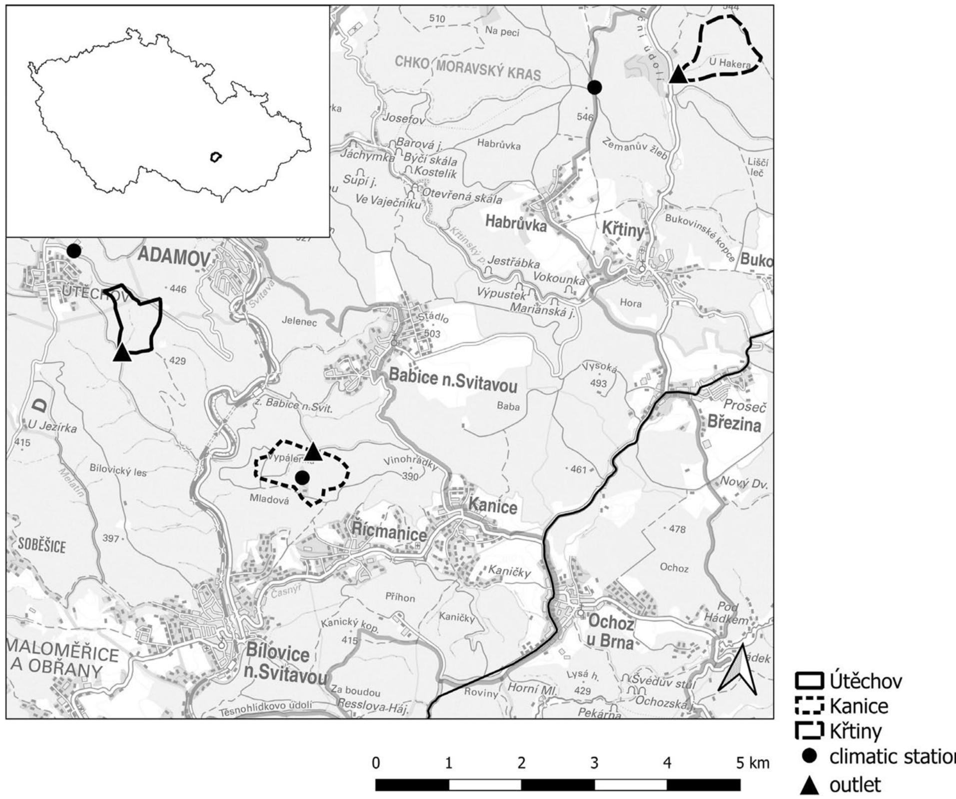

Fig. 1 Localization of the micro-catchments within the Czech Republic

granodiorites (Bajer 2015). They have similar morphological characteristics (they are elongated spring valleys). The climate of the region is moderately warm (Quitt 2009); the differences in the micro-climate are determined by the relief and altitude. According to the long-term climatic standard 1980–2010 (Czech Hydrometeorological Institute 2022) the mean annual temperature reaches 10.0 °C and precipitation 511 mm (Brno, Tuřany; 49.153°N, 16.688°E); in 2020 the precipitation reached 642 mm. In 2020, the annual precipitation totals measured at own field climate stations reached 851 mm, 908 mm, and 878 mm for KA, KR, and UT, respectively. The year 2020 significantly exceeded the average precipitation totals in all three catchments.

2.2 Methodology

Based on our own measured field climatic and streamflow data from the whole year 2020 in three forested micro-catchments with different stand types (species composition), a comparative analysis of the parameters of the rainfall-runoff process was performed. This was done as a comparison of the hydrographs from individual catchments. Baseflow separation was used to identify extreme runoff events (ERE), which were further analyzed. A set of precipitation and runoff characteristics of EREs from individual catchments were compared against each other. Lastly, a correlation analysis using linear regression in EREs was carried out with the aim of finding if any of the precipitation characteristics could be used to determine resulting runoff characteristics.

2.2.1 Data acquisition

Streamflow was estimated from the water level values using preset rating curve for Thomson weir installed in the discharge profiles of all three micro-catchments (Fig. 1). The water level was measured by ultrasonic sensors US3200 connected to a HYDRO-LOGGER H2 datalogger (Fiedler Automatic Monitoring Systems AMS, České Budějovice, CR) in 15-min intervals. Air temperature and precipitation were recorded in three climatic stations located inside or in the vicinity of the experimental watersheds (Fig. 1; MeteoUNI, Amet, Velké Bílovice, Czech Republic). The climatic stations were installed in forest clearings according to the methodology of the International Co-operative Program (ICP) Forest manual (Raspe et al. 2010). The recording interval was set to 15 min similar to streamflow.

2.2.2 Data preparation

Streamflow, air temperature, and precipitation data were processed into a database of mean/total daily values for the whole year 2020. This database was cleaned of missing or erroneous data caused by battery failure in the water level sensor. Streamflow values were later converted to total daily

Table 1 Hydro-geomorphological parameters of the experimental catchments

Experimental catchment parameters	KA	KR	UT
Afforestation (%)	98	100	100
Main tree species composition	Mixed	Norway spruce	European beech
Main stream length (m)	640	770	660
Main stream elevation max (m a. s. l.)	330	490	371
Main stream elevation min (m a. s. l.)	287	455	333
Main stream gradient (%)	6.7%	4.5%	5.8%
All streams length (m)	970	770	815
Mean altitude (m)	330	510	388
Thalweg length (m)	1030	1090	980
Mean slope gradient (%)	17	21	38
Total basin area (ha)	65	57	38
Basin perimeter (m)	3630	3218	3052
Exposure	North	East	South-east
Geologic subsoil, soil type	Cambisole/granodiorite	Cambisole/graywacke	Cambisole/granodiorite
Average flow rate (L/s)	0.44	0.5	0.39
Average specific discharge (L/s/km^2)	0.68	0.88	1.03
Mean annual temperature (°C)/precipitation (mm) 1990–2020 (Cornes et al. 2018)	9.31/514	9.31/514	9.31/514
Mean annual temperature (°C)/precipitation (mm) 1980–2010 (CHMI 2022)	8.9/559	8.9/559	8.9/559
6-h rainfall periodicity (mm, return time in 2/10/100 years) (Vizina et al. 2015)	29.3/49.1/81.2	30.2/51.6/89.3	29.3/49.1/81.2
Catchment shape analyses			
Shape factor (B_s) (Horton 1932)	1.63	2.08	2.53
Elongation ratio (R_e) (Schumm et al. 1956)	0.50	0.44	0.40
	Elongated	More elongated	More elongated
Compactness coefficient (C_c) (Gravelius 1914)	2.25	2.13	2.48
Fitness ratio (R_f) (Melton 1957)	0.28	0.34	0.32

Table 2 Tree species composition (%)

	Clearing	European beech	Norway spruce	Common oak	Scots pine	European larch	Total
Kanice	4	44	25	6	15	6	100
Křtiny	1	39	56	1	3	-	100
Útěchov	5	52	3	34	5	1	100

runoff (m^3/day) from each catchment. This resulted in 347, 366, and 356 days of streamflow data in KA, KR, and UT, respectively. In the next step, the separation of the hydrograph was carried out in order to identify the daily baseflow values. Baseflow separation was performed using the local minimum method (Gregor 2010) in the BFI + program (version 3, build 7; www.hydrooffice.org). The local minimum method assumes that the baseflow varies linearly between minimum runoff values. These values occur in an interval of a specific number of days [$0.5(2N^* - 1)$], where $2N^*$ is the odd number closest to $2N$ (Sloto and Crouse 1996; Aksoy et al. 2009). The value of N can be determined from the empirical relationship (Institute of Hydrology 1980):

$$N = 0.83A^{0.2} \tag{1}$$

where A is the area of the catchment in km^2.

The N for the individual catchments was as follows:

$$\text{KA}: N = 0.83 \times 0.65^{0.2} = 0.83 \times 0.917 = 0.76 \doteq 1$$

$$\text{KR}: N = 0.83 \times 0.57^{0.2} = 0.83 \times 0.893 = 0.74 \doteq 1$$

$$\text{UT}: N = 0.83 \times 0.38^{0.2} = 0.83 \times 0.824 = 0.683 \doteq 1$$

In the case of all three catchments, the N value reached 1, so BFI + would apply a local minimum of 0.5 N steps forward and 0.5 N steps backward. Given that the analysis was performed on daily data, the closest whole number was used, which was 1 day forward and 1 day backward which effectively corresponds to $N = 2$.

Following the baseflow value, the so-called BFI index was also calculated as the ratio of baseflow to runoff (Yao et al. 2021) reaching values from 0 (when baseflow does not contribute to runoff and 100% of runoff is formed by stormflow) to 1 (when 100% of runoff is formed by baseflow). In relation to forest cover, stormflow is interpreted here as unavailable water that rapidly leaves the catchment without being used by forest stands. As such the BFI index thus indirectly refers to the retention capacity of the catchment and its water use efficiency (Kupec et al. 2018).

2.2.3 Extreme runoff episode identification

Episodes in which the daily runoff exceeded the 90th percentile (72.76 m^3 in Kanice, 420.63 m^3 in Křtiny, and 83.99 m^3 in Útěchov) determined from the cleaned daily values in 2020 were graphically separated from the hydrographs of all catchments (Figs. 2, 3, and 4). The 90th percentile of exceedance was used as a reasonable option to determine above-normal-extreme runoff cases

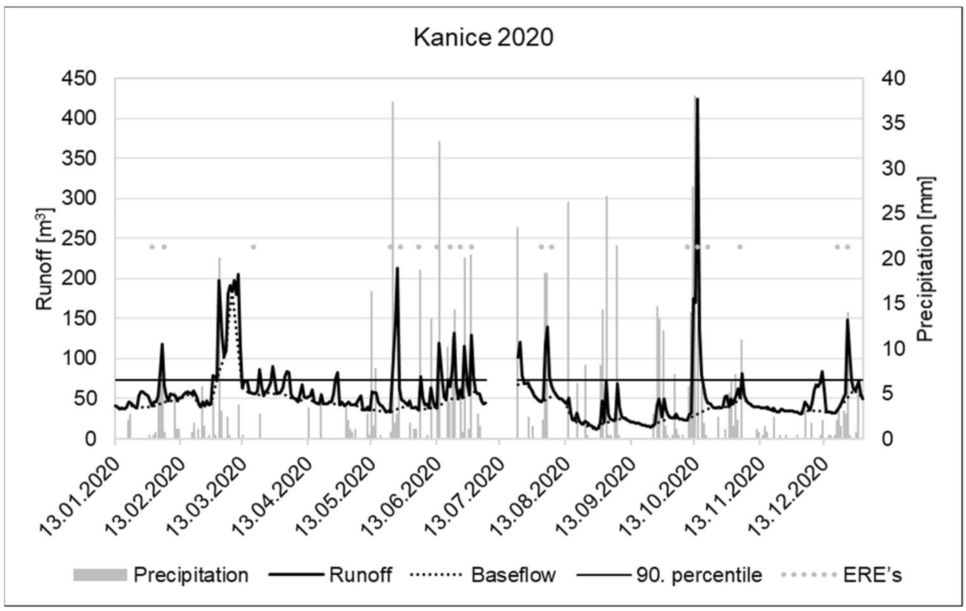

Fig. 2 Daily runoff (full thick, black), its 90th percentile (full thin, black), baseflow (dotted, black), and precipitation (full, gray) in KA (mixed). The time and duration of the EREs (dotted, gray) above the hydrograph

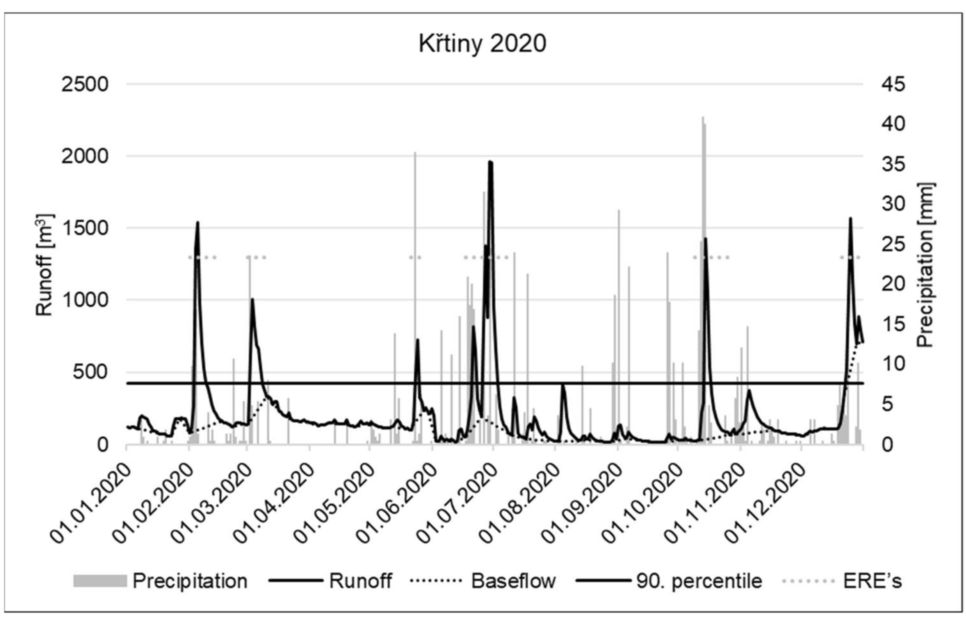

Fig. 3 Daily runoff (full thick, black), its 90th percentile (full thin, black), baseflow (dotted, black), and precipitation (full, gray) in KR (spruce). The time and duration of the EREs (dotted, gray) above the hydrograph

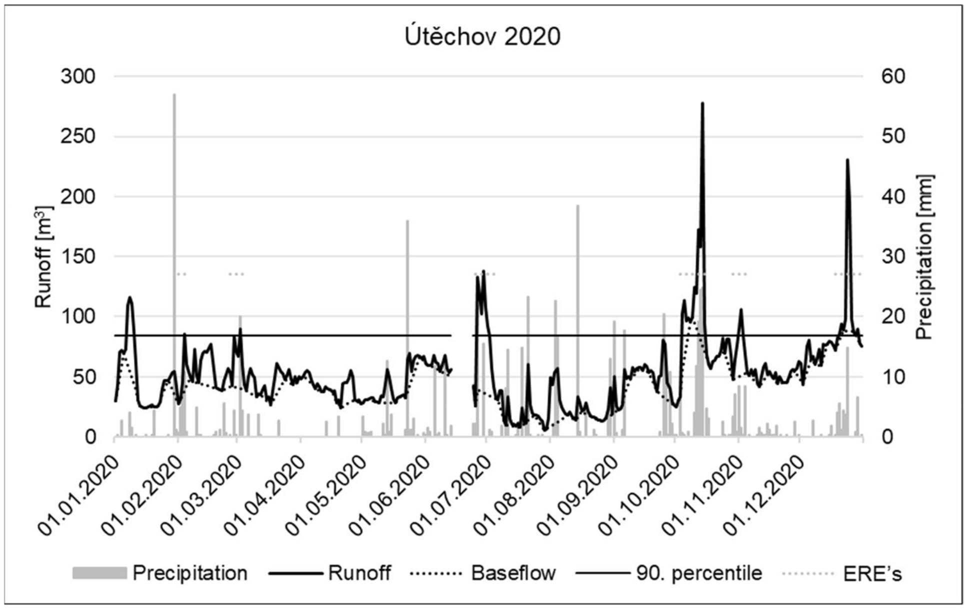

Fig. 4 Daily runoff (full thick, black), its 90th percentile (full thin, black), baseflow (dotted, black), and precipitation (full, gray) in UT (beech). The time and duration of the EREs (dotted, gray) above the hydrograph

(Willems and Lloyd-Hughes 2016). When exceeded, the nearest corresponding intersection of baseflow and runoff was considered as the beginning of the extreme runoff episode (ERE), i.e., when the BFI reached the value of 1. The end of the period was then identified as the day in which the BFI reached the value of 1 again. For all EREs (a total of 31 episodes identified in the three catchments), detailed hydrographs including runoff and baseflow were processed. After a visual evaluation of these hydrographs, some were excluded from further evaluation for objective reasons (see below). Each ERE was then described by a set of the following precipitation and runoff characteristics:

- Precipitation total — the total amount of precipitation in mm for the duration of the episode
- Mean daily rainfall intensity — rainfall total/episode duration
- Maximum daily precipitation — the highest daily precipitation total in mm throughout the episode
- Duration of the episode — the lasting of the episode in days bounded by the days when the BFI index reached a value of 1
- Runoff — total runoff for the duration of the episode calculated from mean daily values in mm
- Baseflow — total baseflow for the duration of the episode calculated from mean daily values in mm
- Stormflow — this was calculated as a complement of baseflow to runoff in mm
- Average BFI — is referred to as flood control efficiency; it was determined as the proportion of total baseflow to runoff of all days in the episode
- Minimum BFI — equals to the lowest BFI throughout all days in the episode
- Median BFI — this was calculated as the median value of BFI from all days in the episode.

The minimum BFI refers to the day on which the lowest BFI value was reached in any given ERE. The lower the min BFI, the more significant portion of runoff was composed of stormflow. In regard to the retention capacity of the catchments, this parameter can be interpreted as a determinant of the absolute capacity of the catchment to mitigate extreme runoff (stormflow). Min BFI was thus further used as an indicator of so-called flood control efficiency (FCE in %).

2.2.4 Data evaluation

The relationship (degree of dependence) between individual precipitation and runoff parameters during ERE was evaluated based on the strength of the linear regression correlation according to the following equation:

$$Correl(X;Y) = \frac{\sum (x-\bar{x})(y-\bar{y})}{\sqrt{\sum x-\bar{y})^2 \sum (y-\bar{y})^2}}$$

where x are the values of the individual precipitation parameters (independent variable) and y of the runoff parameters (dependent variable). Correlation coefficients were used to evaluate which precipitation factors are most important for runoff generation during ERE. Correlation values greater than 0.8 were considered excellent correlation and values less than 0.2 poor correlation (Akoglu 2018).

3 Results

3.1 Hydrological response of the catchments in the precipitation abundant year 2020

The hydrographs here (Figs. 2, 3, and 4) are a graphical representation of daily runoff (m^3), its 90th percentile, daily precipitation totals, and baseflow (m^3) in the calendar year 2020 for individual basins. A total number of 31 EREs were identified during 2020: 8 in KR, 13 in KA, and 10 in UT. Despite significantly above-normal precipitation totals, the runoff coefficient remained at low values (Table 3). This indicated the tendency of the forest stands (plant-soil system) to restore water reserves in the system during wet conditions depleted in the previous period (antecedent drier years). The median BFI for all catchments was remarkably similar and reached above 0.9, while the average BFI values were about 10–15% lower for all three of them. This indicated the importance of EREs on the overall formation of runoff during this year in all three catchments. However, the runoff from the spruce catchment KR was significantly higher than from the other ones with less spruce in the stands. Higher value of the 90th percentile in KR also indicated a significantly more erratic runoff behavior in the spruce catchment. This was indicated by lower mean BFI to median BFI in KR as well. Since the BFI in the spruce catchment was significantly lower than in the other two catchments, the share of unused water in the form of stormflow was also significantly higher there. This increases the amount of runoff but limits the ability of the stands to restore soil water reserves.

3.2 EREs — hydrological response of studied catchments during extreme runoff events

Due to the conclusive importance of EREs for contributing to the total annual runoff from the catchments in the precipitation abundant year 2020, the next step was to parameterize the rainfall-runoff process in individual EREs in more detail so that it was possible to quantify the extent of their influence on runoff generation, and in the context of the different tree species composition of the individual catchments. Detailed flood hydrographs including stormflow above the baseflow lines were processed for the duration of all EREs (a total of 31 episodes). Some EREs, especially occurring in the winter, were excluded from further evaluation after a visual inspection because

Table 3 Basic summary characteristics of the rainfall-runoff process in 2020 in KA (mixed), KR (spruce), and UT (beech) catchments

2020	Annual precipitation	Valuated days of streamflow data (VD)	Precipitation in valuated days (mm)	Specific runoff (L/year/m^2)	Runoff coefficient (%)	90th runoff percentile (m^3/day)	Mean daily runoff (m^3/day)	Mean daily baseflow (m^3/day)	Mean BFI	Median BFI
KA	851	347	785	29.61	3.77	72.76	55.62	42.14	0.85	0.95
KR	908	366	908	129.25	14.23	420.63	201.85	106.93	0.75	0.90
UT	878	356	755	47.66	6.31	83.99	52.87	41.32	0.83	0.91

Valuated days – days of available streamflow data; *specific runoff* = total runoff in VD/catchment area; *runoff coefficient* = total runoff in VD/precipitation in VD they were being caused by sources other than precipitation — freezing of the stream which increased the registered water level because of the icy crust above water level, melting of snow which we could not correctly capture due to not heated rain gauge, etc. Overall, the main sources of error or high levels of uncertainty in the measured data came from either the stream freezing solid, the spillway getting clogged by debris, or battery failure (Deutscher et al. 2021). Four periods in KA and one period in UT (Supplementary) were removed from further evaluation for these reasons. In total, 26 EREs entered the next evaluation, namely, 9 in KA, 8 in KR, and 9 in UT. The evaluated EREs were analyzed based on a set of descriptive characteristics that evaluate both the characteristics of the precipitation that caused the increased runoff and the characteristics of the resulting runoff (Supplementary).

During the EREs, total precipitation reached 387, 353, and 272 mm for KA, KR, and UT, respectively, which corresponds to 49, 39, and 36% of total annual precipitation in the catchments (Table 4). This underlines the importance of these periods for the overall annual water balance. This also means that over 35% of annual precipitation in 2020 in all catchments fell during extreme precipitation events. The average duration of EREs was 7 days in both KA and UT while the stormflow lasted 4 more days (11 days on average) in KR. This might be indicative of different behavior of the spruce catchment. The total daily runoff during EREs reached 9, 76, and 15 mm for KA, KR, and UT, respectively, accounting for 30.4, 58.8, and 31.5% of the total annual runoff from the catchments. Again, it is evident that during EREs, the KR spruce catchment behaves differently to the other two. What is more, in KR, almost 60% of the annual runoff occurred during extreme hydroclimatic events even though they had been caused only by 39% of annual precipitation. This is approximately double the amount of runoff during EREs from the other catchments with predominantly deciduous and mixed tree species composition despite the relatively similar precipitation amounts. The importance of EREs for the formation of runoff (or the retention of the flood waves) in the spruce catchment was extremely relevant. The flood control efficiency (FCE, min BFI reached) during EREs reached average values of 33, 23, and 52% with average precipitation of 38.7, 51.9, and 24.8 mm for KA, KR, and UT, respectively. During a more detailed analysis of the most extreme precipitation events, an indication of the limit of the basin's retention capacity could be observed:

In KA, compared to the mean FCE 33%, low FCE was reached 2 times in a period of 118-mm total precipitation (FCE was 7%) and a period of 50 mm (17%);

In KR, compared to the mean FCE 23%, low FCE was reached in several EREs with total precipitation of 132 mm (3%), 52 mm (6%), and 74 mm (8%);

In UT, compared to the mean FCE 52%, FCE never went below 27%, which was reached twice in EREs with 92 and 42 mm.

3.3 Comparison of catchment response in EREs — what was the determining precipitation parameter for the runoff behavior?

A significant difference in the hydrologic behavior of forested micro-catchments with different tree species composition in a precipitation abundant year was found. The importance of EREs for runoff generation during these extreme hydroclimatic conditions was noted. The results of the following analysis were intended to find out whether there was a specific parameter of the precipitation events that generally determined the runoff response during EREs or if such a parameter was different in catchments with different tree species composition in the stands (Table 5).

There was no precipitation characteristic that could be universally deemed as significantly correlated to the presented runoff characteristics (Table 5). The overall most significant correlation characteristic across all catchments

Table 4 Summary of the descriptive sets of precipitation and runoff characteristics during all EREs

	KA mixed				KR spruce				UT beech			
	Min	Max	Avg	Tot	Min	Max	Avg	Tot	Min	Max	Avg	Tot
Duration of the ERE (days)	4	13	7.4	74	4	18	11.1	89	4	12	7.2	65
Precipitation (mm)	2.7	118.0	38.7	387	10.9	101.3	51.9	353	7.7	92.1	24.8	272
Mean precipitation daily intensity (mm)	0.5	9.1	5.0	50	3.1	8.7	5.1	41	1.3	10.2	3.5	35
Max daily precipitation (mm)	2.7	38.1	20.7	207	5.4	46.6	24.0	199	5.6	24.8	13.2	119
Runoff (mm)	0.5	2.0	0.9	9	4.1	17.8	9.5	76	0.9	3.1	1.7	15
Baseflow (mm)	0.3	0.7	0.5	5	1.4	6.8	3.6	29	0.7	1.9	1.1	10
Stormflow (mm)	0.1	1.4	0.3	4	0.5	14.2	5.0	48	0.0	1.5	0.5	5
FCE (%)	7	45	33		3	79	23		27	91	52	
Mean BFI (%)	59	81	74		46	92	61		56	98	78	

For individual EREs see Supplementary

Table 5 Results of the linear regression between the independent precipitation (in the first column) and the dependent runoff characteristics during EREs

	Precipitation characteristics	Runoff	Baseflow	Stormflow	Flood control efficiency FCE (Min BFI)	Mean BFI	Overall mean correlation of presented characteristics
KA (mixed)	Precipitation total	**0.85**	0.13	**0.95**	*0.79*	**0.83**	***0.71***
	Mean precipitation daily intensity	0.14	0.13	0.32	0.23	0.40	0.24
	Max daily precipitation	0.23	0.05	0.41	0.59	0.59	0.37
KR (spruce)	Precipitation total	0.02	0.52	0.18	0.47	0.51	0.34
	Mean precipitation daily intensity	0.23	0.55	0.04	0.11	0.07	0.20
	Max daily precipitation	0.00	0.43	0.09	0.38	0.31	0.24
UT (beech)	Precipitation total	***0.70***	0.60	0.54	0.42	0.26	0.50
	Mean precipitation daily intensity	0.56	0.66	0.33	0.28	0.10	0.39
	Max daily precipitation	0.62	0.28	***0.71***	0.61	0.55	0.55

Note: Significant correlation (0.8 and above) is highlighted in bold. Weaker but still possibly relevant correlation 0.70–0.79 is presented in bold italics

was found in total precipitation. Although it did exhibit very different values across the catchments reach on average 0.71, 0.34, and 0.50 in KA, KR, and UT, respectively. In the case of the mixed catchment KA, duration of EREs was also supplemented by total precipitation (0.7). Overall, the KR spruce catchment indicated the lowest correlation of precipitation to runoff characteristics.

In more detail, the results showed the following:

In KA (mixed), the runoff characteristics during EREs were most influenced by the precipitation total (three correlation coefficients exceed the limit of significant correlation 0.8; the average degree of correlation reached 0.71 for precipitation). The intensity of precipitation and the maximum daily total were not significant (on average 0.24 and 0.37). FCE was the most dependent on total precipitation (0.79) and the least on mean precipitation intensity (0.23).

In KR (spruce), none of the precipitation characteristics of EREs did strongly affect the runoff characteristics (no parameter reached over 0.55) even though total precipitation was the strongest correlated parameter. The other precipitation characteristics showed even weaker correlation (0.20 and 0.24). FCE was the most dependent on precipitation (0.47).

In UT (beech), runoff characteristics during EREs were most influenced by maximum daily precipitation (0.55 on average) and total precipitation (0.50). Mean precipitation intensity was not so significant (0.39). FCE was the most dependent on maximum daily precipitation (0.61).

4 Discussion

A total of 26 EREs (with an average duration of 7–11 days) were evaluated in three headwater forested catchments in 2020. Their share of the total runoff ranged from 30.4% in the KA mixed catchment to 58.8% in the KR spruce catchment which we consider to be very significant, both for the importance of hydroclimatic extremes on total streamflow, runoff, and annual water balance but also as an indicator of distinctly different hydrological behavior of catchments with different forest stand types.

This difference was further accentuated during extreme runoff events (EREs) following extreme precipitation. It could be observed in the different volume and dynamics of runoff characteristics. We derive these differences mainly from (i) the generally different ecohydrological properties of the different predominant tree species (evergreen vs. deciduous) that make up the forest stands of the described catchments (Švihla et al. 2012; Ledesma et al. 2019; Kupec et al. 2021) and (ii) the influence of climate change on these stands, especially in the KR spruce catchment (Švihla et al. 2014; Deutscher et al. 2016; Rötzer et al. 2017). The results of our study show that while the mixed catchment KA and the beech catchment UT managed to continue to exhibit relatively high levels of FCE even under extreme hydroclimatic conditions, the spruce catchment KR overreacted to these circumstances by an immediate and radical increase in stormflow runoff.

Analysis of BFI was used to identify the different behavior of the three catchments under hydroclimatic extreme conditions. Baseflow volumes and the BFI index can be both usually strongly correlated with the relief and gradient of the catchment (Santhi et al. 2008). To mitigate the potential mixing signal of the terrain configuration, the paired catchment experiment was used and extensive analysis of the shape and other relevant hydro-geomorphological parameters of the three catchments were performed (Table 1). The comparison is complex. However, it can be concluded that all three catchments are quite similar with regards to location, size, and the hydrographic network. The gradient and shape analysis showed that UT (beech) is steeper and prone to faster runoff response as compared to the other two KA (mixed) and KR (spruce). Notably KR is in the highest altitude (510) as compared to KA (330) and UT (388 m a. s. l.) which was manifested by slightly higher total precipitation. However, the steeper slopes of UT and resulting expected higher volumes of runoff from this catchment were not supported by our data. It seems that in the described conditions, the dynamics of BFI were mostly driven by and can mainly be attributed to the tree species composition in the forest stands.

Even though baseflow separation techniques usually offer similar results (Lu et al. 2022), we tried to mitigate the limits of the baseflow calculation method used (local minima) by calculating average BFI on studied catchments using another four methods: fixed interval (Sloto and Crouse 1996), sliding interval (Sloto and Crouse 1996), BFLOW (Lyne and Hollick 1979), and EWMA filter (Tularam and Ilahee 2007). Even though they offer slightly varying results (Table 6), the calculations still indicate a distinctly different behavior of the spruce Křtiny catchment compared to the other two. Regardless of the technique used, rather similar behavior of the Kanice and Útěchov can be observed which is consistent with the way we interpret the results.

We therefore assume that the difference in the dynamics of the immediate catchment response to extreme precipitation events is primarily affected by the present stand type, i.e., its tree species composition (Bosch and Hewlett 1982; Kantor 1995; Kantor et al. 2003). Our team previously demonstrated that the catchment water use efficiency (cWUE) for spruce stands in the temperate uplands is lower compared to catchments with deciduous and mixed stands in dry (precipitation-free periods) (Kupec and Deutscher 2017). Here we now show that this is also true in case of the other extreme — above-normal precipitation. This comes as a surprising effect since spruce stands are usually associated with high flood control potential better than beech in the same areas (Hümann et al. 2011) also even at the headwater small catchment scale (Wahren et al. 2012). However, hints of this have been mentioned before with regards to the expected shift of tree species composition in the region to better combat drought (Lange et al. 2013). It seems that evergreen forests have a higher water use efficiency than deciduous forests (Zhang et al. 2023). As far as we know there are very few studies concerned about the difference of flood control efficiency between coniferous/broad leaved tree species, though many studies focus on water use efficiency, interception, evapotranspiration, throughfall, stemflow, groundwater recharge, and other water balance components (Komatsu et al. 2007, 2008). Some indicate the evergreen forest stands rather reduce water discharge than deciduous ones (Augusto et al. 2002) or evergreen rather reduce flood occurence and intensity (Swank and Vose 1994).

This indicates that the cWUE of spruce stands in this region is overall lower regardless of the amount of available water. During dry periods, the reduced cWUE was mainly attributed to the transpiration processes of the forest stands which lead to decreasing streamflow and the inability to sustain balanced flows (Kupec et al. 2018). In extreme precipitation events, it seems that the reasons for the lower cWUE in spruce stands are caused by the already disrupted soil–plant system as a result of long-term stress induced by the effects of climate change (Zahradník and Zahradníková. 2019; Fernandez-Carrillo et al. 2020; Senf et al. 2020). The lower cWUE was manifested as limited FCE, higher ratio of stormflow, and lower BFI, i.e., a reduced retention capacity of the watershed. This all leads to a reduced ability of the spruce stands for soil water recharge which further increases their drought stress (Juřička et al. 2022). This is also indicated by the fact that in EREs in spruce, there was no strong correlation between precipitation and runoff characteristics (Table 5). The quantity of the precipitated water seemed to have less of an impact on runoff response (no correlation above 0.34 was found) as if the retention capacity of the catchment was always filled or the infiltration simply could not occur (Du et al. 2019). In the other studied catchments with less spruce, parameters describing the amounts of precipitated water in EREs were more strongly correlated to runoff response (reaching around 0.5 in UT and up to 0.71 in KA). However, it should be noted that the above applies to EREs with a duration of approximately 7–11 days; no longer ERE was observed in the studied year 2020. It is possible that these dynamics might change in longer extreme hydroclimatic periods.

Our results also suggest that there is an imaginary threshold in each of the catchments manifested in the way that once the retention capacity of the catchment is reached and filled, the runoff then drains from the catchment in a rapid manner in the form of disproportionally large ratio of stormflow. Defining such a threshold is clearly very complex as it is affected by a few agents. In addition to precipitation properties (total and intensity) and the vegetation cover, catchment morphological properties also play a role in its determination (Tromp-Van Meerveld and McDonnell 2006) as well as the geological substratum and soil properties.

Table 6 Average annual BFI compared with various methods

	Local minima	Fixed interval	Sliding interval	BFLOW	EWMA	Average
Kanice	0.85	0.87	0.82	0.81	0.80	0.83
Křtiny	0.75	0.74	0.72	0.61	0.58	0.68
Útěchov	0.83	0.91	0.84	0.79	0.80	0.83

The fraction of soil particles can also be a significant variable determining the course of BFI (Bloomfield et al. 2009). In the case of underlying geology of igneous and consolidated sedimentary rocks (granodiorites in our case), soil porosity and depth play a more significant role in the drainage characteristics of the catchment rather than a simple difference in the age of the underlying geology (Lacey and Grayson 1998). The soils and parental bedrock in all three catchments are quite similar (Table 1) as they are located close to each other in the same geological formation of the Brno massif. Therefore, the observed differences should be attributed to something else. For shallow rooting trees (such as spruce), the pedological conditions and their heterogeneity in the catchment could also be a significant variable in the runoff regime (Juřička et al. 2022). This could be one of the reasons why the response of the KR spruce catchment was so different to the other two since the present broadleaved trees such as beech generally develop a deeper rooting system. Complex as it is, it can be stated that at the catchment scale, especially in fully forested basins, the forest vegetation was the premium determinant of runoff conditions (Bosch and Hewlett 1982). In principle, forest vegetation also determines the underlying soil properties, or functioning of the plant-soil system, especially in the short and medium term (Jentschke et al. 2001; Fahey et al. 2005; Pichler et al. 2009) relevant for hydroclimatic extremes. For these reasons, when searching for the above-mentioned threshold of disproportionally high stormflow and resulting rapid runoff from the catchments in the short- and medium-term periods (7–11 days) of EREs, we placed primary focus on the characteristics of precipitation and runoff response rather than on the defined relatively independent natural conditions of the experimental forest catchments. While we did not manage to clearly identify the threshold as it is very complex and more research (and broader datasets) is needed in this manner, we managed to find some hints. Most notably, in KA (mixed) the retention capacity of the catchment and its forest stands was filled when precipitation exceeded 50 mm, when FCE dropped below 17%. In other cases, the catchment exhibited FCE of around 33%. In KR (spruce), this retention capacity seemed to be filled already after precipitation above 30 mm, when FCE dropped below 8%. In other cases, the catchment exhibited FCE of 23%. In UT (beech), despite the morphologically highest susceptibility to peak flows (Table 1), FCE remained relatively high 27% even in the one event with 90 mm of precipitation. In other cases, the exhibited FCE reached around 52%.

5 Conclusions

We performed a comparative paired catchment study of three headwater upland forest micro-catchments with different forest types in the precipitation-abundant year 2020. Our team demonstrated that in case of hydroclimatic extremes, there are significant differences in the runoff response from these catchments, depending especially on the tree species composition in the forest stands.

As a result of the impacts of global climate change, the study site has been affected by a previous several-year dry period. In these conditions, an unexpectedly above-normal precipitation abundant year 2020 came. Here, we have shown that mixed and beech predominated micro-catchments exhibited relatively low runoff coefficients of 3.8% and 6.5%, respectively, while the catchment predominated by spruce responded by a much higher runoff coefficient of 14.2%. In the precipitation-abundant year such as 2020, this is indicative of high flood control efficiency of the mixed and beech catchments and a rather low in the case of spruce. This is a surprising fact that might be optimistic with the expected shift in tree species composition in the region focused more on beech stands as opposed to spruce. It also refers to the potential to recharge water storage during periods of high flows which seems to be much smaller in the case of spruce as compared to the other two forest stand types.

Extreme runoff events (EREs) were identified throughout the year and the response of individual micro-catchments was analyzed using baseflow separation. It turned out that these periods were hydrologically very significant as 49, 39, and 36% of the annual precipitation totals fell during them and they were responsible for 30.4, 58.8, and 31.5% of annual runoffs of the mixed, spruce, and beech catchments, respectively. Even here, the spruce catchment responded differently to the relatively similar hydrological behavior of the mixed and deciduous catchments, when almost twice as much of annual runoff occurred during EREs in the spruce catchment. This suggests that the spruce catchment is more prone to suffer from drought since twice as much water was lost from the system during extreme hydroclimatic events as opposed to the other two and less water is thus available for groundwater recharge.

A parameter of flood control efficiency FCE was introduced in Section 2.2 equivalent to the lowest daily BFI value in any ERE as means of interpreting the potential for flood water retention and slowing the stormflow runoff of the individual catchments. Here too, it was shown that the FCE was significantly lower in the spruce catchment (3–79% on average, 23% for all episodes), almost by half than in the case of the beech (27–91% on average 52%) catchment and by a third in the case of the mixed one (7–45% on average 33%).

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