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Original Research

Response of Small-Stream Biota to Sudden Flow Pulses Following Extreme Precipitation Events

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Abstract

Extreme discharge rate increases in small streams caused by sudden extreme precipitation events are classified as small-scale pulse-type disturbances. Small highland brooks in agricultural landscapes (arable land and meadows) are frequently characterised by extremely low flows during normal conditions, plus the rare appearance of high-flow events that periodically may reset their ecosystems. We studied two small highland brooks to assess the impact of extreme discharge rates (flow pulses) upon periphyton, macrozoobenthos, and fish assemblages. No distinct changes were recorded in composition of periphyton assemblage or fish (brown trout, *Salmo trutta* m. *fario*) occurrence following such flow pulses. Cyanobacteria, however, were absent following a flow pulse, while growth appeared to be boosted in green algae (Chlorophyceae). Similarly, there was no negative response observed in macrozoobenthos communities, with density, diversity, taxa richness, and saprobic indices remaining either more-or-less unchanged or considerably enhanced following high-discharge episodes. These observations were confirmed through Sörensen's similarity indices, which indicated no significant change in either periphyton or macrozoobenthos following such episodes.

Keywords: discharge rate, brook, macrozoobenthos, periphyton, fish

Introduction

One of the predicted impacts of ongoing global climate change [1] is on natural processes in flowing and still waters – from basic physico-chemical processes to the complicated structuring of water biota [2]. Hydrological regimes in running waters may also become unstable, which will be reflected particularly in small streams [3]. The hydrological regime is one of the most important factors influencing river systems, as well as the assemblages found within them [4], with extreme discharge rates acting as important ecological filters dictating the composition of hydrocenoses. Knowledge about flood and drought regimes, therefore, including their different modes of action and their effects, is vital in elucidating the links between hydrology and ecology in running waters [5].

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Changes in hydrological regime, however, are not only influenced by extreme droughts or high discharges related to climate change [6]. Technological intervention within stream habitats and improper land exploitation within a river's catchment can also strongly influence hydrological cycles and patterns. Land use, for example, can affect the water retention and soaking capacity of soil, resulting in alterations to surface runoff patterns and consequent flood discharge increases, or dramatic declines in discharge rates during droughts [7]. During discharge fluctuations, many basic physical ecosystem determinants are altered, e.g., decreased discharges result in lowered current velocity, depth, area of flooded streambed, and increased concentration of nutrients and dissolved solids [8], while water temperature, conductivity, sedimentation, and periphyton biomass can all increase.

The question arises, however, as to how destructive such disturbances are for aquatic life and what limits, once exceeded, result in significant destruction or reduction in water biota. The majority of studies published to date have dealt either with the ecological impacts of drought and the flooding of intermittent stream ecosystems [9, 10] or water level fluctuation below hydropeaking power plants. Studies describing the effects of a sudden increase in stream discharge are, however, relatively scarce.

According to [5], extreme increases in discharge in small streams following high precipitation can be classified as pulse-type disturbances operating at a small scale. In order to differentiate such pulse-type disturbances from floods that overflow stream banks (flood pulses), the term "flow pulses" is used. Flow pulses can affect water organisms both directly (i.e., physically) or, perhaps more importantly, indirectly. Sudden increases in water volume, for example, can result in large-scale alterations to substrate composition and stream bed structure, water chemistry, suspended solids, and nutrient distribution [11], resulting in changes in habitat availability and utilisation.

Individual groups of water organisms can exhibit a variety of responses to changes in discharge. Some, for example, may profit while others can be fundamentally endangered; others still may be able to adapt or even withstand short-term changes [12]. In general, small streams have been under-studied regarding the impact of flow pulses. Nevertheless, several studies based on regular or coincidental sampling shortly preceding an extreme discharge episode, thereby enabling objective evaluation of stream biota responses, have been performed. The majority of these studies have demonstrated high levels of resistance and resilience, even by species seldom exposed to flooding [13]. Small streams flowing through large monoculture field complexes, however, are highly vulnerable to extreme and sudden short-term high discharges during severe precipitation events, and these have been largely overlooked up till now.

The objective of this study, therefore, was to evaluate the response of macroinvertebrate assemblage to sudden flow pulses in two small highland streams located in an agricultural landscape, thereby testing the hypothesis that macroinvertebrates of such small streams have adapted to sudden increases in discharge.

Experimental Procedures

The survey took place on two small mountain streams – Němčický (NB) and Kopaninský (KB) brooks – between 29 April and 23 Sept 2010. In total, 11 severe discharge events exceeding 100 $l.s^{-1}$ occurred at NB and nine at KB over the same period (Figs 1, 2). Sampling of periphyton, macrozoobenthos (MZB), and fish took place in spring (31 May), summer (15 July), and autumn (23 Sept) in order to describe seasonal patterns in stream biota. In addition, special-purpose sampling was performed immediately following extreme discharge events on 17 July (181.8 $l.s^{-1}$) and 15 Aug (188.5 $l.s^{-1}$) on NB, and 18 July (885.7 $l.s^{-1}$) and 13 Aug (136.4 $l.s^{-1}$) on KB.

Study Sites

Němčický brook (Morava river drainage basin) is a small first-order stream (upstream 2,184 m long, 2.3% slope) situated in the Drahanská Vrchovina highland re-

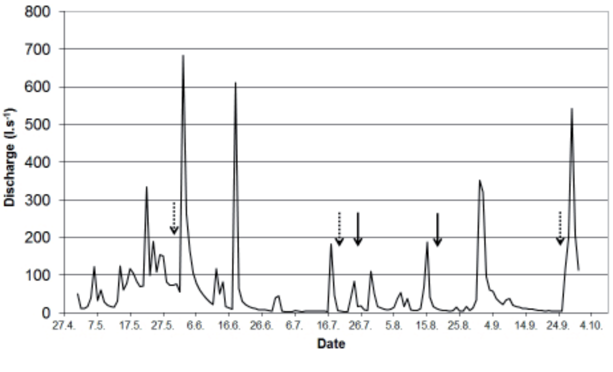

Fig. 1. Maximum daily discharge rates at Němčický brook between 1 May and 30 Sept 2010. Note: dotted arrows are regular sampling and solid arrows are special-purpose sampling following flow pulses.

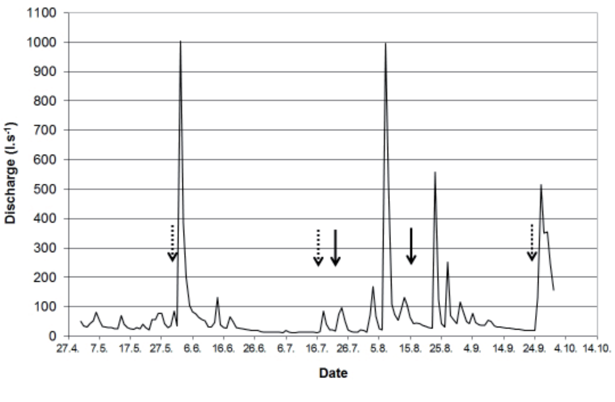

Fig. 2. Maximum daily discharge rates at Kopaninský brook between 1 May and 30 Sept 2010. Note: dotted arrows are regular sampling and solid arrows are special-purpose sampling following flow pulses.

Table 1. Chlorophyll *a* content (µg.cm^{-2}) for Němčický and Kopaninský brooks in 2010 during regular discharge (R) and following a flow pulse (FP).

Stream	Němčický brook			Kopaninský brook		
Sampling	R	R	FP	R	R	FP
Date	31 May	15 July	21 July	31 May	15 July	21 July
Cyanobacteria	0.514	0.095	0.000	0.313	0.001	0.000
Chlorophyceae	0.404	0.331	0.644	0.000	0.954	1.433
Bacillariophyceae	0.550	0.413	0.126	0.260	0.077	0.137
Total	1.450	0.838	0.768	0.573	1.032	1.543

gion of the Czech Republic. The study site is located downstream from the village of Němčice (49°26'7"N, 16°42'31"E), and the upstream drainage area (3.52 km^2) consists almost exclusively of arable land. The stream is largely overshadowed by a tree and bush canopy consisting predominantly of black alder (*Alnus glutinosa*) and willow (*Salix* sp.), while the substrate is composed mainly of stones and gravel with frequent occurrence of submerged roots from riparian vegetation. Daily logged discharge rates fluctuated between 2.7 and 682.7 l.s^{-1} on 22 July and 2 June 2010, respectively. Mean discharge (discharge rates >100 l.s^{-1} excluded) was 31.7 l.s^{-1} over the study period.

Kopaninský brook (Labe River [Elbe] drainage basin; upstream 4,302 m long, 2.3 % slope) is situated in the Bohemian-Moravian highland of the Czech Republic. The study site is situated upstream from the village of Velký Rybník (49°29'17"N, 15°18'27"E) and the upstream catchment area (7.13 km^2) comprises 50% forest, 30% meadow, and 20% arable land. The headwater part of the brook is largely covered over by a dense canopy of willow and black alder, while the actual study site is open and the substrate comprises sand, gravel, stone, and clay sections in approximately equal proportion. The banks are covered by grass with riparian roots hanging down into the water. Daily logged discharge rates fluctuated between 11.7 and 1,004.1 l.s^{-1} on 8 July and 2 June 2010, respectively. Mean discharge (discharge rates >100 l.s^{-1} excluded) was 36.5 l.s^{-1} over the study period.

Periphyton Sampling

Periphytic assemblage samples were scraped directly from natural substrate (pebbles) and transported directly to the laboratory in a cool box. Laboratory processing and determination were performed on the same day according to standard procedures [14]. Chlorophyll *a* (Chl-*a***)** content for the dominant periphytic groups (blue-green algae [Cyanobacteria], diatoms [Bacillariophyceae] and green algae [Chlorophyceae]) was determined *in situ* on samples grown on artificial substrate (PE foil) for a minimum of one month using BenthoFluor sensor equipment (Moldaenke GmbH, Germany).

Macrozoobenthos Sampling

MZB samples were collected semi-quantitatively using a three-minute kick-sampling approach with a 500 µm mesh hand net [15], and then washed through a 500 µm mesh sieve. The resultant samples (both debris and macroinvertebrates) were transported to the laboratory in plastic bags under oxygen atmosphere, whereupon the macroinvertebrates were seperated out and preserved in 4% formaldehyde for future determination.

Fish Sampling

Ichthyological surveys were performed on 15 July and 23 Sept 2010 using a battery-powered Smith-Root electroshocker (Smith-Root Inc., Vancouver, WA, USA; 50 Hz, 400 V). The whole stream profile was sampled over two selected 80 to 100 m stretches. Fish caught were anaesthetized with 0.3 ml.l^{-1} clove oil before being measured (standard length, SL) and weighed. Upon recovery, the fish were released back to the stream. No fish were recorded in NB.

Analysis

Samples were used to determine the saprobic index (SI; [16]) for each stream, and biodiversity scores were assessed using the Shannon-Weaner biodiversity index (H'). In addition, the Ephemeroptera/Plecoptera/Trichoptera ratio (EPT index) was assessed in MZB samples. Appropriate time-set MZB sample pairs (before and after extreme discharge episodes) were compared using Sörensen's similarity index to assess the level of change caused by sudden flow pulses.

Results

Němčický Brook

Altogether, 96 taxa were recorded in NB periphyton, with highest diversity recorded on 23 Sept 2010 at 56 taxa (H' 3.94). Diatoms and green algae were dominant in the

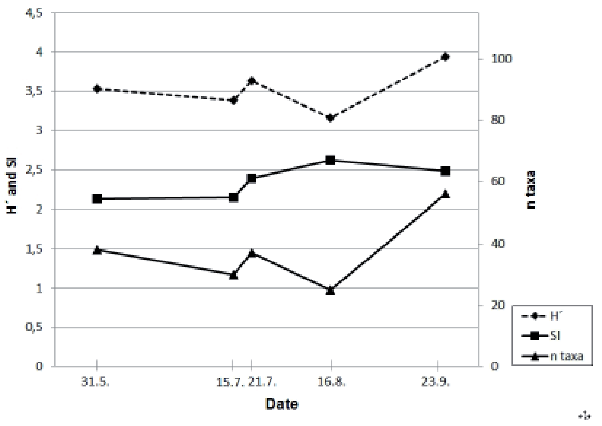

Fig. 3. Temporal changes in number of periphyton taxa (n taxa), Shannon-Weaner diversity index (H´), and saprobic index (SI) at Němčický Brook.

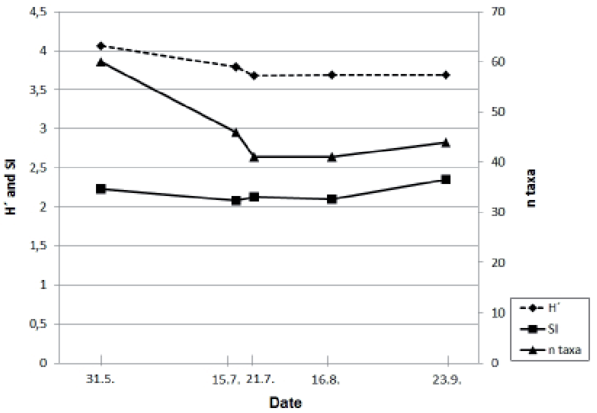

Fig. 4. Temporal changes in numbers of macrozoobenthos (10ˆ2 n ind.) and taxa (n taxa), Shannon-Weaner diversity index (H'), and saprobic index (SI) at Němčický Brook.

periphytic assemblage, with 31 and 18 taxa, respectively. The proportion of heteroptrophic organisms (destruents and consumers) ranged from four on 15 July to 19 on 23 Sept 2010. Sörensen's similarity index, based on periphyton composition on two dates with regular discharge prior to a flow pulse, was 38.7%. Following a period of extreme discharge on 15 July, Sörensen's index increased slightly to 49.2%, but dropped to 24.5% after a subsequent flow pulse on 16 Aug, and fell further to 22.4% during a period of regular discharge on 23 Sept (Table 2). None of the changes in Sörensen's similarity index were significant (p>0.05). Values for H' ranged between 3.16-3.63 and 3.38-3.53 following the two flow pulses (Fig. 3).

Chl-*a* concentrations in NB periphyton declined between 31 May and 21 July (Table 1), with declines in cyanobacteria and diatoms mainly responsible. No cyanobacteria were recorded in NB periphyton following the flow pulse on 21 July; however, Chl-*a* attributable to green algae increased almost two-fold from 0.331 to 0.644 µg.cm^{-2}.

Saprobiological analysis of periphyton indicated mostly beta-mesosaprobity with a tendency to deteriorate to alpha-mesosaprobity during the growing season (from SI 2.13 in May to 2.62 in August and 2.48 in September). Saprobic indices increased during flow pulses, from 2.15 on 15 July (regular discharge) to 2.39 on 21 July and 2.62 on 16 August (Fig. 3).

Fifty MZB taxa were found at NB, with the highest number of individuals (616), taxa (23), and diversity (2.29) recorded during the initial spring sampling campaign on 31 May. Numbers of MZB individuals, taxa, and diversity were higher following flow pulses (263-300, 19-

Table 2. Results for Sörensen's similarity index (%; comparing data for sample date with that for the date preceding) for periphyton (PF) and macrozoobenthos (MZB), along with EPT data during periods of regular discharge (R) and following a flow pulse (FP).

Sampling		R	R	FP	FP	R
Date		31 May	15 July	21 July	16 Aug	23 Sept
Němčický brook						
Sörensen's similarity index	PF		38.7	49.2	24.6	22.4
	MZB		18.8	36.6	41.2	51.5
n EPT taxa		4	4	2	2	2
EPT/total n taxa (%)		17.4	30.8	10.5	9.5	16.7
EPT/total n ind. (%)		46.9	5.6	22.4	7.7	3.8
Kopaninský brook						
Sörensen's similarity index	PF		40.0	48.1	45.8	34.5
	MZB		48.9	54.7	36.1	58.6
EPT taxa		15	11	8	5	16
EPT/total n taxa (%)		55.6	47.8	30.8	22.7	53.3
EPT/total n ind. (%)		27.8	39.0	11.5	30.5	33.9

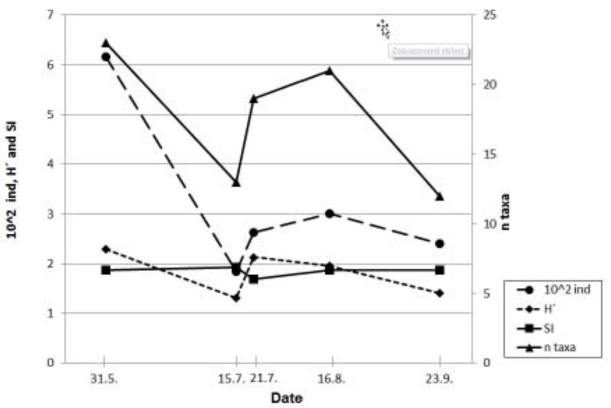

Fig. 5. Temporal changes in periphyton taxa number (n taxa), Shannon-Weaner diversity index (H´), and saprobic index (SI) at Kopaninský Brook.

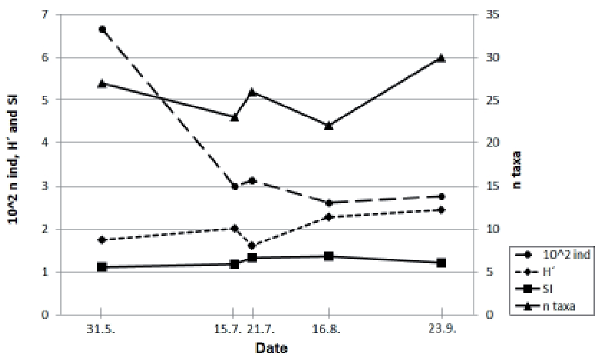

Fig. 6. Temporal changes in number of macrozoobenthos individuals (10^2 ind) and taxa (n taxa), Shannon-Weaner diversity index (H'), and saprobic index (SI) at Kopaninský Brook.

21 and 1.95-2.13, respectively) compared with preceding periods of regular discharge (184-240, 12-13, and 1.31-1.41, respectively) (Fig. 4). Both the number of EPT taxa and EPT taxa proportion of total MZB taxa and individuals declined following flow pulse episodes (Table 2), and some case-making caddisflies (*Halesus digitatus* and *Chaetopteryx* sp.) were no longer recorded in the MZB assemblage.

Saprobiological evaluation of MZB indicated beta-mesosaprobity over the whole study period (Fig. 4), with values following extreme discharge events being slightly better (1.69-1.87) than those during regular discharge (1.87-1.93). Sörensen's similarity index was lowest (18.8%) for samples during regular discharge, rising to 36.6% and 41.2% following the two periods of extreme discharge on 21 July and 16 Aug, respectively (Table 2).

Kopaninský Brook

In total, 121 taxa were recorded in KB periphyton, with the highest diversity recorded on 31 May 2010 (60 taxa, H' 4.06). Saprobiological evaluation indicated betamesosaprobity (SI 2.08-2.35), with values fluctuating slightly over the growing season. Diatoms and green algae dominated within the periphytic assemblage with 40 and 34 taxa, respectively. In September, the occurrence of bacteria (filamentous bacteria in particular) increased compared to summer. Sörensen's similarity index for periphyton composition comparing two days of regular discharge prior to the flow pulses corresponded to 40.0%, while that comparing periphyton before and after a flow pulse (15 and 21 July) was 48.1%. Sörensen's index dropped to 45.8% following the flow pulse of 16 Aug, and dropped further to 34.5% on 23 Sept following a period of regular discharge (Table 2). H' values for periphyton diversity showed little variation over the study, dropping from 4.06 in May to between 3.68 and 3.79 over the summer, with no obvious relationship to discharge rate (Fig. 5).

Concentrations of periphyton Chl-*a* at KB increased from 0.573 to 1.543 μg.cm^{-2} between 31 May and 21 July (Table 1) and, as at NB, cyanobacteria disappeared following the extreme discharge event of 17 July, while diatoms and green algae increased their biomass as expressed in Chl-*a* concentration (Table 1).

In total, 72 MZB taxa were recorded at KB, with *Gammarus fossarum* being the most numerous and contributing to the total density figures by 34.4-63.7% on 16 Aug and 21 July, respectively. Numbers of MZB recorded during the initial May sampling campaign were approximately twice those during summer sampling. MZB numbers recorded between July and September ranged around 300 (262-314 ind.) and showed no effect from extreme discharge rates. The number of taxa ranged between 22 and 30, while the diversity index ranged between 1.61 and 2.45; neither, however, showed any relationship to the flow pulses (Fig. 6). On the contrary, numbers of EPT taxa, as well as their proportion as regards total MZB taxa and number of individuals, declined following such extreme discharge episodes (Table 2). The declines and/or disappearances were most obvious for *Habrophlebia fusca*, genus *Baetis* (Ephemeroptera), *Chaetopteryx* sp., and *Sericostoma* sp. (Trichoptera).

Water quality based on MZB evaluation indicated oligosaprobity with low fluctuation (1.11-1.37) and no relationship with flow pulses. The value for Sörensen's similarity index for MZB during the period of regular discharge (31 May and 15 July) was relatively similar to that for the period before and after the flood pulse (15 and 21 July), at 48.9% and 54.7%, respectively (Fig. 6).

The fish assemblage consisted of the brown trout (*Salmo trutta* m. *fario*) 0+ and 1+ individuals. Their density and biomass amounted to 18.2 ind.10^2 m^{-1} and 200 g.10^2 m^{-1} before (15 July), and 23.4 ind.10^2 m^{-1} and 240 g.10^2 m^{-1} after the period of summer flood pulses (23 Sept).

Discussion of Results

Natural fluctuations in hydrological parameters are a necessary phenomenon for ecosystem prosperity and conservation of biological biodiversity. Such natural processes, however, rarely match human demands on a stream's flow regime and, consequently, many natural hydrological regimes have been subjected to anthropogenic changes [16] that have modified and disturbed stream flow parameters. As a direct result, many aquatic ecosystems are presently subject to either insufficient or extreme discharges that are frequently destructive to aquatic life [17]. When evaluating the impact of extreme discharges, one has to bear in mind that the intensity of such flow pulses is of principal importance. As [5] has pointed out, a rapid increase in flow velocity and shear stress in constrained streams may sweep away biota such as algae, macrophytes, benches, and riparian plants, and move sediment, benthic organic matter, and coarse wood to create major changes in channel morphology. Severe effects, however, may only become apparent in extreme situations associated with several 10-fold increases in discharge, particularly in larger lowland rivers. During such flood events, water biota are affected by a combination of water velocity and physical scouring, once bed movement is initiated [18], and time required for recovery will vary greatly depending upon stream type and the severity of the disturbance. For example, recovery will take longer if the flood is accompanied by landslips that physically alter the stream bed profile and habitat conditions [13].

In this study, we surveyed the impact of extreme discharge rates on small highland streams. Such streams appear to suffer more from such sudden floods than lowland rivers as the discharge following a storm may suddenly increase more than 100-fold. Literature describing the response of biota in small streams is relatively scarce due to the difficulty of forecasting such flow pulse events and in collecting a sample immediately preceding the onset of flooding.

Periphyton Chl-*a* patterns differed between the two streams in this study, with values declining over the beginning of the growing season in NB and increasing almost three-fold in KB (Table 1). One of the main differences between the two streams was the presence of a considerably denser and, during the growing season, thicker canopy over NB, resulting in increased shading and, consequently, there was greater development of periphytic algae at KB open site. Following the flow pulse in July, periphyton Chl-*a* content at NB decreased but increased at KB. This may have been connected with the severity of the flood pulse, which was greater at NB (3.3 increasing to 181.8 $l.s^{-1}$) compared to KB (17.4 increasing to 96.0 $l.s^{-1}$). A higher periphyton Chl-*a* content was also recorded for more open sites (compared to forested sites) by [19], who proved that the periphytic community at open canopy sites was more resilient to flood disturbance while periphyton at forested sites was more resistant.

At both sites, the decline in Chl-*a* content was more obvious for cyanobacteria, which disappeared at both sites following the July peak in flow rates (Table 1). On the other hand, the proportion of total Chl-*a* represented by green algae gradually increased and that for diatoms decreased during the growing season – with no apparent connection to the flood events. This, however, appears to be a common successional phenomenon in periphytic communities with marginal dependence on discharge conditions [20]. A study of epilithic algae in a mid-sized river [21] emphasised that peak flow events result in a mosaic of bed patchiness due to different disturbance histories, and that diatoms tend to be most abundant in patches that have been subjected to scouring. No significant differences have been proved in the responses of NB and KB periphyton on a flow pulse, probably, among other reasons, due to the similar structures of their bottoms. Their periphytic community species richness was affected very little by the flow pulses, with taxa number and diversity fluctuating and/or decreasing only slightly at both NB and KB.

Surprisingly, MZB numbers, taxa, and diversity all increased or fluctuated following periods of extreme discharge, regardless of the peaks in flow at NB and KB. EPT taxa, however, declined both in numbers and as a proportion of total MZB taxa and numbers following episodes of extreme discharge (Table 2), with some mayfly nymphs (*Habrophlebia fusca* and genus *Baetis*) and case-making caddisflies (*Halesus digitatus, Sericostoma* sp. and ***C****haetopteryx* sp.) disappearing altogether following the flow pulses. Cases of caddisflies make them more vulnerable to increased flow velocity, the same being true for non-hiding mayfly nymphs of genera *Habrophlebia and Baetis*. The amphipod *Gammarus fossarum* (the most numerous benthic macroinvertebrate) was able to withstand the impact of suddenly increased flow through its ability to respond rapidly and hide in the substrate. *Gammarus* numbers fluctuated throughout the study, regardless of the discharge rate preceding sampling, with numbers sometimes being considerably higher after peak flows (e.g., at NB on 21 July 2010).

According to [22], invertebrate communities generally react to floods with a reduction in density and taxonomic richness. The effects, however, are relatively short-lived, reflecting the high resilience of many invertebrate taxa [18]. The short time delay between peak flow and sampling (1-4 days for NB and three days for KB) were still sufficient for recovery of the MZB assemblage, whether by recolonization or re-appearance of hiding macroinvertebrates. This suggests that the macroinvertebrate community remained relatively intact during the flow pulse, a conclusion also reached by [13]. In our study, this was further confirmed by the results of Sörensen's similarity index, which tended to fluctuate and showed little or no impact of extreme discharge. Indeed, for both NB and KB, the indices for periphyton and MZB were higher between samples before and after a peak flow event than between the samples collected during the period of stable flow (Table 2).

Despite their frequently mentioned high vulnerability by sudden flood pulses, small highland streams showed good resistance and resilience against the impacts of extreme discharge rate increases caused by extreme precipitation events. No distinct changes were recorded in composition of macrozoobenthos and fish assemblages. Only cyanobacteria were absent following a flow pulse, while green algae growth appeared to be supported.

Conclusion

Extreme rainfall-runoff events are increasingly frequent in the Czech Republic as a possible consequence of current climatic changes. Thus, current research activities should look at the impact of extreme rainfall episodes and subsequent sudden flow pulses uon the biota of running waters. Although the results of this study proved relatively good resistance of water organisms to extremely sudden onsets of high discharge rates in small brooks, long-term dry periods followed by heavy storms can disturb the natural balance of ecosystems with hardly expected consequences.

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