Runoff Trends Analysis and Future Projections of Hydrological Patterns in Small Forested Catchments

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Abstract

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The aims of the present study were (*i*) to evaluate trends in runoff from small forested catchments of the GEOMON (GEOchemical MONitoring) network during the period 1994–2011, and (*ii*) to estimate the impact of anticipated climate change projected by ALADIN-Climate/CZ regional climate model coupled to ARPEGE-Climate global circulation model and forced with IPCC SRES A1B emission scenario on flow patterns in the periods 2021–2050 and 2071–2100. There were no general patterns found indicating either significant increases or decreases in runoff on either seasonal or annual levels across the investigated catchments within 1994–2011. Annual runoff is projected to decrease by 15% (2021–2050) and 35% (2071–2100) with a significant decrease in summer months and a slight increase in winter months as a result of expected climate change as simulated by the selected climate model.

Keywords: climate change; flow pattern; headwater catchments; hydrological modelling

Predicting the future climate and its potential impact on the hydrological cycle is a crucial issue, since water availability affects both ecosystems and society (Prudhomme & Davies 2009). Most recently published studies focus on the impact of climate change on hydrological patterns in meso- or large-scale catchments (e.g. Kliment & Matoušková 2006; Hurkmans *et al.* 2010; Němečková *et al.* 2011; Hanel *et al.* 2012; Somorowska & Pietka 2012; Schneider *et al.* 2013). Much less attention has been paid to the possible effects on hydrological patterns in small headwater catchments, although these areas are considered to be particularly vulnerable to climate change (Haigh & Křeček 2000). In addition, headwater catchments in Central Europe, often forested and located at mountainous regions, are areas of high ecological importance. For instance, a significant decrease in runoff during summer months was estimated for the period 2071–2100 by Benčoková *et al.* (2011a) for the small forested catchments Lysina and Pluhův bor in the western part of the Czech Republic, both being monitored within the frame of the GEOMON (GEOchemical MONitoring) network. The GEOMON network was primarily established for geochemical monitoring related to the impact of acidic atmospheric deposition that strongly affected Central Europe in late 1980s. The catchment hydrology of GEOMON sites has been investigated since 1994 (Fottová & Skořepová 1998; Krám & Fottová 2008; Benčoková *et al.* 2011a). Catchments were selected in order to represent hydrological patterns of different areas of the Czech Republic (Figure 1). The forested areas are considered to be close to the natural Central

European landscape conditions, although they quite often consist of Norway spruce (*Picea abies*) monoculture stands planted outside their natural range, displacing native European beech (*Fagus sylvatica*) species or mixed forests. Nevertheless, forested catchments still represent the most close-to-natural environment, in which direct human impacts – e.g. agriculture, drainage or extensive water use – have been minimized. Thus, the potential impacts of climate change are more unambiguously detectable in comparison with other landscapes.

The aims of the present study were (*i*) to evaluate the trends in runoff from GEOMON catchments during the period 1994–2011 and (*ii*) to assess the impact of anticipated climate change on flow patterns in the periods 2021–2050 and 2071–2100.

MATERIAL AND METHODS

GEOMON monitoring network. The GEOMON catchments are located across the Czech Republic (CR) (Figure 1) and the network was originally established for evaluation of recovery from acidification (e.g. Hruška & Krám 1994; Krám *et al.* 1995). The individual catchments cover an area of 22–261 ha, with a medium size of 70 ha; the mean catchment elevation ranges from 448 to 1282 m (Table 1). Bedrocks consist mainly of crystalline rocks (mainly gneiss and granite, but also mica schist and serpentinite), with the exception of Litavka (LIT) and Červík (CER) underlain by sandstones and other sediments. Prevailing soils are Cambisols, with Podzols developed

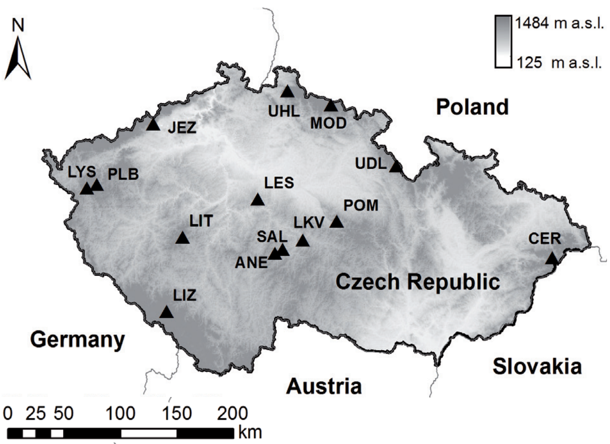

Figure 1. Locations of the GEOMON catchments within the Czech Republic (JEZ – Jezeří, LYS – Lysina, PLB – Pluhův bor, LIT – Litavka, LIZ – Liz, LES – Lesní potok, ANE – Anenský potok, SAL – Salačova Lhota, LKV – Loukov, POM – Polomka, UHL – Uhlířská, MOD – Modrý potok, UDL – U dvou louček, CER – Červík)

only at the wettest catchments (Modrý potok (MOD) and U dvou louček (UDL)). Forests consist mainly of Norway spruce (*Picea abies*) plantations that have dominated most catchments since the beginning of the 19th century. Catchments Uhlířská (UHL), Jezeří (JEZ), and UDL were almost completely harvested during the 1970–1980s as a result of spruce dieback, and reforested with Norway spruce (UHL, UDL) or mixed forest (JEZ) in the 1980s. On the other hand, the catchments of Pluhův bor (PLB), MOD, and Lesní potok (LES) are covered by old spruce stands (ca. 100 years), and the main part of MOD consists of the alpine ecosystem (Table 1).

Catchments were equipped with 2 bulk collectors (open canopy) for precipitation chemistry and 9 collectors for throughfall deposition (regular 10 × 10 m grid) at each site. Samples of each type were combined to yield a single composite sample for bulk and throughfall, respectively, and weighed to determine precipitation depth. Discharges were continuously measured at catchment outlets by gauging stations equipped mostly with a V-notch weir and water level recorder.

The importance of the GEOMON network is outlined by the participation of some catchments in other international monitoring networks. The Lysina (LYS) and Anenský potok (ANE) catchments belong to the International Cooperative Programme (ICP) on Integrated Monitoring of the international network of forested sites (Holmberg *et al.* 2013) organized under the Economic Commission for Europe of the United Nations. The LYS and UHL catchments also belong to the ICP Waters, focused on the effects of atmospheric pollution on surface waters. The Liz (LIZ), UHL, and ANE catchments are part of the Euromediterranean Network of Experimental and Representative Basins (ERB) international hydrological monitoring network. The LYS, PLB (Krám *et al.* 2012), and MOD catchments belong to the International Long-Term Ecosystem Research (ILTER) network. Moreover, the LYS catchment has recently become one of the European Critical Zone Observatories within the SoilTrEC (Soil Transformations in European Catchments) project (Banwart *et al.* 2012).

Analyses of monthly runoff trends were performed for all GEOMON catchments except for LIT (measured data available only since 2006) and Salačova Lhota (SAL) where runoff was significantly affected by the use of local groundwater for municipal supply. Future hydrological patterns were projected for the following eight out of the fourteen GEOMON catchments: LYS, PLB, LIT, LES, ANE, Loukov (LKV), UDL, and CER. In these catchments, the mean annual precipitation varied between ~600 mm (LES) and ~1700 mm (UDL) (Table 2) and mean annual temperature between 4.7°C (UDL) and 8.6°C (ANE) (Table 3).

Hydrological modelling. The Brook90 model (Federer *et al.* 2003) is a deterministic, process-oriented, lumped parameter hydrological model that was designed to be applicable to any land surfaces at a daily time step year-round. Brook90 is a parameter-rich model designed primarily to study evapotranspiration and soil water movement at a point, with some provision for stream flow generation by different flow paths. Water is stored in the model as intercepted rain, intercepted snow, snow on the ground, soil water from one to many layers, and groundwater. Snow accumulation and melt are controlled by a degree-day method with cold content (Linsley 1949). Evaporation is the sum of five components: evaporation of intercepted rain and snow, snow and soil evaporation, and transpiration. The model uses the Shuttleworth and Wallace (1985) method for separating transpiration and soil evaporation from sparse canopies, and evaporation of interception. Actual transpiration is reduced below potential when water supply to the plant is limited.

Required inputs to the model are daily precipitation, and maximum and minimum air temperatures. Additional inputs are daily solar radiation, daily mean wind speed, and average vapour pressure for the day. Six parameter sets are required: canopy, location, soil (for up to 25 layers), flow, initial and fixed parameters. It includes 47 free parameters in total.

The model performance was evaluated by Pearson's correlation coefficient between measured and simulated daily stream flows and by the daily and monthly Nash–Sutcliffe criterion (Nash & Sutcliffe 1970). The calibration and validation period varied from catchment to catchment, and was based on observation length (Table 4).

Meteorological data. Meteorological data for the studied catchments (minimum and maximum daily air temperature, daily precipitation) for the period 1990–2006 were taken from climate stations of the Czech Hydrometeorological Institute (CHMI) located in the catchment surroundings (Table 5). Air temperature data were corrected based on local minimum and maximum temperature lapse rates to represent the average catchment altitudes. The lapse rates for individual months were calculated by linear regression

Table 1. Characteristics of the GEOMON network catchments with exception of Salačova Lhota catchment

Site	Latitude	Longitude	Elevation (m a.s.l.)	Area (ha)	Bedrock (prevailing)	Soil type (prevailing) (FAO classification)	Vegetation cover (prevailing)
LYS	50°02'N	12°40'E	829–949	27	Granite	Spodo-dystric Cambisol	Norway spruce
PLB	50°03'N	12°47'E	690–804	22	Serpentinite	Magnesic Cambisol	Norway spruce
JEZ	50°32'N	13°28'E	475–924	261	Gneiss	Spodo-dystric Cambisol	European white birch, Norway spruce, European beech
LIZ	49°04'N	13°59'E	828–1024	98	Gneiss	Spodo-dystric Cambisol	Norway spruce
LIT	49°42'N	13°51'E	696–840	175	Conglomerates, Sandstone, Quartzites	Dystric Cambisol	Norway spruce
LES	49°58'N	14°59'E	400–495	70	Granite	Eutric Cambisol	European beech, Norway spruce
ANE	49°34'N	15°08'E	480–540	27	Gneiss	Dystric Cambisol	Norway spruce
UHL	50°49'N	15°20'E	780–870	187	Granite	Spodo-dystric Cambisol	Norway spruce
LKV	49°38'N	15°42'E	472–658	66	Granite	Dystric Cambisol	Norway spruce
MOD	50°42'N	15°45'E	1010–1554	262	Mica schist	Ferro-humic Podzol	Norway spruce, Alpine meadow
POM	49°47'N	16°29'E	512–640	69	Gneiss	Dystric Cambisol	Norway spruce
UDL	50°13'N	18°23'E	880–950	33	Gneiss	Ferro-humic Podzol	Norway spruce
CER	49°27'N	13°28'E	640–961	185	Sandstone, Claystone	Dystric Cambisol	Norway spruce

LYS – Lysina; PLB – Pluhův bor; JEZ – Jezeří; LIZ – Liz; LIT – Litavka; LES – Lesní potok; ANE – Anenský potok; UHL – Uhlířská; LKV – Loukov; MOD – Modrý potok; POM – Polomka; UDL – U dvou louček; CER – Červík

Table 2. Water balances for GEOMON catchments; observed data are mostly for the period 1994–2011; modelled future data were available for selected catchments only

Site	Precipitation observed	Precipitation CHMI gridded data	Runoff observed	Runoff/precipitation ratio	Evapotransp. simulated	Precipitation 2021–2051	Evapotransp. 2021–2051	Runoff 2021–2051	Precipitation 2071–2100	Evapotransp. 2071–2100	Runoff 2071–2100
	(mm)				(mm)						
LYS	1025	881 (1040*)	450	0.44	439	960*	494	372	932*	524	327
PLB	861	881	275	0.32	415	813	441	242	790	469	209
JEZ	773		354	0.46	–	–	–	–	–	–	–
LIZ	825		396	0.48	–	–	–	–	–	–	–
LIT	975	747 (966*)	228	0.23	589	902*	492	249	869*	516	217
LES	604	647	115	0.19	428	612	421	124	571	455	77
ANE	648	627	60	0.09	494	627	504	53	588	523	30
UHL	1181		960	0.81	–	–	–	–	–	–	–
LKV	734	698	125	0.17	489	654	499	80	615	535	45
MOD	1778		1844	1.04	–	–	–	–	–	–	–
POM	696		296	0.43	–	–	–	–	–	–	–
UDL	1704	1282 (1704*)	1181	0.69	402	1389*	439	862	1328*	446	801
CER	1256	1229	701	0.56	511	1091	596	470	1004	620	367

*additional precipitation correction was applied to LYS, LIT and UDL RCM corrected data, since the difference between measured station value and gridded values was substantial; LYS – Lysina; PLB – Pluhův bor; JEZ – Jezeří; LIZ – Liz; LIT – Litavka; LES – Lesní potok; ANE – Anenský potok; UHL – Uhlířská; LKV – Loukov; MOD – Modrý potok; POM – Polomka; UDL – U dvou louček; CER – Červík; CHMI – Czech Hydrometeorological Institute

Table 3. Mean annual temperatures (in °C) at selected GEOMON catchments

Site	Observed period	Mean annual temperature			
		catchment (CHMI station corrected data)	CHMI gridded data	2021–2051	2071–2100
LYS	1990–2006	5.0	6.2	7.6	9.4
PLB	1992–2006	5.7	6.2	7.6	9.4
LIT	2006–2012	6.6	7.6	8.8	10.5
LES	1995–2006	8.4	8.3	9.8	11.7
ANE	1993–2006	8.6	7.9	8.7	10.6
LKV	1994–2006	8.2	8.1	8.9	10.8
UDL	1993–2006	4.7	5.9	8.2	10.0
CER	1993–2006	6.6	6.8	8.7	10.4

LYS – Lysina; PLB – Pluhův bor; LIT – Litavka; LES – Lesní potok; ANE – Anenský potok; LKV – Loukov; UDL – U dvou louček; CER – Červík; CHMI – Czech Hydrometeorological Institute

relationships using data from 5 representative climate stations situated 519–1118 m a.s.l. The decrease varied between 0.1–0.3°C per 100 m for the minimum temperature and 0.3–0.7°C for the maximum temperature. Daily precipitation from the CHMI stations were corrected, if the altitude of the catchment and CHMI station differed notably, by a factor calculated as the ratio between mean annual precipitation measured by bulk precipitation collectors at the investigated catchments and precipitation from the climatic stations (for the observed periods). In the case of LIT, the spring-autumn precipitation was measured at the catchment (winter precipitation was taken from the CHMI climate station Rožmitál pod Třemšínem).

The daily average vapour pressure data were estimated by the Brook90 model using saturated vapour pressure at minimum temperature. Wind speed and solar radiation data were not available, therefore the model used a constant wind speed of 3 m/s and potential solar radiation multiplied by 0.55 instead.

Climate change scenarios. Precipitation and air temperature for periods of 2021–2050 and 2071–2100 from the ALADIN-Climate/CZ regional climate model (RCM) coupled to ARPEGE-Climate global circulation model and forced with IPCC SRES A1B emission scenario were used as future forcing data. The grid resolution was ~10 km. Meteorological data were used from grids covering the catchments (Table 6). The model outputs were statistically corrected according to observed values using the percentile approach proposed by Déqué (2007). The control period was 1961–1990. Gridded observed

Table 4. Pearson's correlation coefficients (r) and Nash-Sutcliffe coefficients (NS) in the calibration and validation periods for the GEOMON network of catchments

Site	Calibration period	N days	r (daily)	NS (daily)	Validation period	N days	r (daily)	NS (daily)	N months	r (monthly)	NS (monthly)
LYS	1990–1997	2922	0.75	0.47	1998–2006	3287	0.74	0.45	108	0.91	0.78
PLB	1992–1998	2557	0.77	0.59	1999–2006	2992	0.75	0.56	84	0.86	0.73
LIT	2006–2009	1218	0.69	0.54	2010–2012	1096	0.69	0.47	36	0.82	0.67
LES	1995–2000	1888	0.72	0.47	2001–2006	2130	0.73	0.46	70	0.83	0.68
ANE	1993–1999	2252	0.74	0.38	2000–2006	2496	0.73	0.33	82	0.77	0.55
LKV	1994–1999	1888	0.70	0.45	2000–2006	2469	0.73	0.38	82	0.86	0.68
UDL	1993–1999	2552	0.75	0.55	2000–2006	2557	0.73	0.52	84	0.90	0.80
CER	1993–1999	2552	0.85	0.73	2000–2006	2557	0.86	0.62	84	0.92	0.76

LYS – Lysina; PLB – Pluhův bor; LIT – Litavka; LES – Lesní potok; ANE – Anenský potok; LKV – Loukov; UDL – U dvou louček; CER – Červík

Table 5. Characteristics of meteorological stations of the Czech Hydrometeorological Institute and measured variables

Catch.	Meteorological station	Latitude	Longitude	Altitude (m a.s.l.)	Mean annual temp. (°C)	Mean annual precip. (mm)	Variables	Period
LYS	Marianské Lázně (úpravna vody)	49°59'N	12°42'E	691	6.2	838	Tmax, Tmin, P, Wind, Sunshine duration	1990–2006
PLB	Marianské Lázně (úpravna vody)	49°59'N	12°42'E	691	6.2	860	Tmax, Tmin, P, Wind, Sunshine duration	1992–2006
LIT	Rožmitál pod Třemšínem	49°42'N	14°00'E	550	7.9	721	Tmax, Tmin	2006–2009
							P (winter precipitation), Wind, Sunshine duration	2006–2012
LES	Ondřejov	49°54'N	14°47'E	485	8.2	688	Tmax, Tmin, P, Wind, Sunshine duration	1995–2006
ANE	Košetice	49°35'N	15°05'E	621	7.9	646	Tmax, Tmin, P, Wind, Sunshine duration	1993–2006
LKV	Košetice	49°35'N	15°05'E	621	7.9	648	Tmax, Tmin, P, Wind, Sunshine duration	1994–2006
UDL	Deštné v Orlických horách	50°18'N	16°21'E	635	6.4	1202	Tmax, Tmin, P, Wind, Sunshine duration	1993–2006
CER	Bílá	49°25'N	18°23'E	770	6.8	967	Tmax, Tmin, P, Wind, Sunshine duration	1993–2006

Catch. – catchment; LYS – Lysina; PLB – Pluhův bor; LIT – Litavka; LES – Lesní potok; ANE – Anenský potok; LKV – Loukov; UDL – U dvou louček; CER – Červík

Table 6. Characteristics of the ALADIN Climate/CZ grids

Catch.	ALADIN-Climate/CZ Grid No.	Latitude	Longitude	Altitude (m a.s.l.)
LYS	8034	50°01'N	12°44'E	739
PLB	8034	50°01'N	12°44'E	739
LIT	7450	49°42'N	13°52'E	693
LES	7900	49°59'N	14°42'E	394
ANE	7163	49°32'N	15°08'E	494
LKV	7312	49°38'N	15°16'E	482
UDL	8356	50°16'N	16°22'E	719
CER	7038	49°27'N	18°19'E	731

Catch. – catchment; LYS – Lysina; PLB – Pluhův bor; LIT – Litavka; LES – Lesní potok; ANE – Anenský potok; LKV – Loukov; UDL – U dvou louček; CER – Červík

data used for the correction were produced by the Czech Hydrometeorological Institute. The data were derived by spatial interpolation of point measurements (Štěpánek *et al*. 2011a).

An additional precipitation correction was applied to LYS, LIT, and UDL RCM corrected data, since the differences between point measured station data and simulated gridded values were substantial (Table 2). The correction was made as a mean daily ratio between measured precipitation at a station and gridded data in the overlapping control period. The same correction was then used also for future data.

Assessing trends in monthly and annual observed runoff data. Recent changes in monthly measured runoff were tested with the non-parametric Yue-Pilon method (Yue *et al*. 2002a) at all GEOMON catchments with the exception of LIT, where the runoff observation started much later compared to other catchments and the time series was thus shorter. This method removes serial correlation components such as the lag-one autoregressive (AR (1)) process from the time series. The magnitude of the trend is computed by the Yue-Pilon method using the Theil-Sen approach. If the slope differs from zero, then it is assumed to be linear and the data are de-trended by the slope; the AR (1) is then computed for the de-trended series. The residuals should be an independent series. The trend and residuals are then blended together. The Mann-Kendall test (Yue *et al*. 2002b) is then applied to the blended series to assess the trend significance.

RESULTS

Trends in stream runoff. The small forested catchments investigated represent a wide range of climate and hydrology (Tables 1 and 2). Median runoff was measured as 354 mm and precipitation 861 mm, resulting in a median runoff/precipitation ratio of 0.44. The highest annual runoff (1844 mm) as well as precipitation (1778 mm) were recorded for the dominantly subalpine catchment MOD in the Krkonoše Mts., resulting in a very high runoff/precipitation ratio of 1.04, caused by additional snow input not captured by measurements at the catchment. The lowest precipitation (604 mm) was measured at LES, and the lowest runoff (just 60 mm) was recorded at ANE. The lowest runoff/precipitation ratio of 0.09 was also observed at ANE.

Statistically significant changes in annual runoff were found for LKV (−6.3 mm/year, $P < 0.05$) and Polomka (POM) (6.2 mm/year, $P < 0.1$). For the remaining 10 catchments, significant changes were not detected (Table 7).

There was no general pattern found indicating either a significant increase or decrease of monthly runoff across the investigated catchments (Table 7). The most pronounced changes ($P < 0.05$) were found for just 2 catchments and 2 months, in summer – June at UHL, and July at POM. All of these trends were negative. Less pronounced negative trends ($P < 0.1$) were found for spring and summer at LYS (June and July), LES (April), and CER (April). Increased runoff ($P < 0.1$) was identified in late summer at PLB (August) and winter at POM (December). No statistically significant monthly change was found at six (JEZ, LIZ, ANE, LKV, MOD, UDL) out of the twelve catchments monitored. Thus, the limited trends analyzed did not confirm any expected changes in hydrological patterns that could be attributed to climate change during the observed time periods (Table 7).

Calibration and validation of the hydrological model. There was a good agreement between daily measured and simulated runoff, indicating satisfactory performance of the Brook90 model in the investigated catchments (Table 4). This included agreement in individual flood events from snowmelt and rainfall and summer droughts, representing the simulation of overall vegetation water use. The Nash-Sutcliffe coefficient of efficiency for runoff varied between 0.38 and 0.73 (calibration period) and 0.33 and 0.62 (validation period) for daily data (Table 4). In the case of monthly data, the Nash-Sutcliffe coefficients ranged 0.55–0.80 in the validation period (Table 4). The Pearson's correlation coefficients were 0.69–0.85 (calibration period) and 0.69–0.86 (validation period) for daily data. For monthly data, the Pearson's correlation coefficients were 0.77–0.92 in the validation period (Table 4).

Table 7. Trends in measured runoff data at GEOMON catchments (mm/year)

Month	LYS 1990–2011	PLB 1992–2011	JEZ 1993–2011	LIZ 1993–2011	LES 1995–2011	ANE 1993–2011	UHL 1982–2011	LKV 1994–2011	MOD 1993–2011	POM 1994–2011	UDL 1991–2011	CER 1993–2011
1	−0.54	−0.32	−0.23	−0.18	−0.13	−0.07	−0.09	−0.36	−0.08	0.80	−0.46	−0.44
2	0.04	0.12	−0.48	−0.41	−0.03	−0.05	0.46	−0.72	−0.64	0.67	−0.63	−0.74
3	0.47	1.20	0.31	−0.10	−0.12	0.07	1.17	−0.47	0.64	2.39	−0.93	−0.94
4	0.48	−0.56	−0.62	0.29	**−0.42***	−0.09	−2.56	−0.18	−2.17	0.86	−1.66	**−4.27***
5	0.25	0.24	−0.25	0.65	−0.31	−0.14	−2.06	−0.69	−17.79	0.21	−0.12	−0.63
6	**−0.45***	0.10	0.12	0.71	−0.21	−0.04	**−1.80**	−0.32	0.68	−0.11	−0.33	−1.10
7	**−0.65***	−0.02	−0.09	0.38	−0.58	−0.13	−0.01	−0.55	−0.50	**−1.69**	−0.52	−0.24
8	0.26	**0.25***	0.15	0.68	−0.03	−0.02	−0.73	−0.19	1.61	0.30	0.22	1.92
9	−0.02	0.15	−0.21	0.25	−0.06	−0.04	0.02	−0.44	−2.29	−0.23	−0.20	−0.80
10	−0.02	0.21	−0.13	0.28	−0.07	−0.03	0.41	−0.41	3.01	0.59	−0.44	−0.88
11	0.11	1.04	0.09	0.34	−0.19	0.00	0.68	−0.29	5.06	0.49	−0.43	−0.17
12	−0.19	−0.27	−0.40	−0.21	−0.24	−0.07	−0.70	−0.27	−0.01	**1.24***	−0.19	−1.06
Year	2.91	2.72	−2.80	3.15	−3.46	−0.30	−1.82	**−6.29**	−10.83	**6.20***	−10.36	−8.45

LYS – Lysina; PLB – Pluhův bor; JEZ – Jezeří; LIZ – Liz; LES – Lesní potok; ANE – Anenský potok; UHL – Uhlířská; LKV – Loukov; MOD – Modrý potok; POM – Polomka; UDL – U dvou louček; CER – Červík; *$P < 0.1$; bold and grey highlighted – $P < 0.05$

Future climate. The Aladin-CLIMATE/CZ model estimates an increase in the mean annual temperature of 0.8–2.3°C in the period 2021–2050 (Table 3). The lowest increase in the mean annual temperature (0.8°C) is expected in the area of the Českomoravská vrchovina Uplands where the catchments ANE and LKV are located. The greatest temperature increase is projected for the north-eastern and eastern mountain border area. In the UDL catchment (Orlické hory Mts.) an increase of 2.3°C is expected, while in the CER catchment (Beskydy Mts.) the increase should make 1.9°C.

A similar pattern is predicted for the period 2071 to 2100. The lowest increase in mean annual temperature is projected for the ANE and LKV catchments (+2.7°C) and the greatest increase is estimated for the UDL and CER catchments (4.1 and 3.6°C, respectively) (Table 3).

Precipitation is mostly estimated to decrease or remain more or less the same in the period 2021–2051 (Table 2). Precipitation in the western part of the CR (LYS, PLB) is projected to decrease by 6%. Similar changes are expected for the central part of the CR (LIT, LES, ANE, LKV) with average decreases of 5%, while precipitation in the catchments in the north-eastern and eastern mountains (UDL, CER) is projected to decline more rapidly (by 13 and 18%, respectively) in the period 2021–2051.

A precipitation decrease of ~10% in the W (LYS, PLB) and in the central part of the CR (LIT, LES, ANE, LKV) and of ~21% in the NE (UDL) and E (CER) is projected for the period 2071–2100.

Future runoff and evapotranspiration. In general, mean annual runoff is projected to decrease signifi-

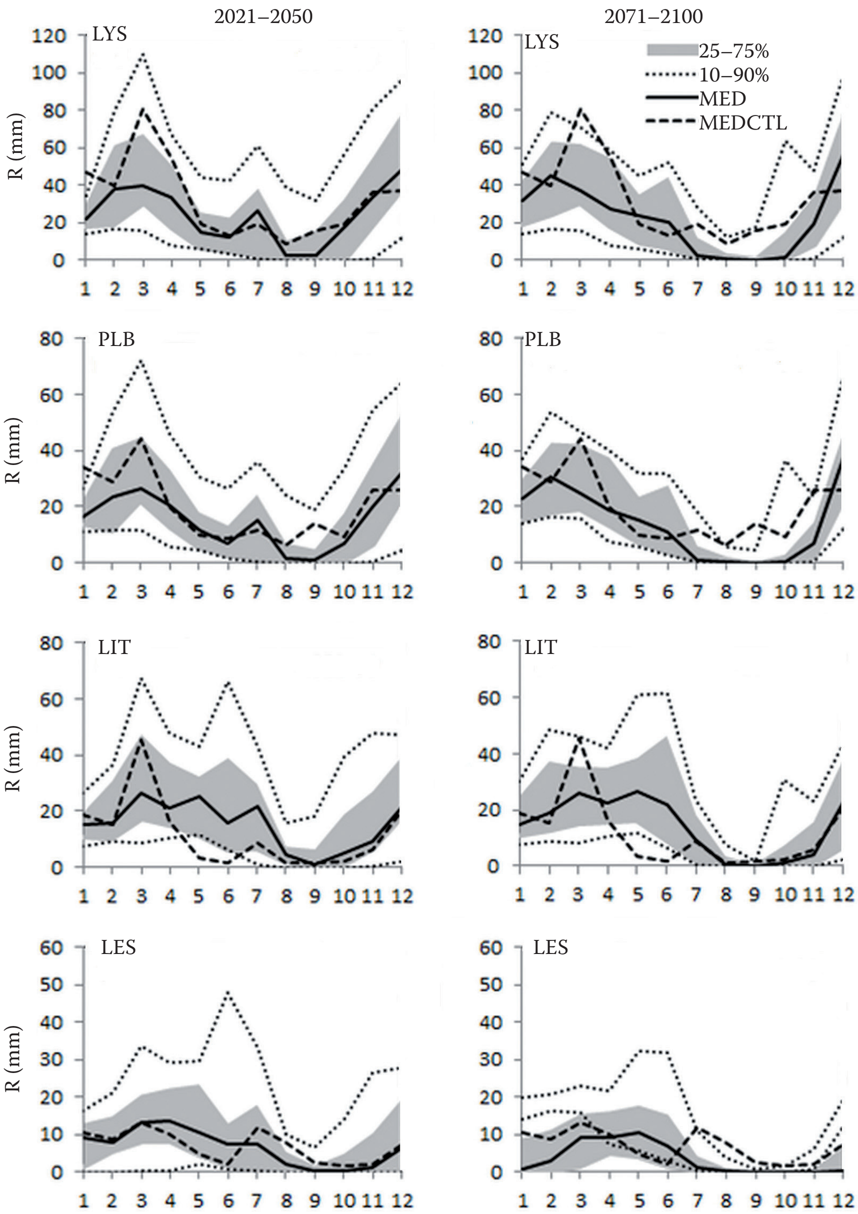

Figure 2. Simulated annual series of mean runoff (R) for the future scenario periods 2021–2050 and 2071–2100 at Lysina (LYS), Pluhův bor (PLB), Litavka (LIT), and Lesní potok (LES); MEDCTL: observed runoff median, MED: future runoff median, 25–75%: runoff inter-quartile range, 10–90%: runoff inter-quintile range

cantly compared to the present situation with the exceptions of the LIT and LES catchments, where increases of 9 and 7% are estimated for the period 2021–2051 (Table 2). In the western part of the CR runoff is projected to decrease by 15% on average (LYS and PLB). The estimated change in the central part of the CR will vary between an increase of 9% (LIT) and a decrease of 36% (LKV). The decreases in the north-eastern and eastern border areas will be rather more distinct, of 27% (UDL) and 33% (CER), compared to the rest of the catchments in the period 2021–2050.

In the period 2071–2100 mean annual runoff is projected to decrease compared to the observed runoff means in all GEOMON catchments. The expected decrease in the western part of the CR should be of 26% on average (LYS, PLB). Runoff declines will vary between 5% (LIT) and 64% (LKV) in the central part of the CR (LIT, LES, ANE, LKV) (Table 2). In the northern and eastern part of the CR, runoffs are projected to decrease by 32% (UDL) and 48% (CER).

Seasonal runoff changes (Figures 2 and 3) are even more substantial in comparison to the annual changes (Figures 2 and 3). A similar pattern can be seen across most catchments for both periods. A large decrease in spring maxima resulting from snowmelt is important especially for the catchments in mountainous areas (UDL, CER) and highlands (LYS, PLB, LIT) (Figures 2 and 3). For 2021–2051, the runoff in most catchments (with the exception of LIT) shows a significant drop in August and September. Declines in runoff will be even more noticeable at the end of the century (2071–2100), when a large decrease from

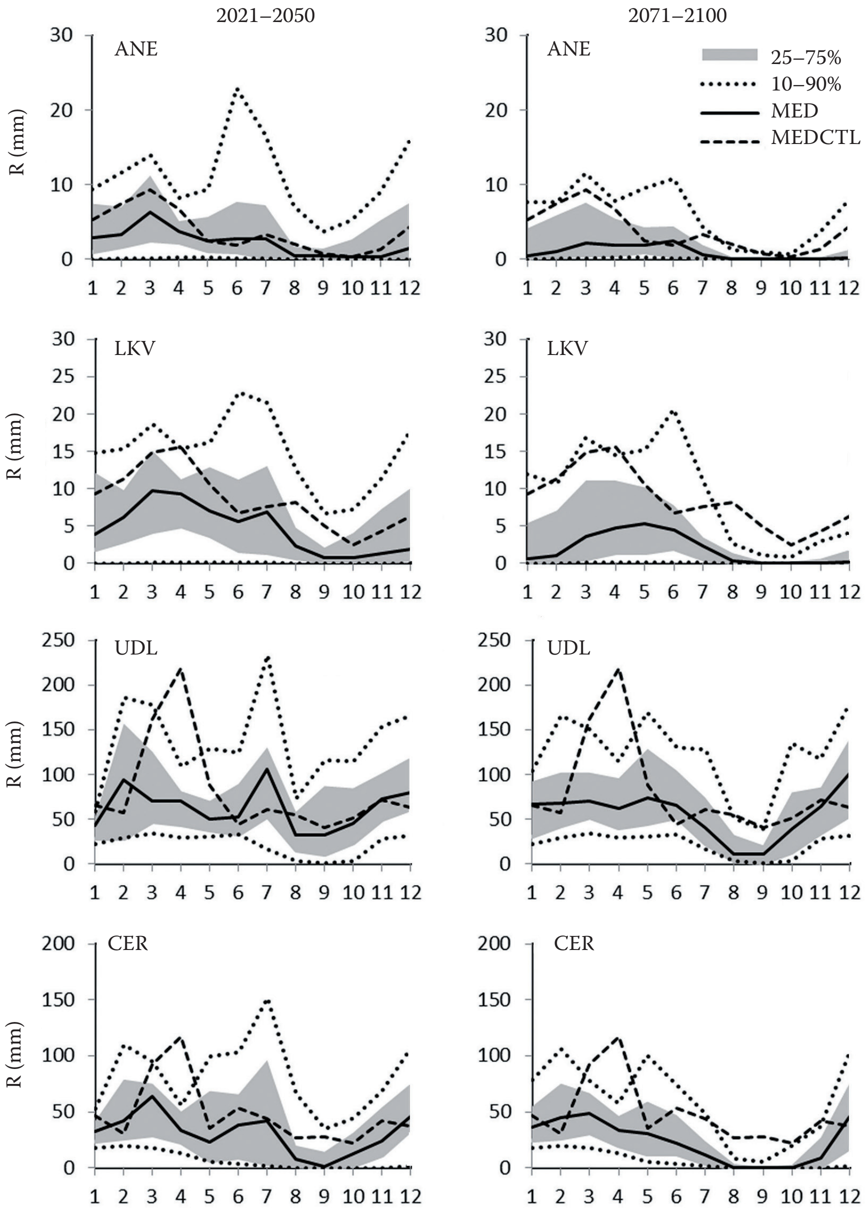

Figure 3. Simulated annual series of mean runoff (R) for the future scenario periods 2021–2050 and 2071–2100 at Anenský potok (ANE), Loukov (LKV), U dvou louček (UDL), and Červík (CER); MEDCTL: observed runoff median, MED: future runoff median, 25–75%: runoff inter-quartile range, 10–90%: runoff inter-quintile range

July to November is projected for almost all of the GEOMON catchments (Figures 2 and 3).

In the western part of the CR (LYS and PLB), there is the mean projected decrease in runoff median in August and September of 80% in the period 2021–2051 and of 89% from July to November in the period 2071–2100 (compared to observed runoff median). An increase in winter runoff median at LYS and PLB (29%) is estimated only for December 2021–2050 or for December and February 2071–2100 (30%) (compared to observed runoff median).

In the central part of the CR (LIT, LES, ANE, LKV), there is an expected decrease in runoff median of 27% on average in August–September 2021–2050 and of 81% in July–November 2071–2100 (compared to observed runoff median). A winter increase of 5% (2021–2050) and of 18% (2071–2100) in December and February is projected only for the LIT catchment.

In the north-eastern and eastern catchments, there should be a decrease in runoff median of 31% (UDL) and 84% (CER) in August–September 2021–2050 and of 44% (UDL) and 90% (CER) in July–November 2071–2100 (compared to observed data). Winter increase of 47% (UDL) and of 29% (CER) is estimated for December and February 2021–2050, of 27% (UDL) for December–February 2071–2100, and of 34% (CER) for December and February 2071–2100.

Evapotranspiration is projected mostly to increase, with the exceptions of the LIT and LES catchments where a decrease (by 16 and 2%, respectively) is expected in the near future (2021–2051) (Table 2). Similarly as with temperature, the lowest increase is predicted for the area of the Českomoravská vrchovina Uplands (ANE, LKV) (2% on the average). The highest increase (17%) is projected for the CER catchment in the Beskydy Mts.

Similarly, the lowest increase in evapotranspiration (7% on the average) is expected in the central part of the CR (LES, ANE, LKV) in the period 2071–2100. The highest increase is projected for the CER and LYS catchments (21 and 19%, respectively). In the case of the LIT, catchment evapotranspiration was simulated to be lower by 12% compared to the period 2006–2012.

DISCUSSION

Trends in streamwater runoff. The fact that there was no pattern found in recent trends across the GEOMON network indicates that the catchments have not yet started to react to climate changes such as the temperature increase documented in the CR (e.g. Brázdil *et al*. 2012). An expected change in flow pattern would be, for instance, a shift in snowmelt maxima to earlier periods or a drop in summer runoffs. However, these expectations were not confirmed by measured catchment runoff with the exceptions of significant June and July decreases at UHL and POM (Table 7). Moreover, UHL was largely deforested by acid rain damage in the 1980s and then reforested by new spruce plantations (Oulehle *et al*. 2008). Thus, the decrease in early summer runoff might be explained by the increased evapotranspiration of newly established forest stands, and cannot be attributable to climate change. Significant changes of annual runoff were detected at LKV (–6.3 mm/year) and POM (6.2 mm/year). Both catchments are located in the Českomoravská vrchovina Uplands with similar landscape and climate (Table 1) and their increase/decrease runoff was almost identical, though opposite. So, we found no evidence of the expected synchrony in the response to observed temperature increases. In other recent studies of trends in surface water baseflow discharges and ground water spring discharges (Fiala *et al*. 2010; Ledvinka & Lamačová 2014), patterns of summer changes across the CR have not been found, too. Fiala *et al*. (2010) studied changes in the low-flow regime of 144 Czech river basins in the period of 1965–2010 and identified that the north-eastern part of the CR might become a drought prone area in the future; however, at a majority of the tested stations the trends were insignificant. Similarly, long-term changes in the deficit volumes of Czech rivers were not found in the period of 1947–2006 (Vlnas 2010). On the other hand, Matoušková *et al*. (2011) and Kliment *et al*. (2011) demonstrated a decrease in runoff during May and June in the period 1962–2008 for several streams across the Czech Republic, despite the fact that no rainfall decrease in these months was registered and general increase of temperature was observed. All of the analyzed catchments were much larger than the GEOMON catchments, and potential increase of evapotranspiration could explain the runoff decrease.

Future runoff. Observed data for comparison with future were used because they better represent the sites than RCM control period (1961–1990) simulations that do not overlap with measurements from sites. However the differences between the simulations for 1961–1990 and observed data for each catchment were negligible compared to the difference with future flow pattern. Median was selected for comparison purposes because the values better represent flow conditions since they are not affected by extremes such as mean. Although the data aggregation using averaged relative changes presented in the result section is not entirely representative since the measurement periods were not the same for all catchments, the described pattern of future flow conditions seems to be valid because it is mostly in agreement with other published projections (see below).

Projections for the catchments situated in the north-eastern and eastern part of the CR (UDL and CER) indicate a large decrease in spring runoff originating from snowmelt. This can be explained by increasing winter temperatures and earlier snowmelt, and partially by the decrease in precipitation, since this parameter is projected to decrease more rapidly in these areas (by 16 and 21% in 2021–2051 and 2071–2100) compared to the western part of the CR (LYS and PLB – a decrease of only 6 and 9% in 2021–2051 and 2071–2100).

Most of the catchments will exhibit summer runoff decreases in both future periods. This is in good agreement with previously published projections (Hurkmans *et al.* 2010; Benčoková *et al.* 2011a; Němečková *et al.* 2011; Hanel *et al.* 2012). The difference at the LIT catchment, showing a rather slight improvement in some months (Figure 2), could be caused by the fact that the recent period used for comparison (2006–2012) included some very dry years (2007, 2008, and 2009) when the stream was dry for several months during summer and autumn. It is assumed that this catchment is highly sensitive to changes in seasonal precipitation distribution (Benčoková *et al.* 2011b) and therefore the projected increase in precipitation in some months (May and June by ~30%) can positively influence the flow pattern and shift the annual balance. However, in this catchment, similarly to other GEOMON catchments, significant droughts in late summer can also be expected (August and September), especially in the period 2071–2100. The inter-quartile range indicates that 75% of flows in these months will be extremely low (Figures 2 and 3).

The increase in winter runoff is rather small compared to some other studies showing future projections of runoff (Hurkmans *et al.* 2010; Benčoková *et al.* 2011a; Němečková *et al.* 2011). However, the results of Hanel *et al.* (2012) based on 15 regional climate model simulations were very variable in the case of winter runoff changes, and an increase was projected only for some isolated areas in the northern part of the CR by a majority of the scenarios used. Similarly, the projected increase in winter runoff for GEOMON catchments will be more affected by shifts in snow melt than changes in precipitation distribution.

Uncertainties in our study are associated with different sources including the emission scenarios, driving global climate model (GCM), RCM, correction of the RCM outputs, and finally the uncertainty in the hydrological model. The selected RCM Aladin-Climate/CZ has been tested and utilized for application in the area of the CR (Farda *et al.* 2010; Štěpánek *et al.* 2011b), and the model outputs were statistically corrected according to observed values (Dequé 2007). However, the selection of only one scenario with a single GCM forcing can be a major source of uncertainty in our future projections. Estimation of the magnitude of possible uncertainties was beyond the scope of the present study.

CONCLUSION

General patterns in runoff (annual as well as monthly) for the period 1994–2011 were not found across the GEOMON network, indicating that the catchments have not yet started to react to climate changes such as the temperature increase documented in the CR.

The future annual runoff was projected using the combination of the Aladin-Climate/CZ regional climate model forced by the SRES A1B scenario and BROOK90 hydrological model. Anticipated climate change is expected to result in annual decreases in runoff by 15% (2021–2050) and 35% (2071–2100), with significantly pronounced decreases in summer months and slight increases in winter months.

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