Silva Gabreta	vol. 24	p. 21–45	Vimperk, 2018

Natural disturbance by bark beetle offsets climate change effects on streamflow in headwater catchments of the Bohemian Forest

Burkhard Beudert[1,*], Jana Bernsteinová[2], Joseph Premier[1] & Claus Bässler[1]

[1]*Bavarian Forest National Park, Freyungerstraße 2, D-94481 Grafenau, Germany*
[2]*Faculty of Sciences, Charles University, Prague, Albertov 6, CZ-12000, Prague, Czech Republic*
[*] Burkhard.Beudert@npv-bw.bayern.de

Abstract
In central Europe, large strictly protected areas, such as the Bavarian Forest and Šumava National Park (NP) in the Bohemian Forest, and their management have come under public pressure after adopting a "benign neglect" approach concerning natural disturbances. Here the extensive dieback of Norway spruce by bark beetle (*Ips typographus* L.) raised concern about its regional eco-hydrological effects (i.e. runoff yields) and how they interact with the effects of prevailing climate change. To address these questions, we first analysed the hydrological response of nine conterminous mostly forested catchments in the Bohemian Forest to changes in climatic factors. The catchments (39.1–333.9 km², mean elevation 800–1134 m a.s.l.) cover the Bavarian Forest NP and most parts of the Šumava NP along and across the Czech-German border. From 1978 to 2013, independent of land use changes and physiographic features, regional summer runoff decreased by 70 mm (−21% of long-term median) despite increased summer precipitation (51 mm, 8%), while winter runoff did not change (8 mm) although precipitation declined (−54 mm, −9%). This feature results from a timing effect in streamflow due to earlier snowmelt, which is driven by the regional warming in winter, especially in April, by about 3.3 K, irrespective of altitude. However, the overall decline in annual runoff yields (−59 mm, −7%), despite constant precipitation, is related to higher water vapour losses due to the increased air temperature in summer (1.5±0.3 K) while the long-term means varied between 8.9 and 13.4°C depending on altitude. A dataset consisting of three sub-catchments inside the national parks (0.7–89.7 km²) was analysed for disturbance effects (58–62% of catchment area) on precipitation runoff behaviour. The larger ones, Upper Vydra and Upper Große Ohe, strictly followed the overall trends in runoff and high flows in winter but did not show annual trends. An analysis of runoff precipitation ratio revealed a significant step change in the Bavarian Forest NP sub-catchments once cumulative disturbance exceeded 30% area (1998/1999). After this step change, catchment evapotranspiration significantly decreased by 62–120 mm and runoff increased to the same extent. The sub-catchment in the Šumava NP did not respond probably due to timing and/or scale effects. Overall, the observed declining trends in runoff yields were not caused by precipitation changes but were due to warming only. However, in small embedded catchments of the national parks, reduced evapotranspiration losses after bark beetle outbreaks and windthrow currently but temporarily compensate for climate change effects. Shifting streamflow from early summer to late winter is the common hydrological response of all catchments to warming, which in the longer term may negatively affect the water supply to vegetation and people in autumn.

Key words: streamflow, climate change, natural disturbance, protected area, national park

Introduction

Streamflow changes due to climate change are reported from most parts of the world and comprise both increases and decreases depending on the size, timing and interrelation of regionally specific climatic factors. A global analysis of streamflow revealed increased streamflow in high latitude North America and Eurasia and projected increases of 10–40% by 2050, while in Southern Europe decreased streamflow was reported with further decreases of 10–30% projected (Milly et al. 2005, Milliman et al. 2008). Stahl et al. (2010, 2012) found very similar regionally consistent trends (1964–2004) in annual streamflow, with negative signs in southern and eastern regions of Europe and positive signs in northern and western regions. Generally, streamflow trends in high latitude and western European regions are governed by increasing and/or seasonally altered precipitation, which balanced or exceeded concurrent opposing warming effects (Klein Tank et al. 2002). In eastern and southern Europe, however, streamflow responded negatively to the reduced annual precipitation yields, increased temperature (European Environment Agency 2017), and more frequent droughts (Gudmundsson & Seneviratne 2015).

Apart from precipitation issues, many studies from snow dominated or influenced regions reported changes in streamflow timing and flood peaks due to earlier snowmelt by warming in winter and early spring (McCabe & Clark 2005, Stewart et al. 2005, Wilson et al. 2010, Renner & Bernhofer 2011, Dudley et al. 2017). In addition, increasing temperature and/or radiation input during summer alone, which in energy limited central Europe correlates with evapotranspiration, should enlarge water vapour losses from catchments well supplied with water (Teuling et al. 2009).

Despite this, in the Bohemian Forest region, streamflow did not change significantly between 1965 and 2015, corresponding to unaltered annual and summer precipitation (European Environment Agency 2017). Former work on single catchment streamflow over varying periods did not report significant changes in annual runoff yields or precipitation but did reveal rising air temperatures (1953–2005, Kliment & Matoušková 2008; 1961–1998, Buchtele et al. 2006; 1962–2008, Kliment et al. 2011). More recent studies attributed changes in seasonal streamflow of two high elevation catchments to earlier snowmelt and discussed the relevance of forest cover and vegetation change on discharge dynamics (Bernsteinová et al. 2015, Langhammer et al. 2015). Klöcking et al. (2005) and Beudert et al. (2007) found altered runoff partitioning and increased precipitation related runoff following a large scale bark beetle outbreak.

Land use change (Führer et al. 2011, Tomer & Schilling 2009) and disturbance of forest ecosystems by management (Bosch & Hewlett 1982, Sahin & Hall 1995, Andreassian 2004) or by windthrow and bark beetle outbreaks (Adams et al. 2012, Bearup et al. 2014) are known to change streamflow. The magnitude of such disturbance effects might be sufficient to mask climate change effects. Moreover, post-disturbance succession of vegetation cover and its water demand proceeds continuously, which may also generate streamflow trends (Jones 2011).

In both the Bavarian Forest and Šumava national parks in the centre of the Bohemian Forest region, outbreaks of the host-specific Norway spruce bark beetle (*Ips typographus* L.) and windthrow led to extensive areas of dead spruce during the last 25 years. Concerns about the quality of drinking water and the moderation of floods could be allayed (Beudert et al. 2015, Bernsteinová et al. 2015). However, decreasing runoff yields and low flows in autumn especially, which indicate the availability of groundwater and thus drinking water, have frequently been attributed to the occurrence of disturbed or dead but unmanaged spruce stands despite public awareness of regional climate change (i.e. spring warming, changes in phenology). To provide information and scientific evidence, we analysed the hydrological response of nine conterminous mostly forested catchments in the Bohemian Forest, covering the whole (Bavarian Forest) or a major part (Šumava) of the national parks and non-conservation areas, to changes in climatic factors. Disturbance effects on streamflow in particular were examined in three sub-catchments inside the national parks, which have been heavily affected by bark beetle outbreaks and/or windthrow.

Two hypotheses about the drivers of observed eco-hydrological changes in our Bohemian Forest catchments were tested. (i) Rising air temperature has been the major driver of change in runoff yields. Increased energy input has altered the extent and timing of phase transitions of water depending on its seasonal occurrence. (ii) Extended changes in vegetation structure due to large scale bark beetle outbreaks has been decreasing evaporation losses thereby counteracting warming effects on streamflow.

The overarching goal of this study is to provide clarity and insight into man-made environmental changes, which have the potential for threatening ecosystem services.

Material and methods

Catchments characteristics

We selected nine catchments and three nested sub-catchments along and across the Czech--German border, which drain north-eastern and south-western slopes of the Bohemian Forest (Fig. 1). The German streams are tributaries of the Regen and Ilz streams, which belong to the Danube River basin and thus to the Black Sea drainage system. The Czech streams belong to the Vltava/Labe (Elbe) River basin, which is a part of the North Sea drainage system (Fig. 1). The study area covers 1 156 km^2 with an elevation range of 1016 m between 440 m a.s.l. (gauging station Schönberg, Große Ohe catchment) and 1456 m a.s.l. (Großer Arber summit, Weißer Regen catchment).

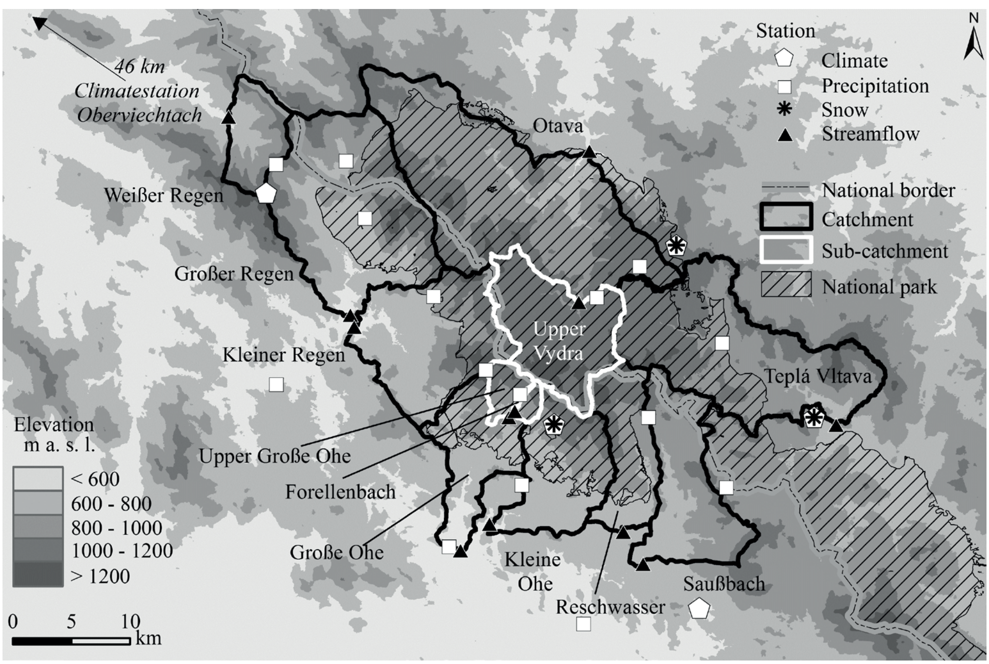

Fig. 1. Digital terrain model of the study area in the Bohemian Forest with nine catchments (black line) and three sub-catchments (white line) along and across the Czech-German border. The gauges (black triangle) and the name of the catchments are indicated. The location of regional climate and precipitation stations is shown (white symbols).

Table 1. Basic catchment characteristics and runoff data (mean ± standard deviation) for the 1978–2013 period (except for Forellenbach: 1992–2013). Code – catchment acronym; percent of disturbed area refers only to the national parks (n.a. – not applicable).

Catchment	**Code**	**Coordinates**	**Area**	**Elevation (m a.s.l.)**			**Slope**	**Forest**	**NP**	**Disturbed area** (%)		**Runoff**
			(km^2)	min.	mean	max.	(°)	(%)	(%)	2003	2013	($mm.y^{-1}$)
Otava	OT	N49.1406 / E13.5124	333.9	564	1083	1453	7.9	85	93	0	31	848±146
Upper Vydra	UV	N49.0252 / E13.4964	89.7	973	1134	1453	5.8	90	100	18	62	1228±232
Teplá Vltava	TV	N48.9272 / E13.7928	176.9	761	1008	1362	8.1	75	44	2	15	549±115
Regen												
Großer Regen	GR	N49.0186 / E13.2301	175.7	558	877	1336	11.1	88	43	0	11	933±182
Kleiner Regen	KR	N49.0095 / E13.2342	115.9	560	848	1453	9.5	85	34	11	26	757±161
Weißer Regen	WR	N49.1716 / E13.0912	39.1	576	918	1456	13.5	90	0	n.a.	n.a.	1011±199
Ilz												
Große Ohe	GO	N48.8370 / E13.3534	86.6	440	800	1453	8.8	79	59	11	40	798±136
Kleine Ohe	KO	N48.8567 / E13.3875	78.3	556	831	1373	8.4	73	56	18	42	799±171
Reschwasser	RW	N48.8487 / E13.5427	59.4	664	938	1373	8.7	79	63	40	60	970±180
Saußbach	SB	N48.8246 / E13.5656	89.6	645	888	1263	8.2	76	1	3	19	826±151
Upper Große Ohe	UGO	N48.9382 / E13.4124	19.1	769	999	1453	11.4	98	100	39	58	1000±201
Forellenbach	FB	N48.9427 / E13.4196	0.7	787	894	1293	8.4	98	100	39	61	1030±175

The bedrock in this part of the Bohemian massif consists of magmatic (mostly granite) and metamorphic rocks (paragneiss, migmatite, orthogneiss), which are overlain by quaternary sediments, mostly periglacial solifluction deposits and fluvial sediments (Rohrmüller et al. 2000, Šefrna 2003, Babůrek et al. 2013). Fissured rock and lower regolith form the aquifers which in the Bavarian Forest NP catchments contribute more than 50% to annual runoff (Beudert et al. 2007) and maintain the low or drought flow of streams. Predominant soils are acid cambisols with varying contents of coarse material and with differently marked signs of podsolization (kryptopodzol), rankers and initial soils. The share of mineral and organic wet soils and bogs differs between the Czech and German catchments due to topography as could be shown for the Upper Große Ohe (25%) and Upper Vydra (46%) (Bernsteinová et al. 2015).

The catchments were selected according to the length of continuous discharge records in order to cover a substantial period for the detection of long-term runoff trends – in our case 36 years (1978–2013). On the German side, Weißer Regen (WR, Lohberg), Großer Regen (GR, Zwiesel) and Kleiner Regen (KR, Lohmannmühle) in the Regen basin as well as Große Ohe (GO, Schönberg), Kleine Ohe (KO, Grafenau), Reschwasser (RW, Unterkashof), and Saußbach (SB, Linden) in the Ilz basin fulfilled this requirement. On the Czech side only Otava (OT, gauging station Rejštejn) and Teplá Vltava (TV, Lenora) offered such long-term records. However, the size of the Czech (511 km²) and German (645 km²) parts of the study area are comparable. It covers the whole (Bavarian Forest) or a major part (Šumava) of the national parks, as well as non-conservation areas. Additionally, the nested headwater catchments of the Upper Große Ohe (UGO, Tafelruck), Forellenbach (FB, Schachtenau), and Upper Vydra (UV, Modrava) were included for a more detailed study of precipitation runoff behaviour (Fig. 1).

The catchments vary markedly in size from 39.1 km² (WR) to 175.7 km² (GO) in the Regen system and from 0.7 km (FB) to 89.6 km (SB) in the Ilz system, while in the Czech catchments cover respectively 89.7 km² (UV) to 333.9 km² (OT) (Table 1).

The minimum elevation (gauging station) ranges between 440 m a.s.l. (GO) and 973 m a.s.l. (UV) while maximum elevation varies in a narrow range from 1263 m a.s.l. (SB) to 1456 m a.s.l. (WR). UV has the highest mean catchment elevation (1134 m a.s.l.) but also the lowest slope (5.8°) whereas, in contrast, WR has an intermediate average elevation (918 m a.s.l.) and the steepest slope (13.5°). Generally, mean slope is lower in the Czech catchments (5.8–8.1°) than in the German catchments which vary between 8.2° (SB) and 13.5° (WR).

The land cover is predominantly forest (73–98%) with the remaining vegetation made up of fens and peat bogs at higher elevations and agricultural crops and meadows in the lower parts of the larger catchments (Table 1). Norway spruce (*Picea abies* (L.) Karst.) accounts for about 70% of the forested area in the German catchments and even more in the Czech catchments. UV, UGO and FB are completely located inside the national parks and cover mostly their core zones. Excluding WR, which is completely outside the parks, the catchment areas are comprised of 1% (SB) to 93% (OT) national park.

By 2013, the areas disturbed by the host-specific spruce bark beetle (*Ips typographus* L.) and windthrow accounted for 62% (UV), 58% (UGO) and 61% (FB) of the purely national park catchments. The respective percentages in all other catchments (Table 1) ranging from 3% (SB) to 60% (RW) refer to the national park area only, as the extent of harvested or salvage-logged bark beetle or windthrown areas outside the national parks is unknown. Related to the whole catchment (Fig. 2), the respective percentage of disturbed area reduced to <1% (SB) and 38% (RW). This approach necessarily disregards disturbance effects (disruption of the water and element cycle) by regular forest or other management practices. The cumulative course of disturbed spruce stands differed between the national parks (Fig. 2). German catchments showed a bi-modal course which levelled off in the late 2000s, when Czech catchments were subject to a pronounced increase following the hurricane Kyrill in January 2007.

Mean annual runoff Q (Table 1) varied between 549 mm (TV) and 1 228 mm in the high elevation headwater catchment UV. But Q differs considerably (385 mm) between TV and GR, which are of same catchment size, but GR of lower minimum and mean elevation. This refers to the rain shadow effect that the summit region along the border creates at easterly located areas.

The meteorological divide can also be demonstrated by means of long-term (1978–2013) annual precipitation yields (P), which differ markedly between stations located west and east of the summit line (Table 2). P at Churáňov (1118 m a.s.l.) was 1 119 mm.y^{-1} and thus smaller than at Waldhäuser (1 382 mm.y^{-1}), which is lower-lying (940 m a.s.l.) but west of the summit line. Moreover, it was equal to Grainet (1 131 mm.y^{-1}) which is located almost 500 m lower than Churáňov and south of it.

Annual means of air temperature (T) decreased with altitude from 5.7°C (804 m a.s.l.) to 4.8°C (1118 m a.s.l.) at Czech stations and from 7.4°C (596 m a.sl) to 3.5°C (1436 m a.s.l.) at German stations (Table 2). While the long-term variability of T is the same across all stations, mean T related to altitude is lower at Czech than at German sites as indicated by lower values at Lenora (804 m a.s.l.) than at Waldhäuser (940 m a.s.l.).

Data sources and preparation

Long-term discharge records (Table 1) and climate time series (Table 2) in daily resolution were obtained from publicly available sources: Bavarian climate and precipitation data from

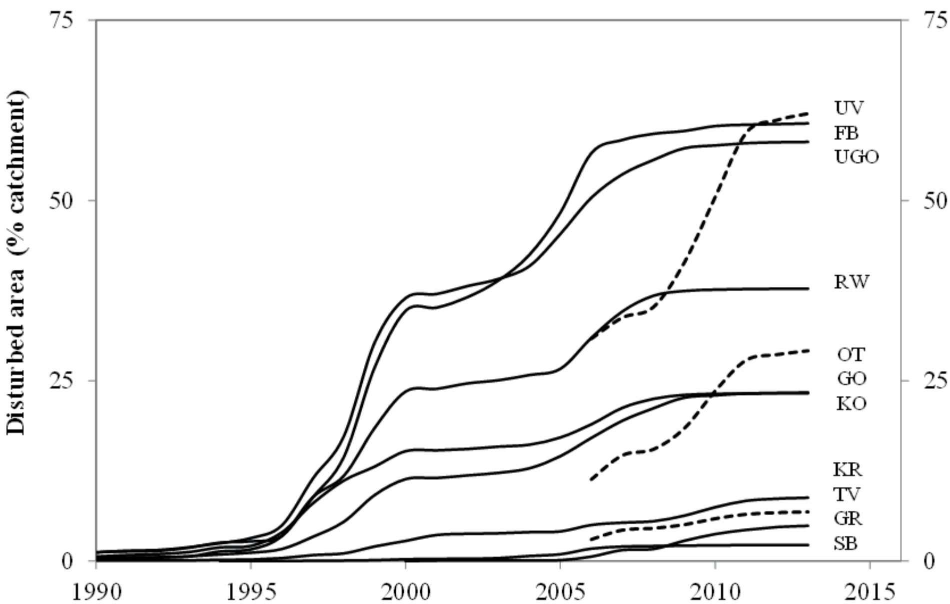

Fig. 2. Cumulative development of disturbed forests (% catchment area). Czech and German catchments are indicated by broken and solid lines, respectively: Weißer Regen (WR), Großer Regen (GR), Kleiner Regen (KR), Große Ohe (GO), Kleine Ohe (KO), Reschwasser (RW), Saußbach (SB), Otava (OT), and Teplá Vltava (TV); subcatchments: Upper Große Ohe (UGO), Forellenbach (FB), and Upper Vydra (UV).

Table 2. Regional stations used to calculate climate characteristics and to test for trend (1978–2013). Means (± standard deviation) of precipitation (P) and air temperature (T); * – snow records available; the code designates the catchment (see Table 1) for which the station data are used to calculate an area based precipitation proxy as input into the linear-mixed model.

Station	Code	Coordinates	Elevation (m a.s.l.)	P (mm.y^{-1})	T (°C)
Churáňov *	TV	N49.0673 / E13.6114	1118	1119±157	4.8±0.8
Lenora *	TV	N48.9334 / E13.7677	804	869±121	5.7±0.8
Großer Arber[1)]	GR	N49.1130 / E13.1342	1436	1491±199	3.5±0.7
Waldhäuser	KO	N48.9323 / E13.4650	940	1382±200	6.0±0.7
Grainet	–	N48.7893 / E13.6291	628	1131±172	7.3±0.8
Oberviechtach	–	N49.4520 / E12.4366	596	810±134	7.4±0.8
Filipova Huť	–	N49.0284 / E13.5175	1112	1229±137	
Borová Lada	–	N48.9915 / E13.6622	892	963±149	
Železná Ruda	OT	N49.1362 / E13.2278	763	1273±201	
Kvilda	OT	N49.0515 / E13.5680	1052	1164±164	
Regen *	WR	N48.9662 / E13.1426	583	985±119	
Brennes	WR	N49.1346 / E13.1462	1040	1590±225	
Zwieslerwaldhaus	GR	N49.0923 / E13.2487	699	1360±205	
Waldschmidthaus	KR	N48.9746 / E13.3864	1350	1766±258	
Buchenau	KR	N49.0315 / E13.3272	740	1349±187	
Racheldiensthütte	GO	N48.9555 / E13.4261	875	1585±227	
Schönberg	GO	N48.8398 / E13.3401	547	1095±143	
St. Oswald	KO	N48.8859 / E13.4261	754	1095±160	
Mauth-Finsterau	RB	N48.9359 / E13.5747	1011	1286±200	
Röhrnbach	RB	N48.7789 / E13.4946	533	1060±134	
Philippsreuth	SB	N48.8807 / E13.6633	917	1306±206	
Waldkirchen	SB	N48.7237 / E13.6058	617	1142±153	

[1)] 1983–2013

the German Meteorological Service, Bavarian Forest NP (station Waldhäuser), and Bavarian State Institute of Forestry (Racheldiensthütte and Waldschmidthaus stations); Bavarian discharge data from the Bavarian Hydrological Service, except for gauge Schachtenau (Forellenbach), which was provided by the Federal Environment Agency, and all Czech data from the Czech Hydrometeorological Institute.

Daily discharge data were divided by catchment area to get runoff depths (mm) of annual, seasonal (hydrological quarter and half years, beginning in November) and monthly runoff, as well as the highest and lowest daily runoff for each month. Monthly runoff data were checked for inhomogeneity using break point procedures (see below). Weak inhomogeneity was only found for KR (1992), KO (1998), and TV (1984), but regarded as transient and not substantial when mass curves were visually assessed.

Daily records of snow depth and snow melt dynamics were taken from Churáňov, Lenora, Waldhäuser, and Regen climate stations. The reference crop evapotranspiration for grass

(Doorenbois & Pruitt 1977) was calculated by using the radiation-based approach of Priestley & Taylor (1972) hereinafter used as a proxy of potential evapotranspiration and named ETP. The net radiation balance was derived according to FAO Guideline 56 (Allen et al. 1998) based on daily temperature, relative humidity (RH), actual sunshine duration records (SD) and extra-terrestrial radiation using an albedo of 0.23. A fixed factor of 1.26 on the radiation component which is valid in humid environments (Jensen 1992) was used to take the aerodynamic component into account. Due to data requirements, ETP was calculated for Churáňov and Waldhäuser station only.

Catchment precipitation of UGO (1980–2013) and FB (1992–2013) was based on P records from six monthly totalizing samplers and calculated according to Klöcking et al. (2005) including Racheldiensthütte and Waldschmidthaus (Table 2). Catchment P of UV (1980–2013) was taken from Langhammer et al. (2015). For the other catchments, the available data or model results of catchment P required for sound analyses on precipitation–runoff behaviour are lacking.

Data gaps in monthly P records for UGO (20 out of 2 448 monthly values) were filled using best fit monthly transfer functions according to Klöcking et al. (2005). This procedure was also applied to all other stations based on the complete Churáňov and Waldhäuser data sets, respectively. The time series of UV catchment P was extended to 2013 by using Filipova Huť data.

For the linear mixed-effects model only (see below), a surrogate of catchment P was generated by averaging monthly records of the two nearest high and low elevation stations (code in Table 2). Catchment P of the three nested catchments was taken as such (see above). A proxy of monthly mean catchment T was generated by applying mean monthly lapse rates between the next high and low elevation climate stations (Table 2) adjusted to mean catchment elevation.

Catchment morphological characteristics were derived from the Aster Global Digital Elevation Model provided by NASA (2009). Vegetation characteristics were extracted from the Corine Land Cover 2006 database published by European Environment Agency (2016), the Official Topographic Information System provided by the Bavarian Agency for Digitisation, High-Speed Internet and Surveying (https://www.ldbv.bayern.de/) and the spatial databases obtained from the Bavarian Forest NP and Šumava NP. Bark beetle infested and wind thrown spruce trees for both data sets were identified on annually recorded colour-infrared images (Lausch et al. 2011) and aggregated to a cumulative curve over time. The spatially distributed datasets were analysed by the Arc Editor 10.1 Spatial Analyst Tools package (ESRI).

Statistical analysis

The homogeneity of Q data was checked using ANKLIM-software package (Štěpánek 2005). All single series except UGO were proved homogeneous. Q of UGO, FB and UV, the heavily disturbed nested catchments inside the national parks were additionally tested against Q in WR, which is forested to a similar extent, under regular forest management outside the national parks and free of inhomogeneity over the period of comparison (Reeves et al. 2006).

In the second approach, the annual runoff coefficient ($Q.P^{-1}$) was calculated by expressing annual runoff (R) as a fractional percentage (%) of annual catchment precipitation (P). This approach was confined to the nested catchments for which catchment P were available (UV and UGO since 1980, FB since 1992). $Q.P^{-1}$ is an additional measure to disentangle the importance of changes in P and/or vegetation (Velpuri & Senay 2013) from changes in Q. The "segmented regression with breakpoint" procedure (SegReg, Oosterbaan 1994) was applied to detect significant changes (step changes, inflection points) in $Q.P^{-1}$ over time. The SegReg procedure partitions an independent variable (time) into two intervals and calculates separate line segments for each interval. The breakpoint was checked using ANKLIM-software package (Štěpánek 2005).

For UGO and FB, the same step change was detected by using both approaches, thereby determining the before and after period (Smith 2002). Differences in mean values of P and Q and their balance between these periods were tested by a two sample T-test and checked by the Mann-Whitney-test using the "Real Statistics Resource Pack software" (Release 4.3, www.real-statistics.com, 2016). According to the geological and geomorphological conditions (see above), extensive aquifers and deep groundwater loss are absent in this landscape. Consequently, differences in sub-surface water storage are negligible in longer term mean hydrologic budgets (Hudson et al. 1997), which justifies the use of the catchment balance as a proxy of actual evapotranspiration (ETA).

Meteorological and hydrological data sets were tested for linear trends during the 1978 to 2013 hydrological years by using the Mann-Kendall non-parametric test. The Regional Kendall test for spatial consistency of trends was applied on P data of the Czech (n = 6) and the German side (n = 14) and the whole study area, and on German Q data (n = 7) and the whole study area (n = 9) by using the "Kendall-Family of trend tests" (Helsel et al. 2006). For the Czech part of study area (n = 2), a mean regional Q was calculated by weighting Q with size of the two catchments to allow the application of the Mann-Kendall test. Regional T trends are presented as arithmetic means (± standard deviation) over five stations. The trend is given as the difference between the last and the first value of the regression line of any parameter emphasizing that the magnitude of any change is restricted to the period it was calculated for and improving readability. An *a priori* test for autocorrelation ("acf" package) in Q data using R 3.1.3 (www.r-project.org) resulted in a weak correlation at a lag of 7 in very few data sets only.

A linear-mixed effect model was performed to investigate the influence of catchment size, elevation, and slope, the proportion of forests and of T and P as the main drivers on log-transformed Q measures. The function "lme" (R package lme4) was applied on T, P, and Q in monthly/seasonal/annual resolution. In addition, the proportion of area inside the national park has been considered as a proxy of disturbed forests in the model, since relevant data from forests outside the national parks were not available. In the model, we accounted for repeated measurement using sub-catchment as a random effect. Furthermore, we considered a correlation structure representing first order autocorrelation. For all comparisons within and among the models, we used standardized effect sizes of the parameter estimates using an expected mean of 0 (t-values = estimates divided by the respective standard error, values ≥ 2 and ≤ -2 exceed $p<0.05$). We report conditional (variance explained by both fixed and random factors, i.e. the entire model) and marginal (variance explained by fixed factors) coefficients of determination (Pseudo-R-squared for Generalized Mixed-Effect models, function "r.squaredGLMM" from R package MuMIn). Collinearity was checked by calculating the variance inflation factor according to O'brien (2007), which was <<3 between all explanatory variables and thus far below the typical thresholds of 5 or 10. For all statistical procedures, the significance level was set to $p<0.05$.

Results

Our analysis of runoff yields in the Bohemian Forest catchments revealed consistent changes in Q and its seasonality but not in low and high flow measures. All are strongly related to the drastic warming trend, while precipitation was constant. In contrast, disturbance effects on

Table 3. T-values of variables in a mixed linear model explaining log-transformed runoff (monthly sum, minimum and maximum daily sum) of nine catchments and three sub-catchments. Significant values are in bold (p<0.001) and italics (p<0.01).

	Period: Winter			Summer		
Parameter	**Sum**	**Minimum**	**Maximum**	**Sum**	**Minimum**	**Maximum**
(Intercept)	**3.4**	1.1	0.1	*3.1*	−1.6	−0.6
T (°C)	**28.2**	**22.4**	**18.5**	**−6.2**	−1.9	**−11.9**
P (mm)	21.0	3.9	29.8	31.6	7.2	49.8
Area (km²)	−0.7	−0.5	−0.8	−0.9	−0.6	−1.2
Mean elevation (m a.s.l.)	0.7	−0.1	1.3	1.1	0.6	1.3
Forest (%)	0.9	1.6	0.1	1.1	1.4	0.5
National park (%)	−0.6	−0.8	−0.1	−0.2	−0.8	0.8
Mean slope (°)	−0.3	−0.7	−0.3	−0.3	−0.8	0.0
R^2m	0.29	0.19	0.29	0.29	0.11	0.51
R^2c	0.39	0.34	0.37	0.40	0.34	0.56

Q are only discernible in the small national park sub-catchments.

Drivers of hydrological response in the Bohemian Forest catchments

The linear mixed-model explained 34% and 56% of variation in Q measures (Table 3). Neither physical site conditions such as area size, elevation and slope, nor vegetation and land use characteristics exerted any significant influence on hydrological catchment response. Precipitation (P) is the main driver (p<0.001) of Q concerning both the seasonal sum and the extremes, but this is more pronounced in summer than in winter. In winter, T is a comparably strong positive driver (p<0.001), especially for the minimum daily sum. High T is linked to a higher portion of liquid P and to Q generation via snow melting which, on a monthly basis, frequently occurs independently from precipitation. In summer, however, T exerted a much smaller but significant negative effect on Q yields and maximum daily sum while the minimum was not affected. Generally, in summer high T is linked to stable weather conditions with less P but higher evapotranspiration losses in this region.

Model runs using seasonally and annually aggregated values of P, T and Q confirmed these results regarding both insignificant effects of catchment characteristics on Q measures and also significant effects of T.

Changes in runoff and its seasonal distribution

From 1978 to 2013, the nine non-nested catchments showed decreasing Q, ranging from −82 mm (TV) to −32 mm (OT) but a single significant change (p<0.05) was in RW only. Regional Q in the German and Czech part changed by −55 mm and −58 mm, respectively, and by −59 mm (p<0.05) for the whole study area (Fig. 3).

This is first of all the result of an overall drop in summer Q of −70 mm (p <0.001), or −73 mm (p<0.001) and −67 mm (p >0.05) in the German and Czech part, respectively. The change in single catchments varied between −39 mm (WR) and −122 mm (RW, p <0.05). This decrease originated mainly from an overall decrease in early summer (May to July) of −58 mm (p <0.001) and, respectively, −62 mm (p <0.001) and −52 mm in the German and the Czech part. More precisely, the reduction in summer Q was mainly due to the May contribution of −47 mm (p<0.001) for the whole study area, −48 mm (p<0.001) in the German and −54 mm ($p<0.05$) in the Czech part individually and, mostly significantly, in each single catchment ranging from −33 mm (SB) to −71 mm (RW).

Secondly, regional Q in winter changed little in both the German and Czech parts (+19 mm, −27 mm, respectively); change rates varied between −62 mm (TV) and 39 mm (GO) (Fig. 3). For the whole study area, changes were mostly negative from November to January (−24 mm) and positive from February to April (27 mm), which in all catchments developed mostly in December (−22 mm, $p<0.001$) and March (+24 mm, $p<0.001$), summing up to a zero-change (8 mm).

Changes in the maximum daily Q (not shown) generally followed the changes in Q sum. A rise in winter (1.6 mm, $p<0.05$) was due to an increase in March (2.3 mm, $p<0.01$). In summer, the maximum Q decreased by (−2.3 mm, $p<0.01$) due to a drop in May (−3.4 mm, $p<0.01$). The minimum daily Q did not change in a comparable manner across all seasons and months, with the exception of March (+0.3 mm, $p<0.05$) and May in which it declined in all catchments (−0.7 mm, $p < 0.001$).

Nested catchments showed smaller changes of annual Q, 27 mm (UGO) and −13 mm (UV), and the same changes in summer (−85 mm and −82 mm) compared to the superordinate catchments. In contrast, changes in winter Q were more pronounced (129 mm and 52 mm). Marked monthly increases ($p<0.05$) were observed in UGO (70 mm) in March and in UV (91 mm) in April, which contribute to the common picture of increasing Q in winter. In March, the maximum daily Q increased by 6 mm and 8 mm in UGO and UV, and in April also for UV ($p<0.05$), which in most other catchments showed declining daily maxima.

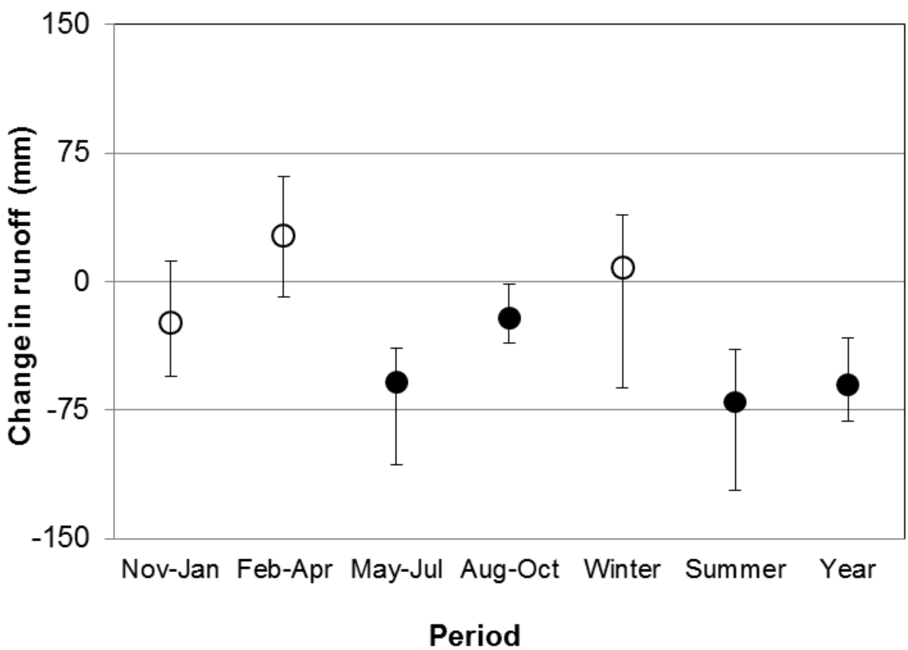

Fig. 3. Median (dots) and extreme (vertical lines) changes in runoff yield (left) of 9 catchments over seasons, hydrological half-years and years (1978–2013). Filled circles: $p<0.05$ according to Regional Kendall test results.

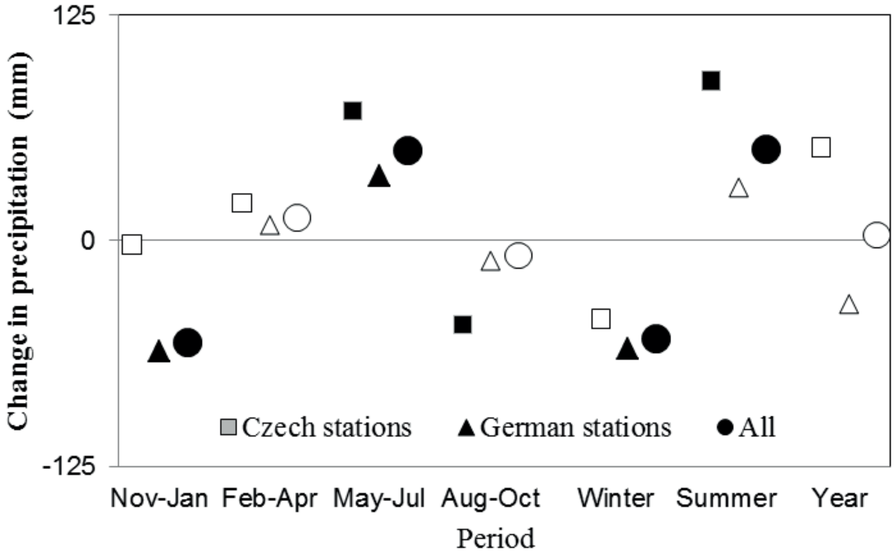

Fig. 4. Mean changes in precipitation yields at 6 Bohemian and 14 Bavarian stations and for the whole study area over seasons and years (1978–2013). Filled symbols: $p<0.05$ according to Regional Kendall test results.

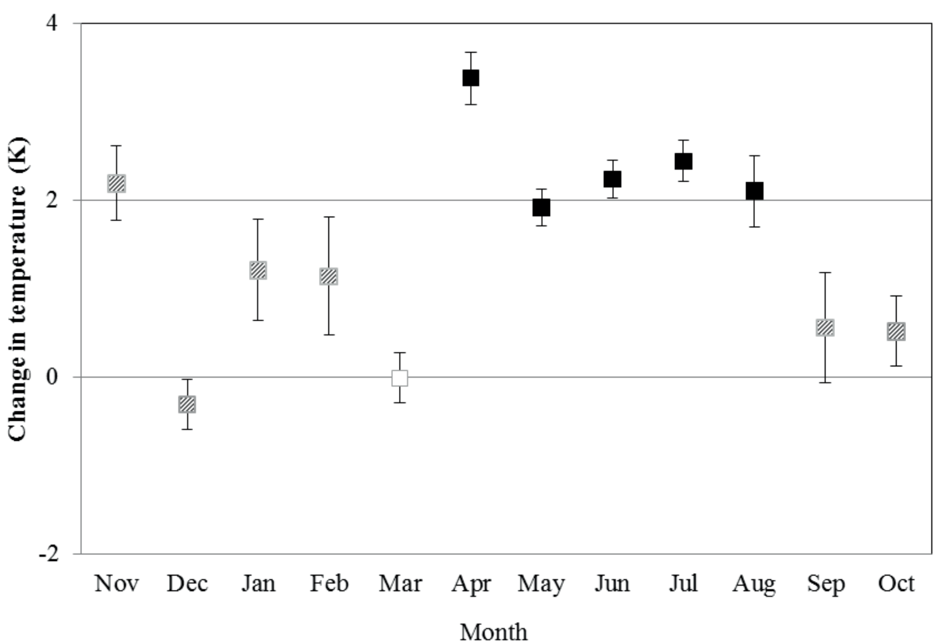

Fig. 5. Mean change and standard deviation in monthly mean air temperature at five stations (1978–2013). Filled squares indicate statistical significance at all stations of $p<0.05$, and for April ($p<0.001$). Hatched fills indicate one-directional changes at all stations, though not significant at all stations.

Changes in climatic elements and their seasonality

Mean precipitation (P) varied from 869 mm at 804 m a.s.l. to 1 766 mm at 1350 m a.s.l. There is an overall positive correlation ($p<0.05$) of P to elevation for all seasons. The lapse rate of annual P for the whole study area was 0.56 $mm.m^{-1}$ ($p<0.01$), and that of German stations only 0.66 $mm.m^{-1}$ ($p<0.001$). Except Železná Ruda in the north of the study area, at a given height, P was higher on the German than the Czech side underpinning the rain shadow effect the summit range exerts along the border. At all stations, changes in monthly P were mostly insignificant due to high year-to-year variability, with a few exceptions for May (increasing). The change in annual P varied between −142 mm and 134 mm and its magnitude was independent of elevation (not shown).

For the whole study area, there was an increase in summer P (51 mm, $p<0.002$) and a decrease in winter P (−54 mm, $p<0.002$) resulting in unaltered annual yields (3 mm, Fig. 4). But there were regional differences: in the Czech part, the increase in summer (89 mm, $p<0.001$) was larger than in the German part (30 mm), while the decrease in winter was smaller (−43 mm) than in the German part (−60 mm, $p<0.01$). Overall, P changes were more positive (less negative) at Czech than at German stations. Changes in winter occurred from November to January (−57 mm, $p<0.001$), but exclusively at German stations (−61 mm, $p<0.001$). Summer P increased from May to July in both the Czech (72 mm, $p<0.001$) and the German part (36 mm, $p<0.01$). This increase developed mostly in May and at all stations.

Air temperature (T) showed marked changes of similar size at all stations across the study region (Fig. 5). December was the only month with a small negative change and March was without change. For May to August, an increase of about 2 K (1978–2013) was found ($p<0.05$ at least) while the average rise in April by 3.3 K was highly significant at all stations. Thus, regional spring and summer warming occurred in a sequence of five consecutive months. In summary, T of winter and summer season increased by 1.3 K ($p<0.1$ at least) and 1.5 K ($p<0.05$ at least) respectively, resulting in a warming of 1.5 K ($p<0.01$ at least) for the whole year. The small standard deviations show that warming in spring and summer is a common transboundary feature in this region. In autumn and winter, however, larger deviations point to the site specific topographic influences.

Warming in late winter moved the date of final snow melt by six weeks from 22 April to 10 March at the lowest station (583 m a.s.l., Regen, $p<0.001$) (Fig. 6) and tended to move by three weeks from 7 May to 20 April at the highest station (1118 m a.s.l., Churáňov). At medium elevations (804–945 m a.s.l.), it moved from April/May to March/April by about four weeks ($p<0.001$). The snow cover period in autumn began nine to 32 days earlier (Regen, $p<0.01$), or remained unaltered (Lenora). Consequently, the length of the snow cover period did not change (Churáňov), or tended to decrease by 11 to 18 (Regen, Waldhäuser), or decre-

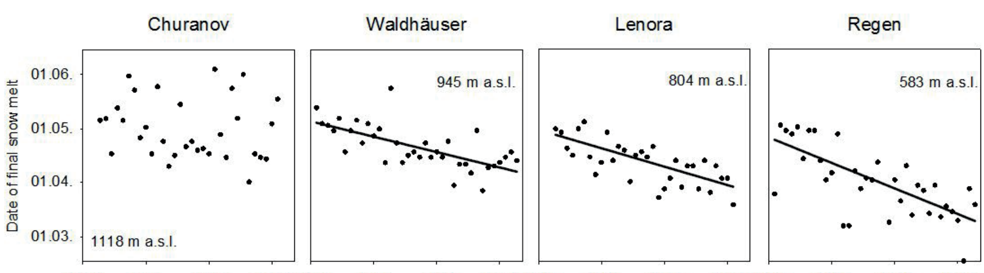

Fig. 6. Trends in final day of snow cover at German and Czech climate stations. Solid regression line indicates $p<0.05$. Note that the period for time series analysis was 1978–2013 for German stations and 1980–2011 for Czech stations.

Table 4. Absolute and relative changes in relative humidity (RH), actual vapour pressure (e_a), saturation deficit (e_s-e_a), sunshine duration (SD) and potential evapotranspiration (ETP) of the summer half-year at Churáňov (1978–2011) and Waldhäuser station (1978–2013).

Station	**Change**	**SD** (hours)	**RH** (%)	e_a (hPa)	e_s-e_a (hPa)	**ETP** (mm)
Waldhäuser	absolute	113	3,8	1.7	−0,5	44
	relative	12%	5%	17%	−15%	11%
	significance	n.s.	0.05	0.001	n.s.	0.001
Churáňov	absolute	3	5,9	1.5	0,0	23
	relative	0%	8%	16%	−1%	6%
	significance	n.s.	0.05	0.001	n.s.	0.05

ased by 36 days (Lenora, $p<0.05$). Moreover, the maximum snow depth ranging from 39±20 cm at 583 m a.s.l. up to 137±22 cm at 945 m a.s.l. did not change, indicating no change in the maximum snow water equivalent at any elevation. Annual snowfall at Regen (187±82 cm) and Waldhäuser (410±114 cm) tended to decrease by 41 cm and 112 cm. But, due to the exceptional warming in April, snowfall in this month decreased by 4 cm ($p<0.05$) and 20 cm ($p<0.01$), which equals the long-term mean at both sites.

Mean actual vapour pressure increased by about 16% at Churáňov ($p<0.001$) and 17% at Waldhäuser ($p<0.001$) in the summer half-year (Table 4), mostly generated from May to August. Saturation vapour pressure increased by about 10% at both stations due to warming (see above), the saturation deficit slightly decreased or remained constant and relative humi-

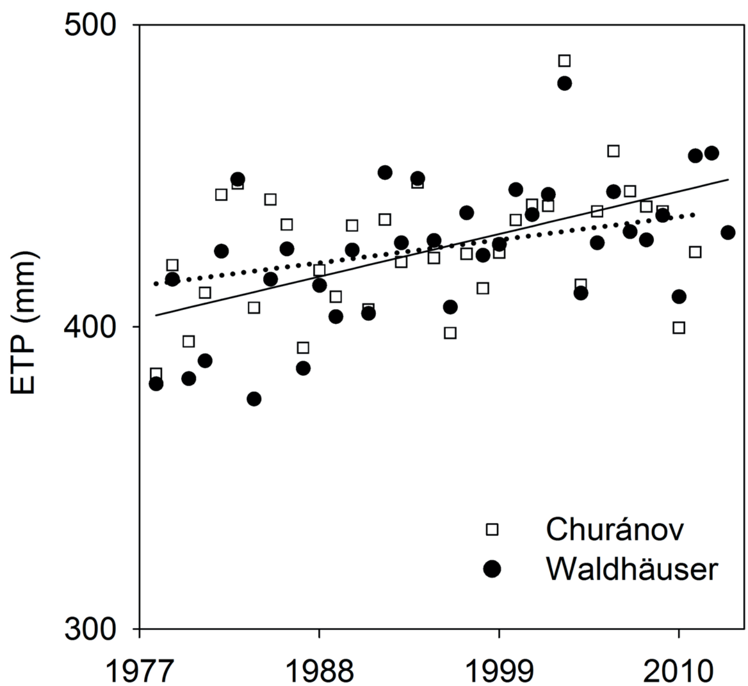

Fig. 7. Time series of summer potential evapotranspiration (ETP). Solid regression line: Waldhäuser, $p<0.001$; dotted regression line Churáňov, $p<0.05$.

dity increased ($p<0.05$). Therefore, changes in ETP which increased (Fig. 7) by 23 mm (6%, $p<0.05$) and 44 mm (11%, $p<0.001$) most probably equate to changes in ETA.

At Waldhäuser, sunshine duration increased in summer (113 hours) and even more greatly in winter (149 hours, $p<0.01$). At Churáňov, sunshine changed in winter only (51 hours). Warming in winter (see above) also led to similar changes for the whole year concerning direction and significance of changes in vapour pressure conditions. Annual ETP significantly increased by 44 mm (9%) and 65 mm (13%) at Churáňov and Waldhäuser.

Disturbance effects on catchment hydrology

In UGO and UV (1980–2013), catchment P and Q were free of trends. Moreover, the rate of change in Q was small or even positive (+27 mm, −13 mm) compared to superordinate catchments. Homogeneity tests of Q against time and WR reference data series revealed a single step change between 1998 and 1999 for both UGO ($p<0.05$) and FB. The same step change ($p<0.05$) in annual runoff coefficient $Q.P^{-1}$ was detected by the SegReg approach (Fig. 8) for both the 1980–2013 (UGO) and the 1992–2013 (UGO, FB) study period. $Q.P^{-1}$ increased from 60% to 64% (UGO, $p<0.01$) and, in the shorter period, from 59% to 64% (UGO, $p<0.01$) and from 59% to 68% (FB, $p<0.001$), respectively.

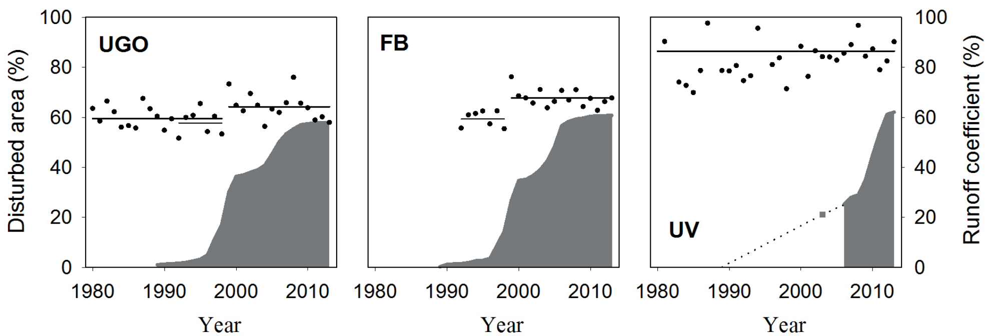

Fig. 8. Cumulative course of bark beetle and storm disturbed area (left axis, grey area) and annual runoff coefficient ($Q.P^{-1}$ – right axis, dots) in Upper Große Ohe (UGO), Forellenbach (FB), and Upper Vydra (UV) catchments. Thick black lines indicate mean $Q.P^{-1}$ in the periods before (UGO only) and after the significant step change in 1998/1999 (UGO, FB), except for UV which is free of changes over the whole study period; thin lines indicate mean $Q.P^{-1}$ for the 1992–1998 period only, to compare UGO and FB. Note that regular surveys of disturbed areas were launched in 1989 (Bavarian Forest NP) and 2003 (Šumava NP).

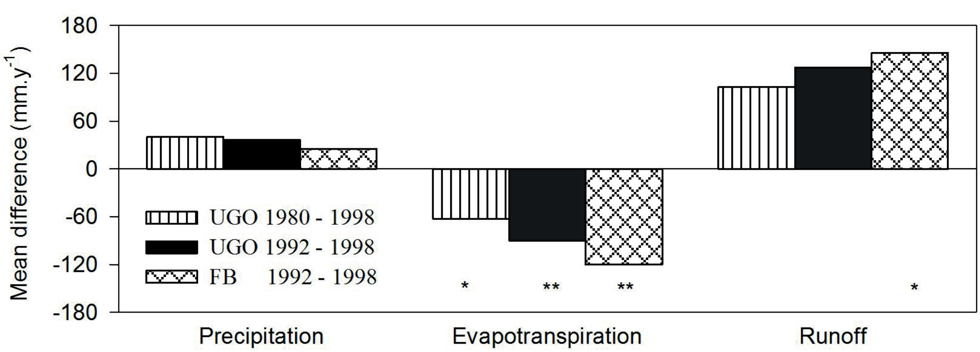

Fig. 9. Mean difference ($mm.y^{-1}$) of annual precipitation (P), runoff (Q) and evapotranspiration (ETA) in UGO and FB between the periods before (1980/1992–1998) and after (1999–2013) the common step change shown in Fig. 8. * $p<0.05$, ** $p<0.01$, *** $p<0.001$.

Mean P did not differ between the periods before and after the step change (25 mm and 40 mm) in both catchments (Fig. 9). However, mean Q increased by 103 and 127 mm (UGO, $p<0.08$) and 147 mm (FB, $p<0.04$) after 1998/1999. In UGO, the catchment balance as a proxy of ETA declined by 62 mm (−10%, $p<0.03$) and 90 mm (−13%, $p<0.01$) to 581±91 mm. In FB, ETA decreased even more after the step change (−120 mm, −19%, $p<0.01$) to 513±92 mm.

This common step change coincides with the occurrence of about 30% cumulative disturbed catchment area in both catchments. Linear trends in ETA (not shown) accounting for −70, −105, and −142 mm, respectively, are weakly significant at most but in general support the magnitude of change derived from the before-after approach. In contrast, UV did not present any change in $Q.P^{-1}$ or in P, R, and ETA. Compared to UGO and FB, whose dynamics of disturbed area was synchronous, UV showed an accelerated course of forest disturbance after 2007 (25% catchment area), fuelled by storm damages, when bark beetle outbreak in UGO and FB had already levelled out.

Discussion

Our analysis of runoff yields in the Bohemian Forest catchments revealed an overall decrease and an overall seasonal shift irrespective of catchment characteristics. Rising air temperature in late winter and summer was the major driver of change while precipitation did not change. Large scale bark beetle outbreaks and windthrow in heavily affected sub-catchments of the national parks reduced the forest cover and thus evapotranspiration losses, thereby counteracting warming effects on streamflow.

The significant decrease in annual streamflow in our study area does not fit the results of recent regional studies, which did not find significant changes in Q in the Bohemian Forest (Buchtele et al. 2006, Kliment & Matoušková 2008, Kliment et al. 2011, Bernsteinová et al. 2015, Langhammer et al. 2015). On the larger scale, the basin of the River Danube upstream of Vienna has shown stable runoff since 1887 (Kling et al. 2012). Moreover, Stahl et al. (2010, 2012), Milli et al. (2005), and Milliman et al. (2008) in their European and global scale analyses even revealed increasing Q in this region, like most streams in central and northwestern Europe. The most confounding factor might be the varying length and the starting date of the study period (Wilby et al. 2008), which in our study was in 1978 and thereby later than in the studies cited. It was dependent on the start of hydrological monitoring programmes in the Große Ohe catchment in 1976 (Beudert & Gietl 2015). In addition, monitoring of forest status by analysis of aerial pictures started at the end of the 1980s. So, the study period of 36 years spans the whole period before, during and after the major damages by bark beetle, which enables this study on disturbance versus climate change effects on precipitation runoff behaviour.

Climatic drivers of the change in annual streamflow

The significant decrease of annual Q in our study area did not coincide with a parallel change in annual P, which usually is the dominant driver and, for example, explains 86%, 80%, and 54% of annual runoff variability in UGO, FB, and UV, respectively. This again is contrary to the above mentioned findings, which showed concurrently unaltered P and Q in the Bohemian Forest or slightly increased P on a larger scale, although seasonal changes may have occurred (European Environment Agency 2017). There is some spatial difference in P changes in our study area, as annual yields on the Czech side (+52 mm) tend to increase, while on the German side conversely to decrease (–35 mm). However, there is also uncertainty in the relevance of these non-significant findings which would increase and decrease the respective changes in Q. The spatial coverage by P stations is quite different between the

Czech and the German part (6 vs. 14) and presumably too coarse bearing the complex terrain in mind. However, the significant and concurrent trends in both regions in winter and summer P (Fig. 4) have been proven to be consistent in the whole study area and can be used in further discussion.

The overall negative change of Q (−59 mm), which reflects an increase in the catchment balance as P was constant, is consistent with positive changes of annual ETP (44–65 mm) at two analysed climate stations (Fig. 7). The latter increase of 9–13% followed the change in vapour saturation pressure according to Clausius-Clapeyron (~7% K^{-1}) when temperature rises by 1.5 K (Fig. 5). Despite this ETP, according to Priestley & Taylor 1972, is a conservative estimate of evapotranspiration in these forested catchments, considering the mean catchment balance in UGO (614±89 mm) for example, the magnitude of change can be taken as a trend estimate in catchment evapotranspiration, which in this humid region is limited by available energy (Budyoko 1974, cit. in Zang et al. 2001). Very similar results of increasing ETA since the mid-1970s are reported from mountain watersheds in the Appalachian Mountains in the Eastern USA (Caldwell et al. 2016). Further USA LTER-catchments at sites with water surplus offered ETA even higher than expected from T increase (Jones et al. 2012). Zhang et al. (2012) derived increasing ET from satellite data in wet regions of the world like central to northern Europe. Teuling et al. (2009) as well as Matsouakas et al. (2011) stressed the close correlation between ETA and available energy, especially in central Europe, and Kaye et al. (2013) reported concurrently increasing ETP and ETA in England and Wales. Also in our study catchments, T exerted a significant negative effect on Q during summer (Table 3). Thus, there is strong support from climatological literature that increasing evapotranspiration losses due to warming could be a major driver of decreasing Q in all catchments of our study area.

Land use and gradual vegetation change as drivers

Despite this initial attribution of changes in Q to warming, other factors influencing the P–Q behaviour must be tested to avoid erroneous conclusions about climate change effects (Jones 2011): human water consumption and land-use change, and gradual vegetation change following disturbances.

In Regen and Freyung-Grafenau county, which completely enclose the German catchments, population size did not change since 1987 and may have increased by less than 3% since 1978 (Bayerisches Landesamt für Statistik 2016). In the districts of Prachatice and Klatovy which enclose the Czech catchments, it deceased by 4.6% since 1980 (Czech Statistical Office 2017). The current population density is 80 km^{-2} and less than 45 km^{-2}, respectively. Since 1987, the gross specific use per capita of drinking water in Bavaria decreased by 24% to 173 $l.d^{-1}$ (Bayerisches Landesamt für Umwelt 2017), but is less than 160 $l.d^{-1}$ in the Bavarian Forest. In the Czech Republic, gross drinking water production has dropped by 52% since 1989, and in both, the Plzeň and South Bohemian region by 18% since 2003 (Český statistický úřad 2017). In both countries, domestic use of drinking water per capita dropped to <135 $l.d^{-1}$. Moreover, drinking water in the study area generally is withdrawn and returned locally thereby not affecting the water budget at catchment outlet. In summary, changes in human water use in the study region rather have increased Q than reduced it.

Forested area increased by 1% since 1990 (European Environment Agency 2016) in the Czech districts, at the expense of cropland and pastures, and by 2% in the Bavarian Forest counties between 1980 and 2014 (Bayerisches Statistisches Landesamt 2017), by conversion of permanent grassland. Despite the fact that ETA is 10–30% larger from forests than from grassland in central European low mountain ranges (Ernstberger 1987), the freshly established forest stands are more similar to pasture than to mature stands regarding water vapour losses (Peck & Mayer 1996). In the Bavarian Forest counties (but not in the Czech districts), agricultural area decreased by 19%, in favour of settlement and transportation infrastructure. Yet less permeable or almost impermeable urban surfaces like roads and roofs reduce evaporation loss (Ramamurthy & Bou-Zeid 2014) and increase fast drainage (Boyd et al. 1993) to channels and streams. In summary, all land use changes in our catchments, if relevant, most probably decreased ETA and increased Q.

Changes in Q due to the vegetation change following disturbance are more difficult to assess as the exact spatial and temporal information on disturbances such as bark beetle outbreaks, windthrow, and forest harvest, as well as on regeneration management in areas outside the national parks, are lacking. However, the direction and strength of their influence on ETA and thus Q can be assessed approximately. In German and Czech forests, the annual harvest of timber including salvage logged timber was less than the long-term growth rate of European beech and Norway spruce (3–4%) (Thünen-Institut 2017). Therefore, forest stocks have been increasing since decades to about 260 and 400 $m^3.ha^{-1}$, respectively (Ministry of Agriculture 2017, Thünen-Institut 2017). Assuming that forest use has taken place in more or less stable rates and that Norway spruce stands, which by far dominate the study area, were on average of middle age (70–100 years) at the starting date of our study, reveals stable or slightly decreasing ETA, while the stands have been aging (Peck & Mayer 1996). The addition of broadleaves into pure Norway spruce stands has been encouraged and accelerated as a forest stabilizing measure (Möges 2007) but an increasing number of deciduous species would reduce ETA and increase Q (Kommatsu et al. 2011, Peck & Mayer 1996).

Extensive disturbances by windthrow and bark beetle started in the middle of the 1990s and were followed by the second wave in the middle of the 2000s (Fig. 2). So, the time since establishment of seedlings has been too short to increase ETA because the young spruce stands reach that of mature stands earliest at the age of about 30–50 years (Peck & Mayer 1996) or later (Wei & Zhang (2010). Moreover, the extent of natural disturbance varied from <1% to 38% (Table 1) but did not explain variation in Q (Table 3). Therefore, the effects of gradual vegetation change on Q, which decreased to a very similar extent in these non-nested catchments, are very unlikely.

Change in streamflow seasonality

Streamflow experienced a marked change in seasonal distribution. Q in summer decreased significantly despite a significant increase in P, while in winter Q remained unaltered despite a significant decrease in P. Balancing changes in summer and winter ETP with P and Q trends resulted in a Q transfer of about 80 mm from summer to winter (Table 5). It originated from the warming in January and February by about 1 K, which more often led to intermittent reduction of snowpack and, more importantly, from the exceptional warming in April and May by more than 2 K (Fig. 5) which caused an earlier final snowmelt (Fig. 6). Temperature and snowmelt altered synchronously across the whole altitudinal gradient thus accelerating water mobilization from snowpack throughout the study site. Thus, the last parts of snowmelt driven groundwater recharge and Q moved from hydrological summer into winter.

This process has affected many snow dominated or influenced catchments, mostly in mountainous regions. Ubiquitous trends to earlier snowmelt and Q metrics due to warming have been reported for the Western and Eastern USA (McCabe & Clark 2005, Maurer et al. 2007, Stewart et al. 2009, Clow 2010, Parr & Wang 2014, Dudley et al. 2017), and for northern and central Europe (Hisdal et al. 2010, Renner & Bernhofer 2011, Stahl et al. 2010, Hlavčová et al. 2015).

Table 5. Streamflow shift (Q_{shift}) from summer to winter half-year due to earlier snowmelt derived from the observed changes in water balance components (Figs. 3, 4, 7) for the whole study area. Note the small deviation from balance (bold).

Period	**P**	**ETP**	**Q**	$\mathbf{Q_{shift}}$
Summer	51	44	−70	−77
Winter	−54	21	8	83
Year	3	65	–59	**3 / 6**

Larger effects on flooding during winter associated with earlier streamflow timing as reported in the above mentioned literature could not be found. Slightly but significantly increased maximum daily Q in winter was only due to an overall increase in March. This finding points to intermittent snowmelt due to warming and increasing precipitation in February, as precipitation decreased in March while temperature did not change. In May, by contrast, the maximum and minimum daily Q decreased significantly despite increased P, underpinning the warming effect via earlier snowmelt. Up to now, however, there is no marked decrease in summer and/or autumn low flow like in southern and east Europe (Stahl et al. 2010, Renner & Bernhofer 2011, Hlavčová et al. 2015). Obviously, the P increase in early summer was large enough to offset water losses due to earlier snowmelt with respect to groundwater recharge. Moreover, low flow in autumn is mostly sustained by slow-flowing groundwater, which in headwater catchments of the Bavarian Forest NP exhibits a mean residence time of 8–15 years (Beudert et al. 2007). Due to this buffering, several consecutive years with large P deficits, especially in winter, are needed to significantly reduce it.

Contrasting streamflow changes in severely disturbed nested catchments

The sub-catchments of the Upper Große Ohe (UGO) and Upper Vydra (UV) in the national parks did not show changes in annual Q and P. But Q and $Q.P^{-1}$ revealed a single step change ($p<0.05$) between 1998 and 1999 for UGO and the embedded FB which coincided with the steep increase in the bark beetle disturbed area by 25 percentage points to more than 30% (1998) over just 3 years (Fig. 2). This is consistent with former findings that reductions in forest cover must exceed a threshold of 20–25% (Stednick 1996, Brown et al. 2005, Beudert et al. 2007) to be detected by Q monitoring, given an annual P of more than 500 mm (Adams et al. 2012). Mean ETA in the subsequent period was by 62–90 mm (UGO) and 120 mm (FB) lower than in the period before, but does not account for the warming effects described above. This is consistent with basic physical characteristics of dead trees, which have lost most of their interception and the complete transpiration surface (Anderegg et al. 2012), thus reducing water loss from canopy. Unmanaged bark beetle disturbed areas are different to clear-cut areas (Edburg et al. 2012) in terms of remaining surface for evaporation, no damage to the living second and third layer trees, understory vegetation, and physical soil integrity. Nevertheless, the comparison with fully or partially cut catchments regarding the effects on ETA and Q may help to understand the historical changes and assess short and medium term eco-hydrological changes.

Bosch & Hewlett (1982) reported a 40-mm first-year increase in Q per 10% change in conifer forest area, while Sahin & Hall (1996) reported a mean increase in Q of 10–25 mm during the first five years after clear-cut. Overall, the Q response depends on climatological regime, physical landscape features, and dominant tree species (Stednik 1996, Brown et al. 2005). After the first bark beetle outbreak (30% area) in UGO and FB, the slope estimation by Bosch & Hewlett (1982) would fit our observed changes in evapotranspiration (net streamflow), while, after the second outbreak (~60% area), the slope of SAHIN & HALL (1996) provides a better fit. The obvious persistence of decreased ETA might be the result of the sequence of two distinct bark beetle outbreaks. Firstly, dense and fast-growing stand regeneration in the stands attacked first profited from additional precipitation on soil surface and water supply (EDBURG et al. 2012) and increasingly compensated for strongly reduced ETA after mature tree mortality (BROWN et al. 2014). The second bark beetle outbreak, which peaked in the mid-2000s, superimposed these succession effects. Applying the concept of WEI & ZHANG (2010) based on canopy height for spruce species in British Columbia, Canada, revealed that hydrological recovery due to the tree regeneration could already be 25% just 10–15 years after the first bark beetle outbreak in UGO and FB, thereby reducing its effects on Q. Moreover and in accordance with BROWN et al. (2005), it gives reason to believe that Q will return to pre-disturbance levels during the next 15–25 years in these sub-catchments, notwithstanding the warming driven changes.

In UV (Šumava NP), there was no detectable trend or step change in Q and $Q.P^{-1}$ in response to disturbances of similar magnitude (62% area) but with a very different course compared to the Bavarian Forest NP (Fig. 2). However, the mean annual ETA (178 mm) resulting from $Q.P^{-1}$ is unrealistically low and its inter-annual variability too large (159 mm) not to raise doubts on data quality. For the embedded Rokytka stream, a $Q.P^{-1}$ of 1 and thus zero ETA was found (KOCUM et al. 2016). Irrespective of that, one may speculate that the first disturbances up to 2006 developed too slowly, allowing full compensation by natural succession while drastic disturbances (30%) caused by the Kyrill storm and bark beetle attack set in too late (2007) to generate significant hydrological changes. On the other hand, the Bavarian Forest NP sub-catchments reacted very quickly to the vegetation cover changes comparable to clear-cut catchments (BOSCH & HEWLETT 1982, SAHIN & HALL 1996). There could be a scale effect in UV when disturbance effects on Q, which are detectable in small catchments, become invisible on a larger scale, where climate change effects may then dominate (BLÖSCHL et al. 2007). The fact that the largest ETA and Q effects were in FB (0.7 km^2), with medium effects in UGO (19.1 km^2) and no effect in UV (89.7 km^2), despite the areal extent of disturbance remaining the same, would support this assumption. Additional indication comes from the large RW and OT catchments with 29% and 38% disturbed area (Table 1), which did not show comparable effects on Q. On the other hand, WEI & ZHANG (2010) and ZHANG & WEI (2012) demonstrated that the effects of climate change and bark beetle attacks can be delineated for much larger catchments (2 860 and 1 570 km^2). In UV, however, there was in fact no change at all in both Q and P, which suggests that the effects of disturbance (increasing) and climate change (decreasing) developed at a similar rate thereby offsetting each other.

Besides annual yields, strong effects on peak discharge were reported in response to extended clear-cut harvesting (HORNBECK 1973, CAISSIE et al. 2002, GUILLEMETTE et al. 2005) but reports about comparable responses to extended bark beetle disturbance are lacking (SLINSKI et al. 2016). There is a common statement that bark beetle effects on peak streamflow are weak and restricted to small events (POTTS 1984, MOORE & WONDZELL 2005, BIEDERMAN et al. 2015). Moreover, harvesting and disturbance effects on stormflow become increasingly less important the larger the event is (HARR et al. 1975, HORNBECK et al. 1979, CAISSIE et al. 2002). This is in line with our findings of slightly increased peak flows. As management intervention like salvage logging did not occur in the core zones of both national parks, the splash damping properties of soil humus layers, coarse woody debris and lower vegetation were not affected by compaction, mixing or destruction by heavy machinery. This would have accelerated runoff generation by increasing surface flow, raised peak flow and forced erosion (SWANSON & DYRNESS 1975, BESCHTA et al. 1978).

Even in summer, in which reduced ETA and increased P could have exerted influence, peak flows did not change as reported by Bernsteinová et al. (2015). Low flow also did not change in summer, thereby confirming the results of Langhammer et al. (2015) and Bernsteinová et al. (2015) for a shorter period. Like in the superordinate catchments, the low summer flow is controlled by groundwater stores, which have delayed responses to altered hydrological processes in the ecosystems. So, decreased ETA and increased P on soil surfaces in regenerating stands (Bearup et al. 2014) must have increased runoff yields but not necessarily low flows.

Summary and conclusions

Nine conterminous catchments in the Bohemian Forest showed a significant decrease in annual runoff yields (1978–2013) due to significant and strong changes in air temperature. Warming acted two-fold: by hastening final snowmelt and streamflow timing in late winter and spring, and by increasing evapotranspiration mostly in summer.

Three sub-catchments in the Bavarian Forest and Šumava national parks heavily affected by bark beetle and windthrow showed differing hydrological behaviour. Streamflow seasonality and flow extremes responded identically to warming but annual runoff yields remained either unaltered or even increased. This indicates that decreased evapotranspiration due to disturbance maintained groundwater recharge and regional drinking water supply. However, during further succession towards new forests and increasing water demand as part of the natural life cycle, these benefits will level out, probably sooner the faster climate change proceeds. How persistent post-mortality hydrological changes are and whether more mixed naturally structured forests change the partitioning of evapotranspiration components in the long term – are some of the questions which future research should focus on.

There is a lot of scientific evidence in this publicly available dataset that a small change in winter flooding and the overall decrease in runoff yield are due to climate change but no evidence to relate them to natural disturbances or the national park management. Up to now, disturbance related eco-hydrological changes have been offsetting or exceeding the warming caused reduction in runoff yields.

Acknowledgements. The publication was supported by the Cross-border cooperation programme Czech Republic–Bavaria Free State ETC goal 2014–2020, the Interreg V project No. 26 "Silva Gabreta Monitoring – Implementation of Transboundary Monitoring of Biodiversity and Water Regime".

References

Adams H.D., Luce C.H., Breshears D.D., Allen C.D., Weiler M. & Hale V.C., 2012: Ecohydrological consequences of drought- and infestation-triggered tree die-off: insights and hypotheses. *Ecohydrology*, 5: 145–159.

Anderegg W.R.L., Kane J.M. & Anderegg L.D.L., 2012: Consequences of widespread tree mortality triggered by drought and temperature stress. *Nature Climate Change*, 3: 30–36.

Andréassian V., 2004: Waters and forests: from historical controversy to scientific debate. *Journal of Hydrology*, 291: 1–27.

Babůrek J., Pertoldová J., Verner K. & Jiřička J., 2013: *Guide to the geology of Šumava Mountains*. Vimperk, 117 pp.

Bayerisches Landesamt für Statistik, 2016: Statistik kommunal 2015, Landkreise Freyung-Grafenau 09 272 und Regen 09 276 [Municipal statistics for the counties of Freyung-Grafenau and Regen]. Online https://www.statistik.bayern.de/statistikkommunal/092.pdf (accessed on 20 June 2017) (in German).

Bayerisches Landesamt für Umwelt, 2017: Trinkwasserverbrauch in Bayern [Drinking water use in Bavaria]. Online https://www.lfu.bayern.de/wasser/trinkwasserversorgung_oeffentlich/trinkwasserverbrauch/index.htm (accessed on 20 June 2017) (in German).

Bässler C., Seifert L. & Müller J., 2015: The BIOKLIM Project in the National Park Bavarian Forest: Lessons from a biodiversity survey. *Silva Gabreta*, 21: 81–93.

Bearup L.A., Maxwell R.M., Clow D.W. & McCray J.E., 2014: Hydrological effects of forest transpiration loss in bark beetle-impacted watersheds. *Nature Climate Change*, 4: 481–486.

Bernsteinová J., Bässler C., Zimmermann L., Langhammer J. & Beudert B., 2015: Changes in runoff in two neighbouring catchments in the Bohemian Forest related to climate and land cover changes. *Journal of Hydrology and Hydromechanics*, 63: 342–352.

Beschta R.L., 1978: Long-term patterns of sediment production following road construction and logging in the Oregon Coast Range. *Water Resources Research*, 14: 1011–1016.

Beudert B, Klöcking B. & Schwarze R., 2007: Grosse Ohe: impact of bark beetle infestation on the water and matter budget of a forested catchment. In: *Forest Hydrology – Results of Research in Germany and Russia*, Puhlmann H. & Schwarze R. (eds) *IHP/HWRP–Berichte*, 6: 41–62.

Beudert B. & Gietl G., 2015: Long-term monitoring in the Große Ohe catchment, Bavarian Forest National Park. *Silva Gabreta*, 21: 5–27.

Beudert B., Bässler C., Thorn S., Noss R., Schröder B., Dieffenbach-Fries H., Foullois N. & Müller J., 2015: Bark beetles increase biodiversity while maintaining drinking water quality. *Conservation Letters*, 8: 272–281.

Biederman J.A., Somor A.J., Harpold A.A., Gutmann E.D., Breshears D.D., Troch P.A., Gochis D.J., Scott R.L., Meddens, A.J.H. & Brooks P.D., 2015: Recent tree die-off has little effect on streamflow in contrast to expected increases from historical studies. *Water Resources Research*, 51: 9775–9789.

Birsan M.V., Molnar P., Burlando P. & Pfaundler M., 2005: Streamflow trends in Switzerland. *Journal of Hydrology*, 314: 312–329.

Blöschl G., Ardoin-Bardin S., Bonell M., Dorninger M. & Szolgay J., 2007: At what scales do climate variability and land cover change impact on flooding and low flows? *Hydrological Processes*, 21: 1241–1247.

Bosch J.M. & Hewlett J.D., 1982: A review of catchment experiments to determine the effect of vegetation changes on water yield and evapotranspiration. *Journal of Hydrology*, 55: 3–23.

Boyd M.J., Bufill M.C. & Knee R.M., 1993: Pervious and impervious runoff in urban catchments. *Hydrological Sciences Journal*, 38: 463–478.

Brown A.E., Zhang L., McMahon T.A., Western A.W. & Vertessy R.A., 2005: A review of paired catchment studies for determining changes in water yield resulting from alterations in vegetation. *Journal of Hydrology*, 310: 28–61.

Brown M.G., Black T.A., Nesic Z., Foord V.N., Spittlehouse D.L., Fredeen A.L. & Meyer G., 2014: Evapotranspiration and canopy characteristics of two lodgepole pine stands following mountain pine beetle attack. *Hydrological Processes*, 28: 3326–3340.

Buchtele J., Buchtelová M. & Tesař M., 2006: Role of vegetation in the variability of water regimes in the Šumava Mts forest. *Biologia*, 61: 246–250.

Caissie D., Jolicoeur S., Bouchard M. & Poncet E., 2002: Comparison of streamflow between pre and post timber harvesting in Catamaran Brook (Canada). *Journal of Hydrology*, 258: 232–248.

Caldwell P.V., Miniat C.F., Elliott K.J., Swank W.T., Brantley S.T. & Laseter S.H., 2016: Declining water yield from forested mountain watersheds in response to climate change and forest mesophication. *Global Change Biology*, 22: 2997–3012.

Clow D.W., 2010: Changes in the timing of snowmelt and streamflow in Colorado: a response to recent warming. *Journal of Climate*, 23: 2293–2306.

Český statistický úřad, 2017: Statistické ukazatele za okresy Prachatice a Klatovy [Municipal statistics for the counties of Prachatice and Klatovy]. Online https://www.czso.cz/ (accessed on 20 June 2017) (in Czech).

Delzon S. & Loustau D., 2005: Age-related decline in stand water use: sap flow and transpiration in a pine forest chronosequence. *Agricultural and Forest Meteorology*, 129: 105–119.

Doorenbos J. & Pruitt W. O., 1977: *Crop water requirement*. FAO Irrigation and Drainage Paper, 24, Rome, 154 pp.

Dudley R.W., Hodgkins G.A., McHale M.R., Kolian M.J. & Renard B., 2017: Trends in snowmelt-related streamflow timing in the conterminous United States. *Journal of Hydrology*, 547: 208–221.

Ernstberger H., 1987: *Einfluss der Landnutzung auf Verdunstung und Wasserbilanz* [*Land use effects on evapotranspiration and water balance*]. Beiträge zur Hydrologie, Kirchzarten, 189 pp. (in German).

European Environment Agency, 2016: Data and maps. Copernicus Land Monitoring Service – Corine Land Cover. Online https://www.eea.europa.eu (accessed on 10 July 2016).

European Environment Agency, 2017: Data and maps. Indicators. Online https://www.eea.europa.eu (accessed on 20 June 2017).

Gilbert R.O., 1987: *Statistical methods for environmental pollution monitoring*. Van Nostrand Reinhold, New York, 334 pp.

Gudmundsson L. & Seneviratne S.I., 2015: European drought trends. *Proceedings of the International Association of Hydrological Sciences*, 369: 75–79.

Guillemette F., Plamondon A.P., Prévost M. & Lévesque D., 2005: Rainfall generated stormflow response to clearcutting a boreal forest: peak flow comparison with 50 world-wide basin studies. *Journal of Hydrology*, 302: 137–153.

HALL J., ARHEIMER B., BORGA M., BRÁZDIL R., CLAPS P., KISS A., KJELDSEN T.R., KRIAUCIUNIENE J., KUNDZEWICZ Z.W., LANG M., LLASAT M.C., MACDONALD N., MCINTYRE N., MEDIERO L., MERZ B., MERZ R., MOLNAR P., MONTANARI A., NEUHOLD C., PARAJKA J., PERDIGÃO R.A.P., PLAVCOVÁ L., ROGGER M., SALINAS J.L., SAUQUET E., SCHÄR C., SZOLGAY J., VIGLIONE A. & BLÖSCHL G., 2014: Understanding flood regime changes in Europe: A state of the art assessment. *Hydrology and Earth System Sciences*, 18: 2735–2772.

HARBOR J.M., 1994: A practical method for estimating the impact of land-use change on surface runoff, groundwater recharge and wetland hydrology. *Journal of the American Planning Association*, 60: 95–108.

HARR R.D., HARPER W.C., KRYGIER J.T. & HSIEH F.S., 1975: Changes in storm hydrographs after road building and clear-cutting in the Oregon Coast Range. *Water Resources Research*, 11: 436–444.

HELSEL D.R., MUELLER D.K. & SLACK J.R., 2006: Computer program for the Kendall family of trend tests (No. 2005–5275).

HLAVČOVÁ K., KOTRÍKOVÁ K., KOHNOVÁ S. & VALENT P., 2015: Changes in the snow water equivalent in mountainous basins in Slovakia over recent decades. *Proceedings of the International Association of Hydrological Sciences*, 370: 109–116.

HORNBECK J.W., 1973: Storm flow from hardwood-forested and cleared watersheds in New Hampshire. *Water Resources Research*, 9: 346–354.

HORNBECK J.W., MARTIN C.W. & EAGAR C., 1997: Summary of water yield experiments at Hubbard Brook experimental forest, New Hampshire. *Canadian Journal of Forest Research*, 27: 2043–2052.

HUDSON J.A., CRANE S.B. & BLACKIE J.R., 1997: The Plynlimon water balance 1969–1995: the impact of forest and moorland vegetation on evaporation and streamflow in upland catchments. *Hydrology and Earth System Sciences*, 1: 409–427.

IPCC 2013: The physical science basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. In: *Climate Change 2013*, STOCKER T.F., QIN D., PLATTNER G.K., TIGNOR M., ALLEN S.K., BOSCHUNG J., NAUELS, A., XIA, Y., BEX, V. & MIDGLEY P.M. (eds) Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

JONES J.A., 2011: Hydrologic responses to climate change: considering geographic context and alternative hypotheses. *Hydrological Processes*, 25: 1996–2000.

JONES J.A., CREED I.F., HATCHER K.L., WARREN R.J., ADAMS M.B., BENSON M.H., BOOSE E., BROWN W.A., CAMPBELL J.L., COVICH A., CLOW D.W., DAHM C.N, ELDER K., FORD C.R., GRIMM N.B., HENSHAW D.L., LARSON K.L., MILES E.S., MILES K.M., SEBESTYEN S.D., SPARGO A.T., STONE A.B., VOSE J.M. & WILLIAMS M.W., 2012: Ecosystem processes and human influences regulate streamflow response to climate change at long-term ecological research sites. *BioScience*, 62: 390–404.

KAY A.L., BELL V.A., BLYTH E.M., CROOKS S.M., DAVIES H.N. & REYNARD N.S., 2013: A hydrological perspective on evaporation: historical trends and future projections in Britain. *Journal of Water and Climate Change*, 4: 193–208.

KLEIN TANK A.M.G., WIJNGAARD J.B., KÖNNEN G.P., BÖHM R., DEMARÉE G., GOCHEVA A., MILETA M., PASHIARDIS S., HEJKRLIK L., KERN-HANSEN C., HEINO R., BESSEMOULIN P., MÜLLER-WESTERMEIER G., TZANAKOU M., SZALAI S., PÁLSDÓTTIR T., FITZGERALD D., RUBIN S., CAPALDO M., MAUGERI M., LEITASS A., BUKANTIS A., ABERFELD R., VAN ENGELEN A. F.V., FORLAND E., MIETUS M., COELHO F., MARES C., RAZUVAEV V., NIEPLOVA E., CEGNAR T., LÓPEZ J.A., DAHLSTRÖM B., MOBERG A., KIRCHHOFER W., CEYLAN A., PACHALIUK O., ALEXANDER L.V. & PETROVIC P., 2002: Daily dataset of 20th-century surface air temperature and precipitation series for the European Climate Assessment. *International Journal of Climatology*, 22: 1441–1453.

KLIMENT Z. & MATOUŠKOVÁ M., 2008: Long-term trends of rainfall and runoff regime in Upper Otava river basin. *Soil Water Reearch*, 3: 155–167.

KLIMENT Z., MATOUŠKOVÁ M., LEDVINKA O. & KRÁLOVEC V., 2011: Trend analysis of rainfall-runoff regimes in selected headwater areas of the Czech Republic. *Journal of Hydrology and Hydromechanics*, 59: 36–50.

KLING H., FUCHS M. & PAULIN M., 2012: Runoff conditions in the upper Danube basin under an ensemble of climate change scenarios. *Journal of Hydrology*, 424: 264–277.

KLÖCKING B., SCHWARZE R., BEUDERT B., SUCKOW F. LASCH P., BADECK F. & PFÜTZNER B., 2005: *Auswirkungen des Borkenkäferbefalls auf den Wasser- und Stoffhaushalt zweier Gewässereinzugsgebiete im Nationalpark Bayerischer Wald* [*Bark beetle effects on water and element budgets of two catchments in the Bavarian Forest National Park*]. Nationalparkverwaltung Bayerischer Wald, Grafenau, 184 pp. (in German).

KOCUM J., OULEHLE F., JANSKÝ B., BŮZEK F., HRUŠKA J. & VLČEK L., 2016: Geochemical evidence for peat bog contribution to the streamflow generation process: case study of the Vltava River headwaters, Czech Republic. *Hydrological Sciences Journal*, 61: 2579–2589.

KOMATSU H., KUME T. & OTSUKI K., 2011: Increasing annual runoff – broadleaf or coniferous forests? *Hydrological Processes*, 25: 302–318.

LANGHAMMER J., SU Y. & BERNSTEINOVÁ J., 2015: Runoff response to climate warming and forest disturbance in a mid-mountain basin. *Water*, 7: 3320–3342.

LAUSCH A., FAHSE L. & HEURICH M., 2011: Factors affecting the spatio-temporal dispersion of *Ips typographus* (L.)

in Bavarian Forest National Park: A long-term quantitative landscape-level analysis. *Forest Ecology & Management*, 261: 233–245.

Matsoukas C., Benas N., Hatzianastassiou N., Pavlakis K.G., Kanakidou M. & Vardavas I., 2011: Potential evaporation trends over land between 1983–2008: driven by radiative or turbulent fluxes. *Atmospheric Chemistry and Physics*, 11: 7601–7616.

Maurer E.P., Stewart I.T., Bonfils C., Duffy P.B. & Cayan D., 2007: Detection, attribution, and sensitivity of trends toward earlier streamflow in the Sierra Nevada. *Journal of Geophysical Research: Atmospheres*, 112: D11118, doi:10.1029/2006JD008088.

Mayer M., 2014: Can nature-based tourism benefits compensate for the costs of national parks? A study of the Bavarian Forest National Park, Germany. *Journal of Sustainable Tourism*, 22: 561–583.

McCabe G.J. & Clark M.P., 2005: Trends and variability in snowmelt runoff in the western United States. *Journal of Hydrometeorology*, 6: 476–482.

Milliman J.D., Farnsworth K.L., Jones P.D., Xu K.H. & Smith L.C., 2008: Climatic and anthropogenic factors affecting river discharge to the global ocean, 1951–2000. *Global and Planetary Change*, 62: 187–194.

Milly P.C., Dunne K.A. & Vecchia A.V., 2005: Global pattern of trends in streamflow and water availability in a changing climate. *Nature*, 438: 347–350.

Ministry of Agriculture, 2016: Information on forests and forestry in the Czech Republic by 2015. Ministry of Agriculture of the Czech Republic, Prague, 31 pp.

Möges M., 2007: Klima-Konzept für den Staatswald. Bis 2012 beplant die Bayerische Staatsforsten alle ihre Forstbetriebsflächen nach dem Programm "Waldumbau zur Anpassung an den Klimawandel" [Climate change concept for the Bavarian state forest]. *LWF Aktuell*, 62: 42 pp. (in German).

Moore R. & Wondzell S.M., 2005: Physical hydrology and the effects of forest harvesting in the Pacific Northwest: a review. *Journal of the American Water Resources Association*, 41: 763–784.

Müller J., Bußler H., Goßner M., Rettelbach T. & Duelli P., 2008: The European spruce bark beetle *Ips typographus* in a national park: from pest to keystone species. *Biodiversity and Conservation*, 17: 2979–3001.

Murakami S., Tsuboyama Y., Shimizu T., Fujieda M. & Noguchi S., 2000: Variation of evapotranspiration with stand age and climate in a small Japanese forested catchment. *Journal of Hydrology*, 227: 114–127.

O'brien R.M., 2007: A caution regarding rules of thumb for variance inflation factors. *Quality & Quantity*, 41: 673–690.

Oosterbaan R.J., 1994: Agricultural drainage criteria. In: *Drainage Principles and Applications*, Ritzema H.P. (ed.) ILRI Publication, Wageningen, 16: 635–688.

Parr D. & Wang G., 2014: Hydrological changes in the US Northeast using the Connecticut River Basin as a case study: Part 1. Modeling and analysis of the past. *Global and Planetary Change*, 122: 208–222.

Peck A. & Mayer H., 1996: Einfluss von Bestandesparametern auf die Verdunstung von Wäldern [Influence of forest stand characteristics on evapotranspiration]. *Forstwissenschaftliches Centralblatt*, 115: 1–9 (in German).

Potts D.F., 1984: Hydrologic impacts of a large-scale mountain pine beetle (*Dendroctonus ponderosae* Hopkins) epidemic. *Journal of the American Water Resources Association*, 20: 373–377.

Priestley C.H.B. & Taylor R.J., 1972: On the assessment of surface heat flux and evaporation using large-scale parameters. *Monthly Weather Review*, 100: 81–92.

Ramamurthy P. & Bou-Zeid E., 2014: Contribution of impervious surfaces to urban evaporation. *Water Resources Research*, 50: 2889–2902.

Renner M. & Bernhofer C., 2011: Long term variability of the annual hydrological regime and sensitivity to temperature phase shifts in Saxony/Germany. *Hydrology and Earth System Sciences*, 15: 1819–1833.

Rohrmüller V.J., Gebauer D. & Mielke, H., 2000: Die Altersstellung des ostbayerischen Grundgebirges [Temporal classification of bedrock in eastern Bavaria]. *Geologica Bavarica*, 105: 73–84 (in German).

Sahin V. & Hall M. J., 1996: The effects of afforestation and deforestation on water yields. *Journal of Hydrology*, 178: 293–309.

Seibold S., Bässler C., Brandl R., Büche B., Szallies A., Thorn S., Ulyshen M.D. & Müller J., 2016: Microclimate and habitat heterogeneity as the major drivers of beetle diversity in dead wood. *Journal of Applied Ecology*, 53: 934–943.

Šerna L., 2003: Soil characteristics of the Otava River basin and relations to floods. *Acta Universitatis Carolinae*, 2: 157–172.

Slinski K.M., Hogue T.S., Porter A.T. & McCray J.E., 2016: Recent bark beetle outbreaks have little impact on streamflow in the Western United States. *Environmental Research Letters*, 11: 074010.

Smith E. P., 2002: BACI design. In: *Encyclopedia of Environmetrics*. El-Shaarawi A.H. & Piegorsch W.W. (eds), John Wiley & Sons, Chichester: 141–148.

Stahl K., Hisdal H., Hannaford J., Tallaksen L.M., van Lanen H.A.J. & Jodar J., 2010: Streamflow trends in Europe. Evidence from a dataset of near-natural catchments. *Hydrology and Earth System Sciences*, 7: 5769–5804.

Stahl K., Tallaksen L.M., Hannaford J. & Van Lanen H.A.J., 2012: Filling the white space on maps of European

runoff trends: estimates from a multi-model ensemble. *Hydrology and Earth System Sciences*, 16: 2035–2047.
Stednick J.D., 1996: Monitoring the effects of timber harvest on annual water yield. *Journal of Hydrology*, 176: 79–95.
Štěpánek R., 2005: AnClim – software for time series analysis. Dept. of Geography, Faculty of Sciences, Masaryk University Brno. Online http://www.climahom.eu/software-solution/anclim (accessed on 16 June 2008).
Stewart I.T., 2009: Changes in snowpack and snowmelt runoff for key mountain regions. *Hydrological Processes*, 23: 78–94.
Stewart I.T., Cayan D.R. & Dettinger M.D., 2005: Changes toward earlier streamflow timing across western North America. *Journal of Climate*, 18: 1136–1155.
Swanson F.J. & Dyrness C.T., 1975: Impact of clear-cutting and road construction on soil erosion by landslides in the western Cascade Range, Oregon. *Geology*, 3: 393–396.
Teuling A. J., Hirschi M., Ohmura A., Wild M., Reichstein M., Ciais P., Buchmann N., Ammann C., Montagnani L., Richardson A.D., Wohlfahrt G. & Seneviratne S.I., 2009: A regional perspective on trends in continental evaporation. *Geophysical Research Letters*, 36: L02404.
Thorn S., Bässler C., Brandl R., Burton P. J., Cahall R., Campbell J. L.,Castro j., Choi C.Y., Cobb T., Donato D.C., Durska E., Fontaine J.B., Gauthier S., Hebert C., Hothorn T., Hutto R.L., Lee E.J., Leverkus A.B., Lindenmayer D.B., Obrist M.K., Rost J., Seibold S., Seidl R., Thom D., Waldron K., Wermelinger B., Winter M.A., Zmihorski M. & Müller J., 2017: Impacts of salvage logging on biodiversity – a meta-analysis. *Journal of Applied Ecology*, 55: 279–289.
Thünen-Institut, 2017: Dritte Bundeswaldinventur – Ergebnisdatenbank [The third National Forest Inventory – data base]. Online https://bwi.info (accessed on 20 June 2017) (in German).
Tomer M.D. & Schilling K.E., 2009: A simple approach to distinguish land-use and climate-change effects on watershed hydrology. *Journal of Hydrology*, 376: 24–33.
Velpuri N.M. & Senay G.B., 2013: Analysis of long-term trends (1950–2009) in precipitation, runoff and runoff coefficient in major urban watersheds in the United States. *Environmental Research Letters*, 8: 024020.
Vormoor K., Lawrence D., Schlichting L., Wilson D. & Wong W.K., 2016: Evidence for changes in the magnitude and frequency of observed rainfall vs. snowmelt driven floods in Norway. *Journal of Hydrology*, 538: 33–48.
Wei X. & Zhang M., 2010: Quantifying streamflow change caused by forest disturbance at a large spatial scale: A single watershed study. *Water Resources Research,* 46: W12525. doi:10.1029/2010WR009250
Wilby R.L., Beven K.J. & Reynard N.S., 2008: Climate change and fluvial flood risk in the UK: more of the same? *Hydrological Processes*, 22: 2511–2523.
Wilson D., Hisdal H. & Lawrence D., 2010: Has streamflow changed in the Nordic countries? – Recent trends and comparisons to hydrological projections. *Journal of Hydrology*, 394: 334–346.
Zhang L., Dawes W.R. & Walker G.R., 2001: Response of mean annual evapotranspiration to vegetation changes at catchment scale. *Water resources research*, 37: 701–708.
Zhang Y., Leuning R., Chiew F.H., Wang E., Zhang L., Liu C., Fubao S., Murray C.P. Yanjub S. & Jung M., 2012: Decadal trends in evaporation from global energy and water balances. *Journal of Hydrometeorology*, 13: 379–391.

Received: 1 September 2017
Accepted: 18 January 2018