ORIGINAL ARTICLE

# Impacts of an extreme flood on the ecosystem of a headwater stream

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## ABSTRACT

Headwater streams are the smallest parts of rivers but make up the majority of river miles. The chemistry and macroinvertebrate composition of such streams are among the most important indicators of their environmental health. Macroinvertebrates are affected namely by runoff genesis and, in many regions of the world, also by acid atmospheric deposition and its consequences. The aim of this paper is to evaluate the impacts of an extreme summer flash flood on the physical environment, chemistry and macroinvertebrates in a small headwater stream located in the Beech-woods National Nature Reserve of the Jizera Mts. (Northern Bohemia, Czech Republic). The studied stream is characterized by a pluvial hydrologic regime with perennial streamflow uniformly distributed within the year, with peak-flows originating mainly from summer rainstorms, and moderate current anthropogenic acidification. During the observed summer flash flood of the return period near 1,000 years, high currents (1-2.5 m $s^{-1}$) flushed out 2.7 $m^3$ of sand and gravel from the streambed, resulting in a devastating effect on macroinvertebrates. Both number of species/taxa and diversity were reduced by about 50% while the abundance of surviving taxa was reduced to about 10% compared with before the flood. The following spring after the event, both number of species/taxa, diversity and abundance increased, partially due to the temporary unsuccessful colonization of the site by several alien species creating a peak of biological diversity, but complete recovery of the original macroinvertebrate assemblages was not observed even during the subsequent two years. On the other hand, a significant drop in sulphate contents and rising alkalinity observed in stream waters during base flow conditions after the flood indicate positive effects on recovery of the aquatic environment by depleting the catchment sulphur pool. Thus, the flood did not significantly alter the long-term recovery of the studied headwater stream from acidification.



## INTRODUCTION

Headwater streams are the smallest part of rivers but make up the majority of river miles, providing habitats that are unique compared to other freshwater environments and used by a specialized subset of aquatic species (Richardson, 2019). Chemistry and macroinvertebrates are among the most important indicators of the environmental health of headwater streams (Fritz *et al.*, 2013), while floods (overflows of stream water beyond normal limits) are among the most important natural hazards (Hickey and Salas, 1995). Extreme floods, defined by a return period exceeding 50 years (i.e. a 2% chance of incidence (Davis, 2007)), have huge destructive power, devastating landscapes and settlements but also aquatic environments (Knox and Kundzewicz, 1997). Macroinvertebrate assemblages of stream bottoms respond to the structure and functions of fluvial ecosystems (Allan and Castillo, 2007), and benthic macroinvertebrates are considered a very effective indicator of environmental health because of their limited mobility, relatively long life cycles and varied sensitivity to different types of pollution (Rashid and Pandit, 2014). Therefore, macroinvertebrate studies have been used for water quality assessments by several environmental monitoring programmes (Rosenberg and Resh, 1993; Dar and Ganai, 2017). While biological diversity in rivers is usually influenced by a combination of pressures from various anthropogenic impacts (Adámek *et al.*, 2010), communities in headwater streams are affected namely by water velocity and associated physical forces (Allan and Castillo, 2007). Thus, in mountain streams an adequate dynamic approach reflecting rapidly changing currents and discharge needs to be considered in analysing their water environment. Most

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studies, however, concentrate primarily on base-flow conditions (Falkenmark and Allard, 2015).

In Central Europe, the biota in many mountain streams has been affected by acid atmospheric deposition and its consequences (Horecký *et al*., 2013). Anthropogenic emissions of acidic precursors (sulphur and nitrogen oxides, and ammonia) increased from the industrial revolution of the 19th century and culminated in the late 1980s (Schöpp *et al*., 2003). In the Czech Republic, mountain waters of low mineralization (and acid-neutralizing capacity) were stressed by strong acidification, with natural acidity (based on humic substances) overwhelmed by anthropogenic acidity (Veselý and Majer, 1996; Stuchlík *et al*., 2006). This resulted in the rapidly decreasing pH of mountain streams and a dramatic decline in water quality including increased contents of heavy metals and toxic forms of aluminium (Křeček and Hořická, 2001, Křeček *et al*., 2019).

Since the early 1990s, with international cooperation to reduce atmospheric emissions (namely, the 1985 Helsinki Protocol on the Reduction of Sulphur Emissions or their Transboundary Fluxes by at least 30 percent; Holen *et al*., 2013), signs of recovery in acidified headwater catchments were seen in Central Europe (Stuchlík *et al*., 1997; Křeček and Hořická, 2006), as well as in other parts of Europe and North America (Godbold and Hüttermann, 1994). However, ongoing recovery could be affected by changing physical forces. The aim of this paper is to evaluate the impacts of an extreme summer flash flood on the physical environment, chemistry and benthic macroinvertebrates in a small mountain stream in the context of atmospheric acid loads and recovery from acidification.

## METHODS

This study was performed in the Jizera Mountains (Northern Bohemia, Czech Republic): in the experimental catchment of the Holubí Potok stream, near the Oldřichov settlement (HPO catchment, 50°52'14"- 50°52'30"N, 15°6'11"- 15°6'21"E, Odra river district 2-04-10-014, Fig. 1, Tab. 1). The site is located in the National Nature Reserve "Beech-woods of the Jizera Mts." covered by semi-native forest stands with Common beech (*Fagus sylvatica*) dominating. This area has a humid continental climate (Kőppen's Dfb) with mean annual precipitation 940 mm, mean air temperature 8.3°C, and an average of 86 days with snow cover (Tolasz *et al*., 2007). Low-base-status soils (sand-loamy brown forest soils) developed on porphyritic granite reach depths of 0.7-1.3 m. The stream channel is characterized by steep gradients with step-pools (Palucis and Lamb, 2017) and a water depth below 0.5 m at bankfull discharge. The bed is covered by non-uniform sediments (sand, gravel and boulders) with a predominantly gravel substrate. Mean annual water temperature is 9.3°C with a monthly minimum of 1.6°C in January and maximum of 16.4°C in July.

In the 1980s, the Jizera Mts. region (part of the so-called Black Triangle) was strongly affected by acid atmospheric loads. Plantations of Norway spruce (*Picea abies*) in the upper mountain ridges were heavy damaged and subsequently harvested by clearcutting, but only moderate defoliation (up to 20%) was observed in beech stands of the investigated catchment (Křeček and Hořická, 2006), reflecting the fact that common beech trees show an intermediate tolerance to atmospheric emissions (Vacek *et al*., 2007).

The experimental catchment was instrumented in 1982 (and re-instrumented in 1995). The outlet is equipped with a composite sharp-crested weir (Thomson V-notch and Poncelet weirs) and water level is measured by an ALA 4020 compound water pressure and temperature recorder, logging every ten minutes. The capacity of the gauging station (0.39 $m^3 s^{-1}$) corresponds to a 12 years return period (see Tab. 4 in the results section). Thus, peak discharges above this limit were estimated by terrain footprints (Herget *et al*., 2014), with the empirical Manning



**Tab. 1.** Morphology of the HPO catchment (for elevation and slope, arithmetic means with range values are given).

| Parameter | Unit | Value |
|---|---|---|
| Area | ($km^2$) | 0.23 |
| Elevation | (m) | 518 (409 – 620) |
| Slope | (%) | 34.5 (0.1 – 83.2) |
| Shape index | (–) | 1.56 |
| Length of streams | (m) | 405 |
| Drainage density | ($km^{-1}$) | 1.76 |
| Slope of the stream | (%) | 11.2 (10.1 – 15.3) |
| Strahler stream order | (–) | 1 |

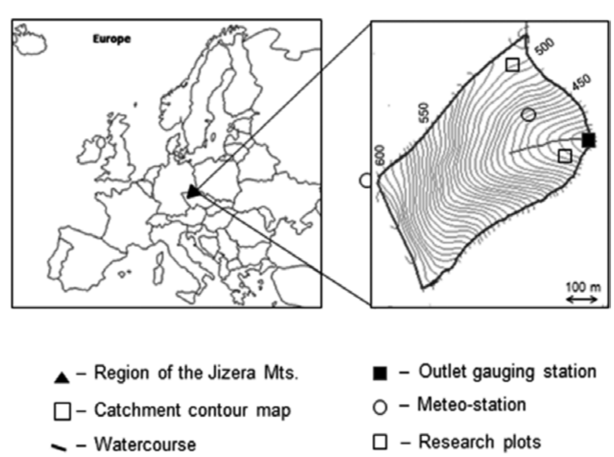


**Fig. 1.** The HPO experimental catchment.

equation (Venutelli, 2005) for mean flow velocity v into the continuity equation describing discharge $Q$ as a product of cross-section area $A$ and flow velocity $v$:

$$Q = A\, R^{2/3}\, S^{1/2}\, n^{-1} \quad \text{(eq. 1)}$$

where: $Q$ - the discharge ($m^3 s^{-1}$), $A$ - the cross-section area ($m^2$) for the specific flood level, $R$ - the hydraulic radius (m) for the flood level determined as a quotient of the cross-section area $A$ ($m^2$) and the wetted perimeter $P$ (m), $S$ - the energy line slope (m $m^{-1}$), and $n$ - the hydraulic roughness coefficient (-).

Flood waves were constructed by HEC – HMS 4.4 (USACE, 2000). The HEC – RAS 5.0.3 package (USACE, 2016) was used to simulate flow velocities and water depth in the HPO stream channel during the extreme event, with two dimensional unsteady flow calculations performed using the observed discharge at the catchment outlet as boundary conditions. The cross section geometry was measured along the stream channel every 10 m from the gauging station to the channel head, and the values of Manning's roughness coefficient $n$ were estimated from the channel configuration using Cowan's composite approach (Wibowo *et al*., 2015):

$$n = (n_0 + n_1 + n_2 + n_3 + n_4)\, m \quad \text{(eq. 2)}$$

where: $n_0$ represents surface roughness (caused by larger or smaller grain size of the sediments at the channel bottom up to minor submerged obstacles); $n_1$ is the value including the effect of surface irregularities; $n_2$ represents variations in the shape and size of the channel cross-section; $n_3$, for barriers; $n_4$, for vegetation; and $m$ is a correction factor for channel meandering.

A digital terrain model of the catchment was created in ArcGIS 10.2 from the contour lines of 5 m resolution and the stream channel layers.

Standard meteorological observations (precipitation, solar radiation, air temperature and moisture, wind speed, soil moisture, registered every hour by the ALA monitoring system) were carried out in a forest opening (relatively well-sheltered from wind effects; Shaw, 2011), located in the centre of the catchment (elevation of 498 m, Fig. 1). Additional observations in two forest plots (30 x 30 m area, elevations of 409 and 507 m) addressed runoff genesis in young and mature beech stands.

Although stream water chemistry at HPO is the subject of long-term monitoring (Křeček and Hořická, 2001), this study of the extreme flood is based on ten samplings of stream water for detailed chemical analyses from 2009-2012 and eight samplings of macroinvertebrates over three years (2010-2012) during comparable base-flow regimes (Tab. 2). Stream water was sampled by a plastic jar near the catchment outlet, filtered through 40-µm polyamide mesh in site, kept in prewashed 0.5 L PET bottle, stored in the refrigerator, and analysed in the laboratory of the Hydrobiological Station Velký Pálenec (Charles University, Prague), which regularly participated in the UNECE ICP Waters international chemical and biological inter-comparisons. Concentrations of major ions were identified by ion chromatography with conductometric detection, pH measured with combination electrodes at the beginning of the determination of alkalinity by Gran titration on a TIM 900 automatic titrator (Radiometer Analytical), and specific conductivity was identified by a conductometric sensor (Radiometer Analytical) at the reference temperature 25ºC (Stuchlík *et al*., 2006). Benthic macroinvertebrates were sampled by a kick net, mesh-size 500 µm (Rosenberg and Resh, 1993) at 6 different microhabitats reflecting the range of stream bed types along a 100 m stretch near the catchment outlet. The sampling dates included periods of snowmelt (March- May), summer (July-August), and the relatively dry autumn period (September-October). Quantification of samples was achieved by using a standard sampling time of 3 min at each microhabitat. Collected animals were preserved in 80% ethanol; determination of organisms and enumeration of each taxon were performed by specialists in the co-authors' team (usually to species level when allowed by the developmental stage). Evaluations of macroinvertebrate assemblages were based on the number of individuals and the number of species/taxa; biological diversity was characterised by indexes of Shannon entropy $D_{SH}$ and Simpson concentration $D_{SC}$, equations (3) and (4), as they translate indexes of species diversity into effective numbers of species (Jost, 2006; Velle *et al*., 2013).

$$D_{SH} = exp(-\textstyle\sum_1^S p_i ln p_i) \quad \text{(eq. 3)}$$

$$D_{SC} = {}^{1}\!/_{\sum_1^S p_i^2} \quad \text{(eq. 4)}$$

where: *S,* total number of taxa; $p_i$, relative number of individuals of taxon *i; ln,* natural logarithm; *exp,* based on the Euler number (2.718).

**Tab. 2.** Macroinvertebrate sampling dates and physical properties of the stream water.

| Sampling day | Discharge $Q_d$ ($10^{-3}$ $m^3$ $s^{-1}$) | Water temperature T (°C) |
|---|---|---|
| 18-Mar-10 | 1.72 | 4.9 |
| 27-Apr-10 | 0.73 | 8.2 |
| 28-Jul-10 | 1.68 | 12.6 |
| 5-Sep-10 | 2.04 | 9.7 |
| 16-Oct-10 | 1.65 | 7.5 |
| 4-May-11 | 0.62 | 6.2 |
| 13-Oct-11 | 1.73 | 7.1 |
| 21-Oct-12 | 2.11 | 5.9 |

GraphPad InStat 3.1 (Motulski, 2007) was employed to analyse basic statistics of the collected data; the non-parametric Mann Whitney two-tailed test was used to identify the statistical significance of changes in both means and standard deviations for chemical and biological characteristics before and after the flood, and trends in time series were tested by Spearman's correlation coefficient. Statistical significance was considered at the 0.05 probability level.

## RESULTS

### Stream flow dynamics

The studied HPO catchment is characterized by a pluvial hydrologic regime (Shaw, 2011) with perennial streamflow uniformly distributed within the year, and peak-flows originating mainly from summer rainstorms. Based on daily flow frequencies observed at the outlet from 1982-2018, the 90% frequency discharge ($Q_{330}$ = 0.53 $10^{-3}$ $m^3$ $s^{-1}$, reached or exceeded for 330 days a year) is the 'minimum residual discharge' needed to protect the aquatic environment, as interpreted by the Water Act 254/2001 Coll. (Tureček, 2002). Peak flow and return periods, interpolated by the Log-normal distribution of the annual discharge maxima (Shaw, 2011), are presented in Tab. 3.

The mean annual discharge was $Q_a$ = 2.5 $10^{-3}$ $m^3$ $s^{-1}$, and the bank-full discharge of $Q_b$ = 0.1 $m^3$ $s^{-1}$ corresponded to a return period between one and two years. In the investigated stream transect (Fig. 1), the bed particle distribution ($d_{10}$ = 4.5, $d_{50}$ = 9 and $d_{90}$ = 18 mm) was fine gravel, and the threshold discharge (Olsen, 1993) to initiate transport of the 16th percentile particle diameter ($d_{16}$ = 5 mm) at an 11% stream gradient was $Q_c$ = 5.4 $10^{-3}$ $m^3$ $s^{-1}$. However, in non-uniform stream channels such as at HPO, smaller particles are sheltered behind larger grains and stones and require a higher flow to set them into motion (Palucis and Lamb, 2017). Considering the empirical channel stability approach (Olsen, 1993), the critical bottom velocity for fine gravel deposits was $v_{crit}$ = 0.85 m $s^{-1}$ (i.e. mean cross-section velocity v = 1.2 m $s^{-1}$); and, the corresponding discharge $Q_{crit}$ = 0.76 $m^3$ $s^{-1}$ (close to the 50 years return period, Tab. 3). Thus, the relative bed stability of RBS = $Q_{crit}/Q_5$ = 3.3 can be considered 'highly stable' (USDA, 2007) ($Q_5$ is the peak flow with five-year return probability).

### Flash flood of 7 August 2010: Physical environment

During the week 3-9 August 2010, a total precipitation amount of 434 mm was recorded in the HPO catchment, with a particularly heavy rainstorm (313 mm $day^{-1}$) on 7 August (Fig. 2). This daily rainfall did not exceed the regional historical record (345 mm $day^{-1}$) of 29 July 1897 (Munzar and Ondráček, 2010), but that record was observed in the upper plain of the Jizera Mts. that has 1.5 times higher annual precipitation on average.

The HEC- HMS 4.4 catchment modelling system reconstructed the flood wave (Fig. 3) with a peak discharge of $Q_{max}$ = 2.38 $m^3$ $s^{-1}$, verified by flood footprints (2.25 $m^3$

**Tab. 3.** Peak discharge frequency at the HPO outlet.

| Return period N (years) | Peak discharge $Q_N$ ($m^3$ $s^{-1}$) |
|---|---|
| 1 | 0.08 |
| 2 | 0.13 |
| 5 | 0.23 |
| 10 | 0.34 |
| 20 | 0.49 |
| 50 | 0.65 |
| 100 | 1.02 |
| 1000 | 2.46 |

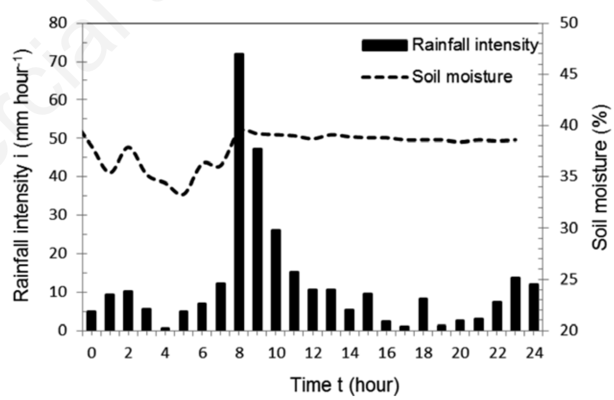


**Fig. 2.** Rainfall intensity (mm $hour^{-1}$) and soil moisture (%) at the 15 cm depth on 7 August 2010.

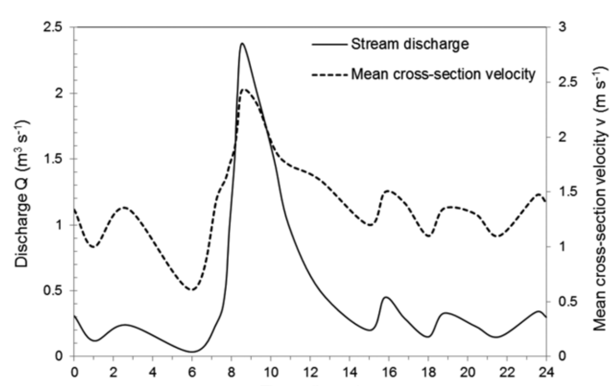


**Fig. 3.** Stream discharge Q ($m^3$ $s^{-1}$) and mean cross-section velocity v (m $s^{-1}$) near the catchment outlet on 7 August 2010.

$s^{-1}$ with a Manning's roughness coefficient n = 0.065). The return period of this event is close to 1,000 years (Tab. 3), though the unit peak discharge (10.35 $m^3 s^{-1} km^{-2}$) is below the European probable maximum given for the EuroMed-eFF database (Amponsah *et al*., 2020). For three hours, rainfall intensities (culminating at 72 mm $hour^{-1}$) exceeded the soil infiltration capacity of 12 mm $hour^{-1}$ (measured by a double ring infiltrometer) and surface flow dominated (documented by the relatively low increase in soil moisture, Fig. 2). The lag time of discharge to rainfall was about 30 minutes (Figs. 2 and 3), and the event runoff coefficient was 0.77. During this flood, the drainage network expanded into two additional ephemeral branches and moved the channel head 30 meters higher. As simulated by HEC-RAS 5.0.3, during the peak flow (2.38 $m^3 s^{-1}$) the discharge travel time in the main channel was 2.8 minutes; detailed currents and depth are given in Fig. 4. After the flood, the basic step-pool morphology (created by big granite blocks) did not change, but, the bed particle distribution in the investigated stream transect was altered from fine to medium gravel.

On 7 August 2010, the HPO stream had discharge above the threshold of stream bed stability ($Q_{crit}$ = 0.76 $m^3 s^{-1}$) for approximately two hours (Fig. 3). While the average annual volume of sediment collected at the HPO gauging station from 1996-2009 was 0.46 $m^3 year^{-1}$, this extreme event resulted in 2.7 $m^3$ of sand and gravel being eroded in the stream channel. There was negligible soil erosion at the two forest plots sheltered by the forest canopy and litter.

Annual streamflow extremes of the HPO outlet from 2002-2012 are given in Tab. 4. The observed minima are consistent with only a limited impact on stream biota, and except for the 2010 event, the maxima reached return periods of only 1-8 years.

**Changes in stream water chemistry and macroinvertebrate assemblages**

Basic characteristics of the HPO stream during a macroinvertebrate survey from 2010 up to 2012 are given in Tab. 2; sampling was performed during base-flow conditions, with discharges of mean daily duration between 150 and 330 days. Values of specific conductivity (71.6-80.3 µS $cm^{-1}$) and calcium content (5.4-7.2 mg $L^{-1}$) reflect low mineral contents; pH values (around 6), relatively high contents of sulphate (19.1-25.3 mg $L^{-1}$) and nitrate (1.9-3.7 mg $L^{-1}$) and depleted alkalinity (18.2-55.9 µeq $L^{-1}$)

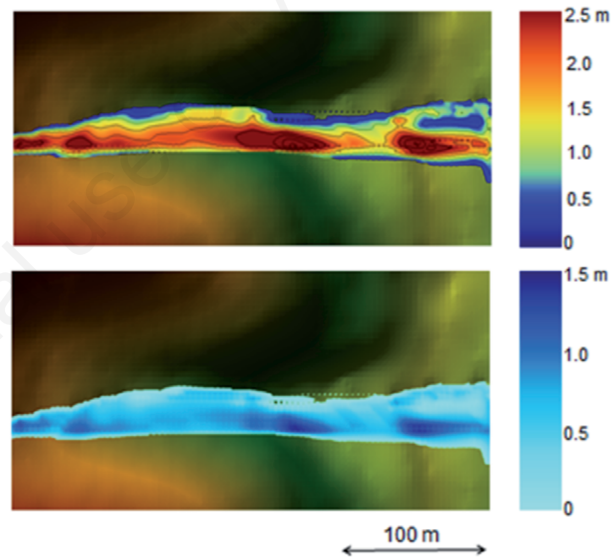


**Fig. 4.** Currents and depth in the schematized stream channel, from the branch junction (left) to the gauging station (right) during the peak discharge on 7 August 2010.

**Tab. 4.** Annual streamflow extremes in the HPO basin, 2002-2012.

| Year | $Q_{min}$ ($10^{-3}$ $m^3 s^{-1}$) | $Q_{max}$ ($10^{-3}$ $m^3 s^{-1}$) | Flood origin (-) | Return period (years) |
|---|---|---|---|---|
| 2002 | 0.42 | 285 | summer rain | 7 – 8 |
| 2003 | 0.35 | 43 | snowmelt | <1 |
| 2004 | 0.33 | 124 | summer rain | 2 |
| 2005 | 0.44 | 145 | summer rain | 2 – 3 |
| 2006 | 0.51 | 272 | summer rain | 6 – 7 |
| 2007 | 0.33 | 100 | snowmelt | 1 – 2 |
| 2008 | 0.32 | 125 | snowmelt | 2 |
| 2009 | 0.38 | 78 | snowmelt | <1 |
| 2010 | 0.35 | 2280 | summer rain | 900 – 1000 |
| 2011 | 0.36 | 141 | summer rain | 2 – 3 |
| 2012 | 0.34 | 120 | snowmelt | 1 – 2 |

(Tab. 5, Fig. 5) are consistent with a moderately anthropogenically-acidified aquatic environment (Veselý and Majer, 1996, Horecký *et al*., 2013).

Changes in stream water chemistry after the flash flood of 7 August 2010 are given in Tab. 5. There were statistically significant declines in specific conductivity (4.8 $\mu S\ cm^{-1}$, 6%) and contents of sulphate (3.9 mg $L^{-1}$, 16%), fluoride (0.1 mg $L^{-1}$, 33%), chloride (0.3 mg $L^{-1}$, 19%) and magnesium (0.2 mg $L^{-1}$, 13%). Contents of calcium and nitrate also decreased, while values of pH and alkalinity increased, but these changes were not statistically significant. Consequently, there was an increasing trend in alkalinity and decreasing trend in conductivity in 2009-2012 (Fig. 5); these trends were statistically signif-

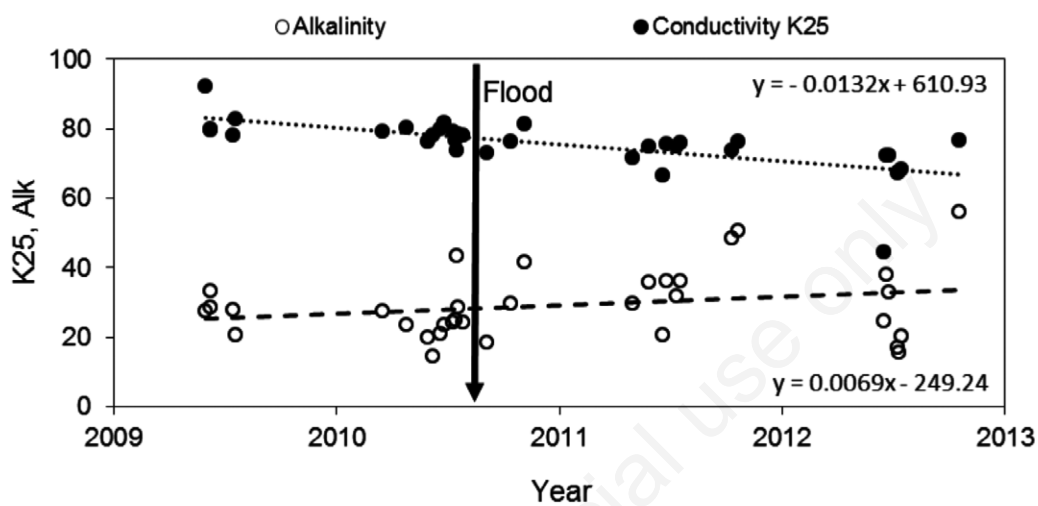


**Fig. 5.** Stream water conductivity (K25, $\mu S\ cm^{-1}$) and alkalinity (Alk, $\mu eq\ L^{-1}$), (HPO catchment, 2009-2012).

**Tab. 5.** Changes of chemical elements in the stream water during comparable base flow at the HPO outlet, before and after the flood.

| Date | $K_{25}$ | pH | Alk | $Na^+$ | $K^+$ | $Mg^{2+}$ | $Ca^{2+}$ | $F^-$ | $Cl^-$ | $NO_3^-$ | $SO_4^{2-}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | $\mu S\ cm^{-1}$ | - | $\mu eq\ L^{-1}$ | $mgL^{-1}$ | $mgL^{-1}$ | $mgL^{-1}$ | $mgL^{-1}$ | $mgL^{-1}$ | $mgL^{-1}$ | $mgL^{-1}$ | $mgL^{-1}$ |
| 10-Jun-09 | 79.4 | 6.0 | 28.6 | 2.7 | 0.4 | 1.5 | 7.0 | 0.3 | 1.7 | 2.4 | 24.7 |
| 17-Jul-09 | 78.0 | 6.0 | 27.9 | 2.7 | 0.4 | 1.5 | 7.1 | 0.3 | 1.7 | 2.5 | 25.0 |
| 18-Mar-10 | 79.3 | 5.9 | 27.6 | 2.6 | 0.5 | 1.5 | 7.2 | 0.3 | 1.6 | 3.0 | 25.3 |
| 27-Apr-10 | 80.3 | 5.9 | 23.4 | 2.4 | 0.5 | 1.6 | 6.7 | 0.3 | 1.6 | 3.7 | 24.3 |
| 28-Jul-10 | 77.9 | 6.0 | 24.3 | 2.5 | 0.4 | 1.3 | 5.7 | 0.3 | 1.6 | 3.1 | 23.0 |
| 5-Sep-10 | 73.0 | 5.9 | 18.2 | 2.3 | 0.5 | 1.3 | 5.6 | 0.3 | 1.4 | 3.7 | 20.9 |
| 16-Oct-10 | 76.1 | 6.1 | 29.4 | 2.3 | 0.5 | 1.3 | 6.8 | 0.3 | 1.4 | 3.1 | 22.1 |
| 4-May-11 | 71.6 | 6.2 | 29.6 | 2.3 | 0.5 | 1.2 | 5.4 | 0.2 | 1.2 | 2.7 | 20.0 |
| 13-Oct-11 | 73.8 | 6.4 | 48.5 | 2.6 | 0.7 | 1.3 | 5.8 | 0.2 | 1.3 | 1.9 | 20.5 |
| 21-Oct-12 | 76.5 | 6.0 | 55.9 | 3.0 | 0.6 | 1.4 | 6.9 | 0.2 | 1.2 | 2.5 | 19.1 |
| **Before** | | | | | | | | | | | |
| Mean | 79.0 | 6.0 | 26.4 | 2.6 | 0.4 | 1.5 | 6.7 | 0.3 | 1.6 | 3.0 | 24.4 |
| SD | 0.91 | 0.05 | 2.08 | 0.12 | 0.05 | 0.08 | 0.55 | 0.01 | 0.04 | 0.47 | 0.79 |
| **After** | | | | | | | | | | | |
| Mean | 74.2 | 6.2 | 36.3 | 2.5 | 0.6 | 1.3 | 6.1 | 0.2 | 1,3 | 2.8 | 20.5 |
| SD | 1.86 | 0.17 | 13.80 | 0.30 | 0.08 | 0.08 | 0.60 | 0.02 | 0.11 | 0.62 | 0.99 |
| Means diff. | - 4.8 | 0.2 | 9.9 | - 0.1 | 0.2 | - 0.2 | - 0.6 | - 0.1 | - 0.3 | - 0.2 | - 3.9 |
| (%) | - 6 | 3 | 38 | - 4 | 50 | - 13 | - 9 | - 33 | - 19 | - 7 | - 16 |
| P | 0,01 | 0.21 | 0.25 | 0.72 | 0.06 | 0.01 | 0.19 | 0.02 | 0.01 | 0.72 | 0.01 |
| Significant | Yes | - | - | - | - | Yes | - | Yes | Yes | - | Yes |

*SD, standard deviation; P, Mann Whitney two-tailed P-value.*

icant, with Spearman's correlation coefficient $R_S$ values of 0.62 and 0.51, respectively, exceeding the critical value $R_{Scrit} = 0.35$ at the 0.05 probability level. These results correspond with the long-term recovery of stream water from acidification, as reflected by the statistically significant rising trend in annual pH values of both precipitation and stream water from 1995-2015 (Fig. 6; Spearman's correlation coefficient $R_S$ of 0.82 and 0.84, respectively, exceeding the critical value $R_{Scrit} = 0.41$ at the 0.05 probability level).

Macroinvertebrate assemblages of the HPO stream were composed of 82 taxa (distinct taxonomical units) that belong to 7 orders of aquatic insects (included larvae, pupae and adults) and the subclass Oligochaeta. A complete list of taxa collected in eight sampling dates from 18 March 2010 to 29 October 2012 along with numbers of individuals of each taxon is given in Appendix 1. Plecoptera was the most abundant group (17 taxa and a maximum number of individuals of 743 on 27 April 2010) followed by Diptera (36 taxa and max. 507 individuals on 28 July 2010) dominated by families Simuliidae and Chironomidae. Trichoptera (14 species and max 229 individuals on 13 October 2011) and Coleoptera (9 species and max. 43 individuals on 28 July 2010) were also abundant, while Ephemeroptera were very rare (4 species, max 11 individuals on 29 October 2012). Oligochaetes were not determined to species level, and their numbers reached a maximum of 10 individuals on 13 October 2011. Heteroptera and Odonata were only found a total of three times, and we identified only a single taxon in each of these orders (Appendix 1, Tab. 6, Fig. 7).

The flood had an immediate devastating effect on macroinvertebrate assemblages and negatively influenced both the number of species/taxa and the number of individuals of each taxonomical group as well as their total values (Tab. 6, Fig. 7). For the whole period following this event changes in individual groups were statistically significant only for "other Diptera", the total number of individuals (N) and taxa (S) that declined significantly after the flood (Tab. 6). On the other hand, there was a long-term drop in the number of taxa in all groups except Oligochaetes and particularly mayflies, where the number of taxa temporarily increased. Both calculated indexes of diversity followed the same trend, as they reached the highest value ever 9 months after the flood; this resulted in a statistically nonsignificant effect of the flood on their values (Tab. 6).

The dominant species (occurring on all eight sampling dates) were *Leuctra nigra* with mean number of individuals (mni) 96, *Plectrocnemia conspersa* (mni 17), and *Nemurella pictetii* (mni 11). Slightly less dominant species (present on seven sampling dates but in relatively low numbers) were *Heterotanytarsus apicalis* (mni. 6), *Dicranota* sp. (mni. 5), *Agabus* sp. (mni 3), and *Odeles marginata* (mni 3). All those species were also present on at least one sampling date after the flood (7 August 2010) when the macroinvertebrate assemblages were significantly reduced (Tab. 6, Fig. 7), indicating their resistance to extraordinary high currents and streambed changes. Further frequent species were found in six samples: *Siphonoperla torrentium* (mni 22), *Leuctra pseudosignifera* (mni 26), *Protonemura auberti* (mni 43), *Sericostoma* cf. *personatum* (mni. 6), *Trissopelopia longimana* (m.n.i. 90, the second most numerous species), and *Eloeophila* sp. (mni 1). After the flood, the abundance of the all these species gradually returned to their original numbers (Appendix 1). Two wider taxonomical groups in this category were not identified to species level: family

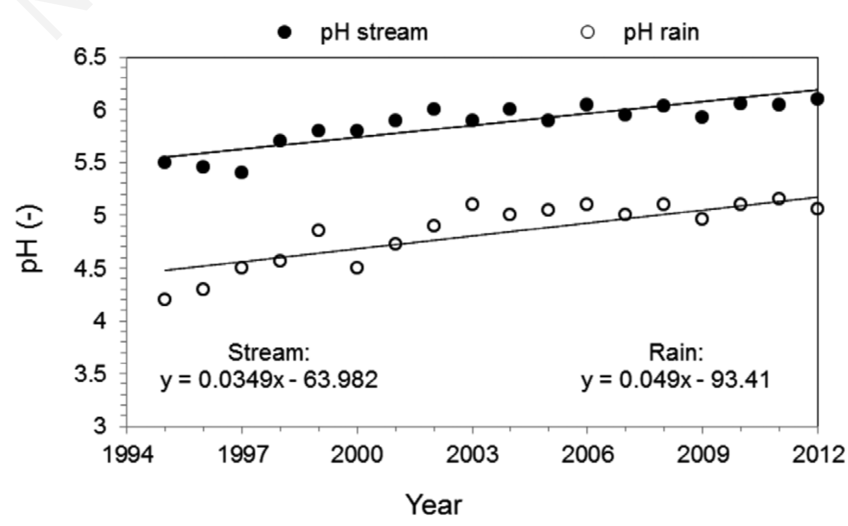


**Fig. 6.** Mean annual pH values of rain and stream water (HPO catchment, 1995-2012).

Simuliidae (mni 119), one of the most numerous organisms in the study that did not re-establish their original abundance after the flood, and the rare but regularly present Oligochaetes (mni. 3). There were also high numbers of individuals belonging to taxa with multiple early instars like *Protonemura* sp. juv. (mni. 144) and *Plectrocnemia* sp. juv. (mni. 29), but the lack of precise identification makes this information difficult to interpret.

In addition, there was a group of species that occurred only one to three times but reached noticeable numbers

**Tab. 6.** Number of species/taxa in all collected groups of macroinverterbrates and population characteristics before and after the flood.

| | OLI | ODO | EPH | PLE | TRI | CHR | ODI | COL | HET | N | S | $D_{SE}$ | $D_{SC}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 18-Mar-10 | 1 | 0 | 1 | 13 | 7 | 13 | 9 | 2 | 0 | 1048 | 46 | 13 | 7 |
| 27-Apr-10 | 1 | 0 | 0 | 11 | 10 | 13 | 6 | 6 | 0 | 1327 | 47 | 10 | 5 |
| 28-Jul-10 | 0 | 0 | 0 | 7 | 7 | 12 | 8 | 4 | 1 | 891 | 39 | 11 | 7 |
| 5-Sep-10 | 1 | 0 | 0 | 5 | 3 | 3 | 3 | 3 | 0 | 86 | 18 | 6 | 3 |
| 16-Oct-10 | 1 | 0 | 0 | 7 | 3 | 2 | 3 | 1 | 1 | 128 | 18 | 8 | 6 |
| 4-May-11 | 1 | 0 | 2 | 8 | 6 | 17 | 6 | 1 | 0 | 563 | 41 | 17 | 11 |
| 13-Oct-11 | 1 | 1 | 2 | 8 | 8 | 10 | 5 | 3 | 0 | 830 | 38 | 11 | 8 |
| 29-Oct-12 | 0 | 0 | 1 | 6 | 5 | 12 | 3 | 3 | 0 | 839 | 30 | 8 | 5 |
| **Before** | | | | | | | | | | | | | |
| Mean | 0.7 | 0 | 0.3 | 10.3 | 8.0 | 12.7 | 7.7 | 4.0 | 0.3 | 1089 | 44 | 11.3 | 6.3 |
| SD | 0.58 | 0 | 0.58 | 3.06 | 1.73 | 0.58 | 1.53 | 2.00 | 0.58 | 221 | 4.36 | 1.53 | 1.15 |
| **After** | | | | | | | | | | | | | |
| Mean | 0.8 | 0.2 | 1.0 | 6.8 | 5.0 | 8.8 | 4.0 | 2.2 | 0.2 | 489 | 29.0 | 10.0 | 6.6 |
| SD | 0.45 | 0.45 | 1.00 | 1.30 | 2.12 | 6.30 | 1.41 | 1.10 | 0.45 | 366 | 10.82 | 4.30 | 3.05 |
| Means diff. | 0.1 | 0.2 | 0.7 | -3.5 | -3.0 | -3.9 | -3.7 | -1.8 | -0.1 | -600 | -15.0 | -1.3 | 0.3 |
| (%) | 14 | - | 233 | -34 | -37 | -31 | -48 | -45 | -33 | -55 | -34 | -12 | 5 |
| P | 0.82 | 0.41 | 0.34 | 0.20 | 0.13 | 0.29 | 0.04 | 0.29 | 0.81 | 0.03 | 0.04 | 0.45 | 0.88 |
| Significant | - | - | - | - | - | - | Yes | - | - | Yes | Yes | - | - |

*OLI, Oligochaeta; ODO, Odonata; EPH, Ephemeroptera; PLE, Plecoptera; TRI, Trichoptera; CHR, Chironomidae; ODI, other Diptera; COL, Coleoptera; HET, Heteroptera); N, total number of individuals; S, total number of taxa; $D_{SE}$, Shannon entropy; $D_{SC}$, Simpson concentration; SD, standard deviation; P, Mann-Whitney two-tailed P-value.*

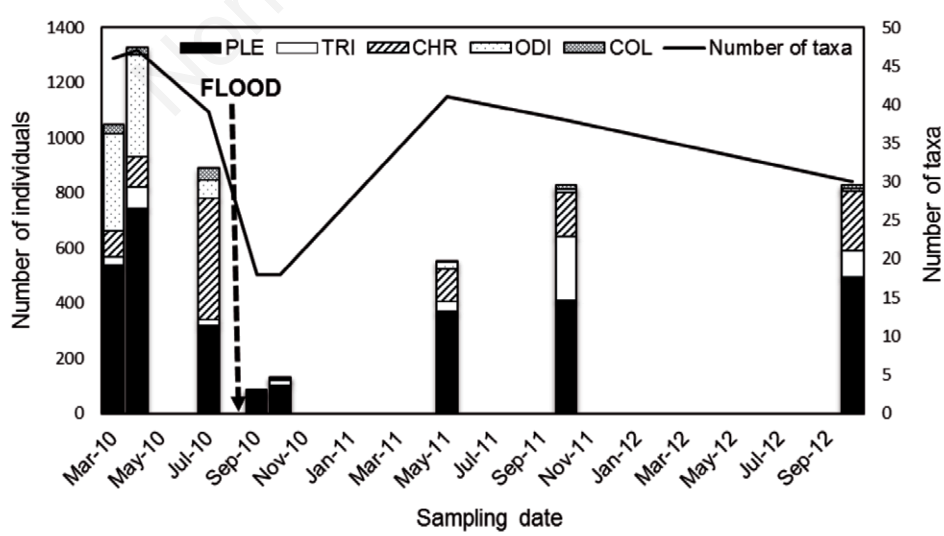


**Fig. 7.** Number of individuals in the most abundant groups of macroinvertebrates (stacked-bars) and the total number of taxa in all present taxonomical groups (line) in the HPO stream, 2010-2012. PLE, Plecoptera; TRI, Trichoptera; CHR, Chironomidae; ODI, other Diptera; COL, Coleoptera.

per sample. Some of them were present before the flood only, such as *Leuctra aurita* (mni 64), *Leuctra prima* (mni 12), *Leuctra major* (mni. 6), *Diura bicaudata* (mni 2), *Crunoecia irrorata* (mni 2), *Philopotamus ludificatus* (mni 2), *Potamophylax* cf. *cingulatus* (mni 6), *Ibisia marginata* (mni 3) and *Limnius* sp. (mni 9). Other species appeared only after the flood, such as *Baetis rhodani*, *Siphlonurus aestivalis*, *Nemoura cinerea* (mni 110), *Pseudodiamesa branickii* (mni 24), and *Chaetocladius piger* group (mni 10) - all found on 4 May 2011, the third sampling after the flood and the first with significant signs of recovery (Tab. 6, Fig. 7). There were also chironomid species that did not belong to any of the above categories: *Micropsectra* cf. *aristata* (mni 34) and *Heterotrissocladius marcidus* (mni 25) that were abundant before the flood but did not reach their original numbers after the flood. Other species were present at too low abundances to support any conclusions. Notable, however, was the finding of the very rare *Georthocladius* sp. (mni 1) that was present only during two samplings following the flood, when all macroinvertebrate assemblages were significantly reduced.

## DISCUSSION

Annual peak flows in the HPO are generated mainly by summer rainstorms, producing flash floods of relatively short duration (Tab. 4, Fig. 2, Fig. 3). The peak discharge of 2.38 $m^3 s^{-1}$ observed on 7 August 2010 was estimated to have a return period of 1,000 years (Tab. 4). This extreme event eroded and transported 2.7 $m^3$ of sand and gravel (6 times more than the mean annual sediment outflow) from this relatively short first order headwater stream, while negligible soil erosion was found on slopes covered by beech forests, likely reflecting their canopy interception, leaf litter deposits and deep rooting (Chang, 2012).

For several decades, water chemistry in the HPO stream has been influenced by the acid atmospheric deposition of sulphur and nitrogen compounds (Křeček and Hořická, 2001). In comparison with the upper plain of the Jizera Mts., acidification of the HPO catchment was limited by the lower (65%) annual precipitation and the stands of semi-native beech (*Fagus sylvatica*), which have lower winter deposition and leaf litter decomposition (Godbold and Hüttermann, 1994). Thus, since 1994, pH values in HPO stream waters did not decrease below 5.3, despite precipitation having a much lower pH (Fig. 6), and consequently reactive aluminium and its labile (toxic) forms were not found.

The chemical impacts of the extreme summer flood of 2010 include statistically significant declines in specific conductivity and contents of sulphate, fluoride, chloride and magnesium. Together with decreased concentrations of other chemical compounds (except nitrate, which increased), this was evidently the result of the dilution of stream discharge by the high volume of rain (Fig. 2, Tab. 5). Accompanied by rising values of pH and alkalinity, this indicates a depletion of the sulphur pool in soils related to catchment runoff genesis. During intense rainstorms, streamflow in forested catchments is generated primarily through the organic and upper mineral soil horizons along streams (Chang, 2012), and these areas simultaneously contribute the majority of storm-associated sulphate to streams. Thus, after the August 2010 flood, the contents of sulphate in the HPO stream decreased by 16% (Tab. 5). However, changes in stream water chemistry during the following two years after the flood (Tab. 5, Fig. 5, Fig. 6) reflect the continued recovery of the HPO basin from acidification, evidenced also by the long-term trend in pH values in both precipitation and stream waters (Fig. 6). Thus, it is clear that the recorded flood did not significantly alter the recovery of the HPO surface waters from acidification.

The macroinvertebrate composition in HPO is consistent with a small headwater mountain stream with a heterogeneous bed, relatively low regular flow (mean annual discharge of 2.5 $10^{-3}$ $m^3 s^{-1}$) and slightly decreased pH values due to anthropogenic acidification (Tabs. 3 and 5; Fig. 6), being similar to other first-order headwater streams of the European Black Triangle as well as other mountain streams affected by anthropogenic acidification (Horecký *et al*., 2013; Stockdale *et al*., 2014). While such streams are very susceptible to hydrological extremes (floods and droughts), the most dominant species, such as the omnivorous stoneflies *Leuctra nigra* and *Nemurella pictetii* and the predatory caddisfly *Plectrocnemia conspersa*, are well adapted to such conditions (Horecký *et al*., 2006, 2013) and so survived the flood of 2010 (Appendix 1).

Before the flood, the water chemistry of HPO (characterized by moderate acidity was not limiting for the presence of even less acid-tolerant species such as the mayfly *Leptophlebia marginata*, stoneflies *Siphonoperla torrentium* and *Diura bicaudata*, caddisfly *Rhyacophila* cf. *polonica*, Simuliidae and many species of the family Chironomidae. These species do not inhabit strongly acidified streams with pH below 5 (Horecký *et al*. 2006; Hardekopf *et al*., 2008). Continuing recovery from acidification during the two years after the flood brought a further improvement in water chemistry (Fig. 5), and the abundance of both dominant and less acid-tolerant species increased, as reported also from other acidified headwater catchments in the Czech Republic (Horecký *et al*. 2013; Beneš *et al*., 2017) and abroad (Edwards, 1998; Garmo *et al*., 2014; Stockdale *et al*., 2014).

The flood had a devastating effect on the stream macroinvertebrates that was particularly pronounced for several months afterwards. Total number of species/taxa

(S), Shannon entropy ($D_{SE}$) and Simpson concentration ($D_{SC}$) were reduced by about 50%, while the abundance of taxa was reduced by about 10% compared with before the flood (Tab. 6, Fig. 7). These changes cannot be explained by natural seasonal variability that for dominant taxonomical groups (stoneflies, true flies, caddisflies and beetles) is much lower according to Beneš *et al*. (2017).

Moreover, because of the larger regional extent of the flood, there were likely limited local resources of adult insects for stream recolonization. By the end of the first year after the flood, both the number of taxa and number of individuals increased, but they remained significantly lower (Tab. 6). Complete recovery of macroinvertebrate assemblages was still not observed even two years after the flood, similarly as found by Smith *et al*. (2019). Simuliidae and other filter feeding taxa such as *Micropsectra aristata* and *Philopotamus ludificatus*, but also species inhabiting moss-grown or soft substratum such as *Trissopelopia longimana* and *Ibisia marginata*, did not reach their numbers before the flood or even totally disappeared. This may indicate a continued lack of fine particulate organic matter or organic substratum. Interestingly, sampling in May 2011 demonstrated an unsuccessful colonization of the HPO stream by alien species that had not been present before the flood (*Baetis rhodani*, *Siphlonurus aestivalis*, *Nemoura cinerea*, *Diamesa dampfi / permacra*, *Chaetocladius piger* group, *Pseudodiamesa branickii*). These species temporarily inhabited the stream but then later disappeared, resulting in a distinct but ephemeral peak of biological diversity (Tab. 6, Appendix 1). Similar results were found by Stubbington *et al*. (2009), who described declines in invertebrate abundance as an impact of flooding in perennial streams, as well as Snyder and Johnson (2006), who reported prolonged such effects over several consecutive years.

## CONCLUSIONS

The extreme summer flash flood (with a return period close to 1,000 years) resulted in a devastating effect on stream macroinvertebrates in the studied catchment. Both the number of species/taxa and the total number of individuals were significantly reduced for the two years following the flood. A temporary peak in the total number of species/taxa and species diversity nine months after the flood was the result of unsuccessful colonization by alien species. On the other hand, the flood event partly contributed to the recovery of the stream from anthropogenic acidification, particularly through a decline in sulphur contents in the stream water (associated with a depletion of the sulphur pool of soils). The overall course of long-term recovery was not altered, however.

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