

Episodic runoff generation at Central European headwater catchments studied using water isotope concentration signals

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Abstract: Hydrological monitoring in small headwater catchments provides the basis for examining complex interrelating hydraulic processes that govern the runoff generation. Contributions of different subsurface runoff mechanisms to the catchment discharge formation at two small forested headwater catchments are studied with the help of their natural isotopic signatures. The Uhlirská catchment (Jizera Mts., Czech Republic) is situated in headwater area of the Lusatian Neisse River. The catchment includes wetlands at the valley bottom developed over deluviofluvial granitic sediments surrounded by gentle hillslopes with shallow soils underlain by weathered granite. The Liz catchment (Bohemian Forest, Czech Republic) is situated in headwater area of the Otava River. It belongs to hillslope-type catchments with narrow riparian zones. The soil at Liz is developed on biotite paragneiss bedrock. The basic comparison of hydrological time series reveals that the event-related stream discharge variations at the Uhlirská catchment are bigger and significantly more frequent than at Liz. The analysis of isotope concentration data revealed different behavior of the two catchments during the major rainfall-runoff events. At Uhlirská, the percentage of the direct runoff formed by the event water reaches its maximum on the falling limb of the hydrograph. At Liz, the event water related fraction of the direct outflow is maximal on the rising limb of the hydrograph and then lowers. The hydraulic functioning of the Uhlirská catchment is determined by communication between hillslope and riparian zone compartments.

Keywords: ¹⁸O isotope; Headwater catchment runoff; Subsurface runoff; Tracer; Rainfall-runoff episodes.

INTRODUCTION

The rainfall-runoff dynamics and runoff generation processes represent an area of research with continuous development (e.g., Lamacova et al., 2014; Wenninger et al., 2008). Progress in the use of environmental tracers in hydrology significantly enhanced understanding of hydrological processes at hillslope and catchment scale. Specifically, studies based on isotopic (stable water isotopes, e.g., Dincer et al., 1970) and geochemical (major cations and anions, e.g., Pinder and Jones, 1969) tracers revealed a substantial role of the subsurface flow contribution to runoff events, which partly contradicted the traditional concept of the runoff formation. Typically, groundwater mixing and residence times are studied by isotopic tracers (e.g., Maloszewski and Zuber, 1996; McGuire and McDonnell, 2006). Recently, concurrent use of isotopic and geochemical tracers has been found helpful in identification of subsurface mixing mechanisms (e.g., Glynn and Plummer, 2005; Kirchner et al., 2010). In temperate boreal headwater catchments, the mixing was found to take place mostly in riparian zones (Burns et al., 2003), including wetlands (Kurtz et al., 2007). McGlynn et al. (2003) studied riparian and hillslope zone contributions, they concluded that riparian water dominated between events, throughout small runoff events, and during early portions of large events. Later, Zuecco et al. (2015) presented a method for the quantitative description of the hysteretic behavior of runoff water chemical/isotopic composition at the event timescale suitable for automatic classification. They recognized eight types of hysteretic loops including two basic clockwise and anticlockwise patterns.

Tesar et al. (2004) examined relations between the soil water regime and runoff formation at the Liz catchment. They identified two distinct zones, a shallow soil profile and a deep drainage layer, each with specific rainfall-runoff transformation

mechanisms. First, rainwater moves vertically through the soil to recharge the drainage layer, then water flows on the surface of sloping less permeable horizon to the stream. The relative importance of both mechanisms during runoff formation changes according to the actual soil water conditions, which results in accumulation and percolation phases of the catchment runoff. Regarding the percolation phase, Tesar et al. (2004) proposed that instability driven flow mechanism could be responsible for sudden rapid vertical transport of water to the drainage layer and subsequently to the stream. The manifestation of such mechanism at the catchment scale is similar to the threshold behavior related to bedrock topography control mechanism (known as fill and spill behavior, Tromp-van Meerveld and McDonnell, 2006). Weekly monitoring of the stable ¹⁸O isotope in water at the Liz catchment was established in 2009 (Urban, 2014). This data set has not been thoroughly examined yet. Effect of the analysis could be enhanced by confrontation with results from more intensely studied catchment Uhlirská.

The first studies dealing with runoff formation at Uhlirská (e.g., Cislérova et al., 1998; Sanda and Cislérova, 2009) highlighted the correlation between the hillslope soil moisture and subsurface runoff and the total outflow from the catchment. Based on multiple regression analysis, Hrnčíř et al. (2010) presented dynamic thresholds of rainfall totals controlling the magnitude of stormflow at hillslope and catchment scales. Sanda et al. (2009) analyzed a selected summer stormflow episode using water isotopes and SiO₂. The separation of the catchment hydrograph revealed a significant pre-event water component (more than 75%), whereas the subsurface stormflow from the shallow soil at the hillslope transect contained about 50% of the pre-event water. These results accent importance of the water mixing within the soil profile as well as the role of the

near-stream zones and/or valley aquifer in the catchment-scale runoff generation.

Stable isotopes and SiO₂ content in the outflow from the hillslope transect and streamflow at Uhlirška were analyzed for a set of 20 rainfall-runoff events by Sanda et al. (2014). The results indicate that the rising limb of the outflow hydrograph at the hillslope trench scale is dominated by event water via fast preferential flow while at the catchment scale the rise of the stream discharge is dominated by pre-event water. The general concept of runoff formation presented by Sanda et al. (2014) includes the rainwater recharging the hillslope groundwater which subsequently contributes to the groundwater in the granitic sediments below Histosols in a riparian wetland. Alternatively, the subsurface runoff from the shallow hillslope soil is conducted in both man-made and natural surface channels to the stream. All studies reveal that Uhlirška catchment represents a catchment type with a significant effect of valley aquifer (i.e., so-called groundwater supplied wetland).

Blazkova et al. (2002) applied simple hydrological model TOPMODEL to predict water table levels at Uhlirška. Major runoff mechanism contributing to a rapid surface runoff in the model were variable source areas in the valley. Vogel et al. (2010) used the model based on Richards' equation for vertical soil water flow and the advection-dispersion equation for transport of the stable isotope to study the role of preferential flow in the formation of shallow subsurface runoff at the hillslope. The applied modeling approach explained the process of mixing between the new rainfall-event water and the old pre-event water reasonably well and confirmed the critical importance of the preferential pathways for the formation of subsurface runoff at the hillslopes. In the follow-up modeling study, Dusek et al. (2012) estimated that the pre-event water forms 47–74% of the subsurface runoff (which is in good agreement with experimental results of Sanda et al., 2009).

Finally, Dusek and Vogel (2016) concluded on the basis of simulation results that there is no single-valued rainfall threshold for the activation of preferential flow and initiation of stormflow at Uhlirška. The rainfall amount needed to initiate stormflow varied, depending greatly on initial hillslope saturation, initial spatial distribution of soil water, and rainfall distribution in time.

The current study aims (i) to compare results of long-term isotope sampling conducted at two forested headwater catchments in Central Europe, (ii) to analyze contribution of event and pre-event water to the catchment direct outflow, and (iii) by confronting results from the two catchments, to gain new insight into the role of different runoff mechanisms in the stream discharge formation at the headwater catchments of interest.

MATERIAL AND METHODS

Liz catchment

Liz catchment (average altitude 941 m a. s. l.; average annual temperature 6.3°C; average annual precipitation 861 mm; and drainage area 0.99 km²) lies in the south-western part of the Czech Republic in the Bohemian Forest. The catchment belongs to hillslope-type catchments with negligible influence of riparian zones. The soil type is the oligotrophic forest Eutric Cambisol developed upon biotite paragneiss bedrock. The catchment is fully covered by acid spruce-beech forest. The majority of trees are 94 years old with a height of about 28 m and a diameter of about 40 cm. Two automatic monitoring stations (in an open area and at the spruce forest bottom) for continuous measurements of air and soil temperatures, soil water pressure, and soil water content are operated. In order to

describe the variability of the soil water regime in the catchment, four additional automatic soil-water monitoring stations have been set at sites with different vegetation cover and altitude. Precipitation is measured in both the open area and the spruce and beech forest (throughfall and stemflow). Stream discharge is recorded in the closing profile of the catchment.

Uhlirška catchment

Uhlirška catchment is located in the Jizera Mountains, northern Bohemia (819 m a. s. l.; 4.7°C; 1400 mm; 1.78 km²). Deluviofluvial granitic sediments in the valley bottom areas (riparian zones/wetlands) are surrounded by gentle hillslopes with shallow soils developed on crystalline bedrock. The soils at hillslopes are shallow sandy loams classified as Cryptopodzols and Podzols. A sharp transition to the bedrock starts at the depth of about 70 cm. Histosols are typical for the bottom of the valley with groundwater-supplied wetland. Headwater regions in the Jizera Mts. represent a typical Central European temperate boreal zone with a large amount of precipitation, humid climate, and a recent history of nearly complete deforestation due to acid rain in the 1980s and 1990s. At present, the Uhlirška catchment is covered mostly with sparse young forest dominated by spruce trees (22 years old and the average height of 15 m). Forest openings are covered mainly with grass (height about 30 cm). The catchment has been equipped with an extensive monitoring and sampling network. Monitored variables include soil water pressure and soil water content, air and soil temperatures, atmospheric pressure and humidity, net radiation, wind velocity, precipitation, sap flow in spruce trees, subsurface runoff and stream discharge at the catchment outlet. Several perennial groundwater boreholes are also monitored.

Sample collection

The present study utilizes the ¹⁸O-isotope data measured at Liz and Uhlirška catchments over the period of 2009–2015 and 2016–2015, respectively. The δ¹⁸O values were determined for (i) precipitation collected from the rain gauges (or from snowfall and snowpack samples during winter), (ii) groundwater collected from wells and a spring, and (iii) stream water collected at the watershed outlets.

At the Liz catchment, the precipitation samples were collected as weekly cumulative samples (rainfall during vegetation season and snow during winter). In order to minimize the evaporation from the free water level of a sample, a few oil droplets were added to the collecting bottle. During the winter seasons, precipitation samples were collected using a storage gauge. The stream water at the outlet section and the spring was sampled weekly; the instantaneous samples were taken manually.

At the Uhlirška catchment, the precipitation sampling frequency during vegetation season was related to the precipitation intensity; the samples were collected at daily intervals, provided that the amount of rainfall since the previous sampling had exceeded 5 mm. During winter, weekly cumulative precipitation was sampled using a storage gauge. The stream water at the catchment outlet section was sampled daily using an automatic sampler (ISCO Teledyne Technologies, Inc.). Sampling became more frequent during major rainfall events (6-hour interval). The groundwater in four groundwater boreholes was sampled monthly; the instantaneous samples were collected manually.

Isotope analysis

Liquid water isotope analyzer (LWIA) utilizing the principle of laser spectroscopy (LGR Inc., 2nd generation) for determination of stable isotope concentrations (¹⁸O and ²H) was used. The ¹⁸O content was measured with the manufacturer declared precision of $\delta^{18}\text{O} \pm 0.2\text{‰}$. The $\delta^{18}\text{O}$ values (given in parts per thousand) represent relative deviations of the measured ¹⁸O/¹⁶O ratios from the isotopic composition of the Vienna Standard Mean Ocean Water (V-SMOW).

RESULTS AND DISCUSSION

Basic hydro-meteorological time series analysis

Runoff dynamics of the two catchments differ obviously (Fig. 1, note the difference in vertical axes scales). At Liz, only a limited number of significant precipitation or snowmelt events induce substantial discharge reaction accompanied by clearly detectable baseflow increases (represented by the lower envelope of the discharge series). Otherwise, the regular precipitation induces minute variations of the catchment discharge. At Uhlirska, the stream reacts more vividly to precipitation. The scale of the event-related stream discharge variations is about five times bigger than at Liz (considering the specific discharge). Regarding the baseflow dynamics, the range of the specific discharge variations is about the same as at Liz, but the time scale of baseflow decline is shorter at Uhlirska. At the same time, a higher frequency of baseflow recharge at Uhlirska is likely related to the more plentiful precipitation input at this catchment.

Autocorrelation functions (ACF) of daily average outflow data series (Fig. 2) illustrate different outflow regime of the two catchments under study. The longer ACF relaxation time found at the Liz catchment reflects the dominance of the slow, baseflow-related runoff processes at this catchment. In consequence, isotopic signature of few major rainfall events can be found in the streamflow isotopic data despite relatively low sampling frequency (once a week). For Uhlirska, the shorter ACF time exposes significance of the fast outflow processes in the stream discharge formation. Moreover, the absence of seasonal autocorrelation component at Uhlirska also indicates highly event-dominated stream flow dynamics. On the other hand, distinct seasonal autocorrelation fluctuation detected for the Liz catchment further supports the significance of baseflow-related runoff process and stable seasonal pattern of groundwater recharge.

Isotope concentration data analysis

The two principle factors that control the isotopic content of precipitation are the temperature of condensation of the precipitation and the degree of a rainout of the air mass. Local water meteoric lines (LWML) of both sites differ from Global meteoric water line (Craig, 1961) in both slope and deuterium intercept (Fig. 3). However, the slope differences of -0.18 and -0.24 are not uncommon (Holko et al., 2012). In general, LWML's are very similar, thus, both catchments receive isotopically equivalent rainfall/snowfall input.

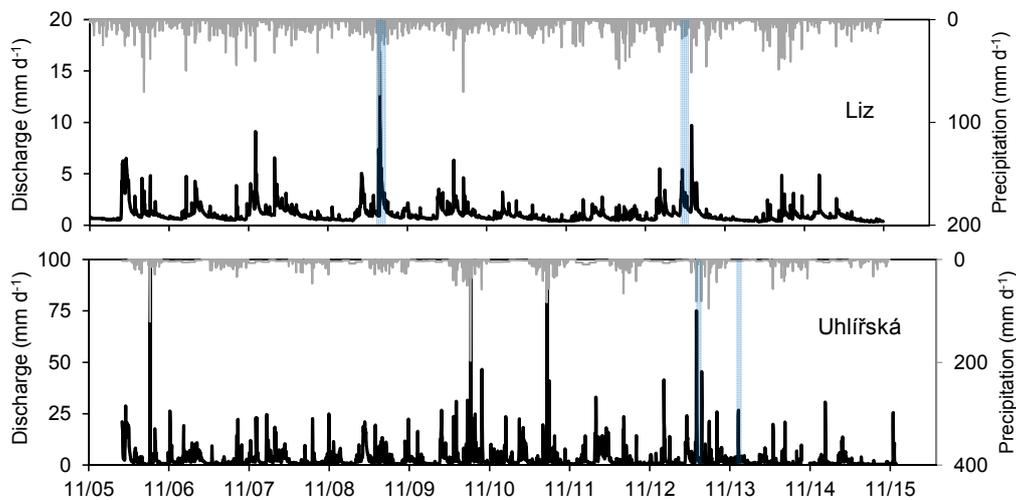


Fig. 1. Daily precipitation and daily specific discharge at Liz and Uhlirska (monthly precipitation averaging for Uhlirska during winter). Highlighted rainfall-runoff episodes are later used for detailed analysis.

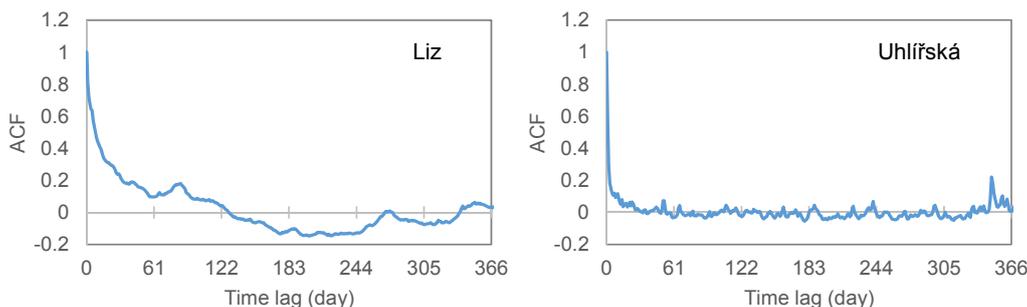


Fig. 2. Autocorrelation function (ACF) of stream discharge data (daily averages from 2007–2014).

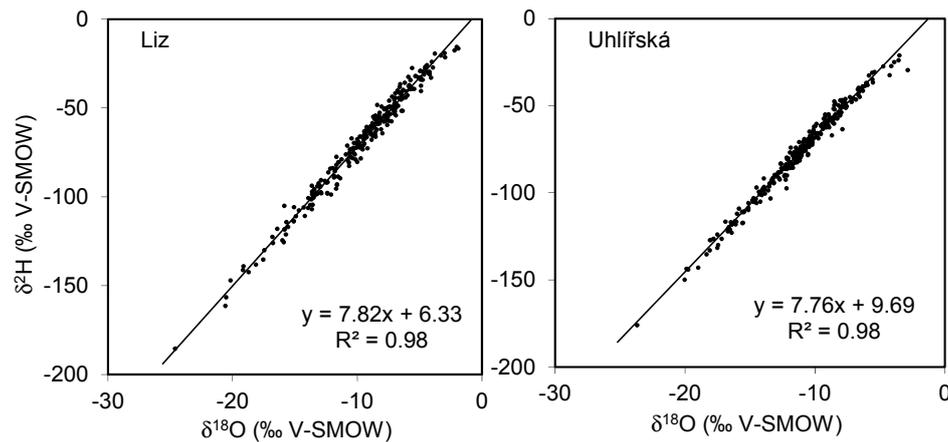


Fig. 3. Local meteoric water lines defined by the isotopic composition of precipitation. Isotope concentrations presented were measured in 2009–2015 for Liz catchment (weekly composed precipitation), and in 2006–2014 for Uhlirská catchment (monthly composed rainfall in summer and weekly composed precipitation in winter).

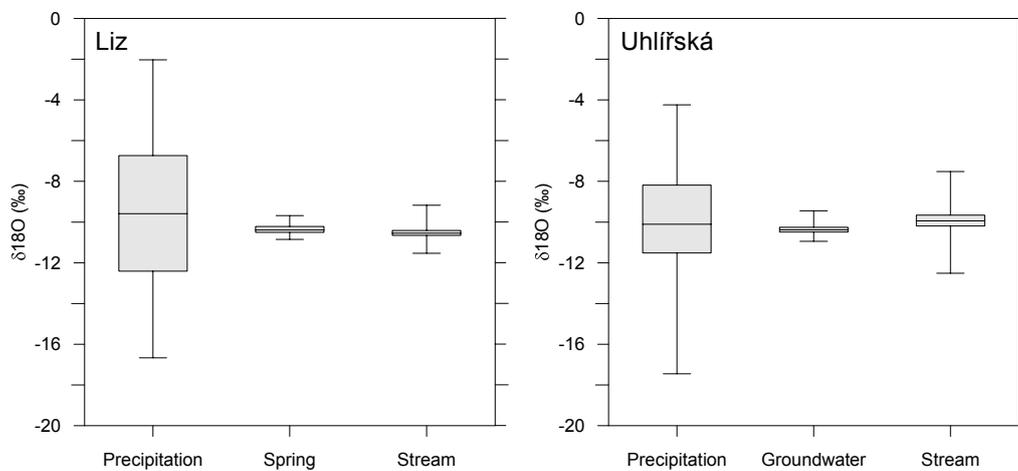


Fig. 4. $\delta^{18}\text{O}$ of water samples collected in both catchments – precipitation, groundwater/spring water, and surface water in the stream. For each dataset, median, lower and upper quartile, and extremes are displayed. Data covering full hydrological years (Liz 2010–2015 and Uhlirská 2007–2015) were included. Monthly cumulative samples of precipitation, weekly instantaneous samples of stream water and spring (Liz), and monthly instantaneous samples of groundwater at (Uhlirská) are presented.

Fig. 4 provides an overview of isotopic composition variability of water samples taken from three main hydrological compartments – precipitation, groundwater/spring water and stream. A similar trend in variability is obvious in both catchments. The interquartile range of precipitation data is five to ten times bigger than that of stream water data. The high variability of precipitation isotopic concentration reflects seasonal fluctuation (monthly samples are presented); summer precipitation is isotopically heavier ($\delta^{18}\text{O}$ value is higher, meaning the heavy water deficit is smaller), winter precipitation is isotopically lighter ($\delta^{18}\text{O}$ value is lower). The stable values observed in groundwater, spring and stream are related to mixing of water with various residence times within the catchment (contribution of various runoff pathways).

Comparing both catchments, a higher isotopic variability of the monthly precipitation was observed at Liz. A lower median value of $\delta^{18}\text{O}$ concentrations in precipitation was detected at Uhlirská, which is in accord with a general finding that greater amount of rainfall received (1400 mm/year for Uhlirská and 861 mm/year for Liz) and higher altitude (difference in site's altitudes about 122 m) are often associated with lower $\delta^{18}\text{O}$ and $\delta^2\text{H}$ values of the liquid forms of precipitation (Dansgaard, 1964; Kendall et al., 1995).

Variability of $\delta^{18}\text{O}$ concentrations in the catchment discharge is considerably higher at Uhlirská, which reflects the intensive contribution of fast event-water runoff.

For the Liz catchment, the median of the isotopic composition of precipitation (-9.59‰) is significantly higher than median values of spring and streamflow (-10.39‰ and -10.54‰). This is probably due to the transpiration loss reducing the amount of isotopically heavier summer precipitation water available for groundwater recharge. Thus, streamflow is predominantly generated from well-mixed groundwater reservoir recharged mostly by isotopically lighter winter precipitation (during snowmelt events). At the same time, the stream water at the catchment outlet section is isotopically lighter than at the spring, while the interquartile range stays unchanged. Thus, it seems that relative contribution of isotopically lighter winter precipitation grows along the stream.

For the Uhlirská catchment, the $\delta^{18}\text{O}$ median of groundwater (-10.38‰) is lower than the median of the precipitation (-10.10‰). This accords with the hypothesis that groundwater origins mainly from isotopically lighter winter precipitation, (intensive groundwater recharge during snowmelt events). However, in contrast to Liz, the $\delta^{18}\text{O}$ median of stream water (-9.94‰) is slightly higher than that of precipitation. Overall higher $\delta^{18}\text{O}$ values in stream water compared to groundwater

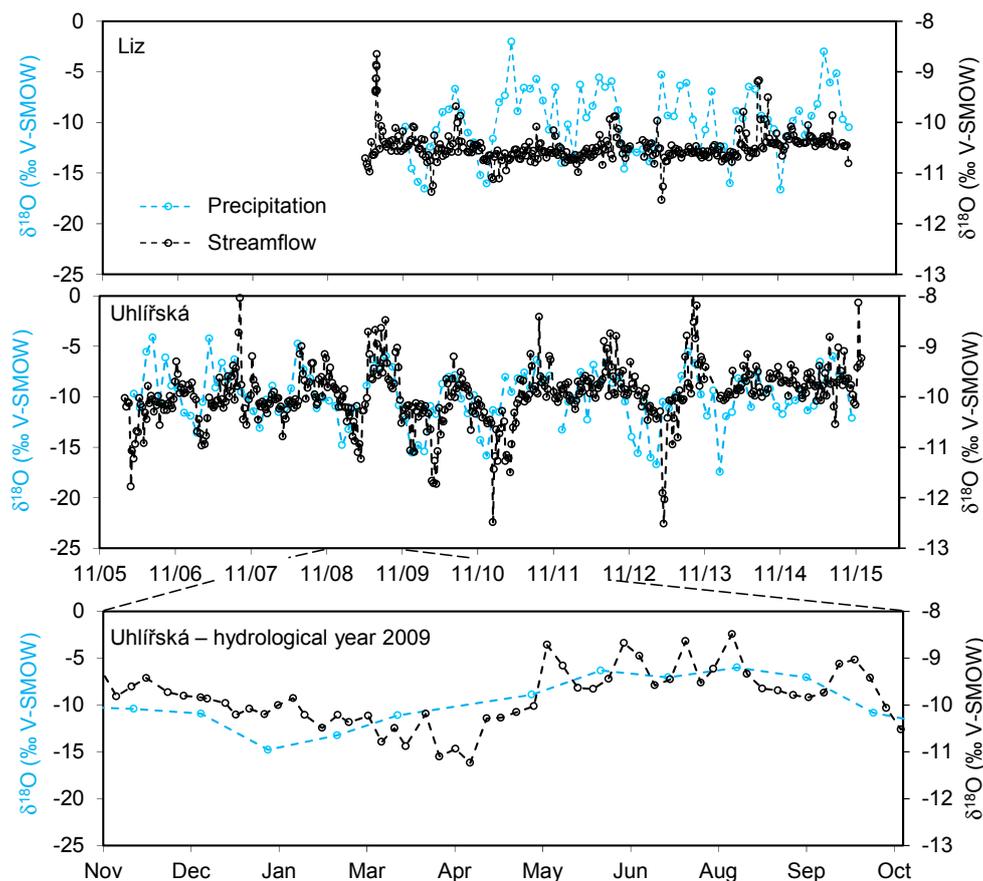


Fig. 5. Time development of isotope concentrations at both catchments (Liz and Uhlirská). Different scales are used for precipitation and streamflow data. The bottom panel shows data observed at Uhlirská during the hydrological year 2009 in detail.

can be explained by high frequency of rainfall-runoff events with substantial contribution of event water to direct runoff during summer. This result may be partly influenced by the fact that discontinuities in the stream water sampling at Uhlirská are more frequent during winter time (e.g., no data for December 2013).

Temporal variation of the isotopic composition of precipitation and catchment discharge is presented in Fig. 5. Intensive isotopic signal attenuation between precipitation and discharge is observed at both catchments (note different concentration scales for precipitation and discharge). Obviously, considerably stronger transformation occurs at Liz (Fig. 5), where the isotopic signature in streamflow is almost stable, defining a clear curve of slight seasonal variations. Only a few episodes of outflow with the contrasting isotopic composition can be detected.

At Uhlirská (Fig. 5), the variability of isotopic concentration in discharge is markedly greater in both components, seasonal and episodic. Moreover, the episodic variations are more frequent. The data show a high degree of similarity between time series of isotopic concentration in precipitation and streamflow. Seasonal variations of both are closely related; note, for instance, the absence of a distinct isotopic decline in winter 2011–2012 observed in both data series. Fast response to isotopically heavy summer storms (stream maxima during summer) and postponed reaction to winter isotopically light precipitation (stream isotopic minima related to snowmelt events, mostly during spring) are illustrated by the 2009 data in Fig. 5.

The abnormally low amount of snow during two consecutive winters 2013–2014 and 2014–2015 induced increasing role of isotopically heavy summer precipitations in the discharge,

which is apparent at both catchments (Fig. 5). Stream water in the hydrological years 2014 and 2015 was isotopically heavier by 0.16‰ at Liz and by 0.35‰ at Uhlirská in average than during four previous years.

Residence times

Previously, based on observed seasonal isotopic variations in precipitation, discharge, and groundwater, Sanda et al. (2014) evaluated residence times of water in the Uhlirská catchment. Their approach (based on the methodology of Maloszewski and Zuber, 1996) relied on crude simplification of the runoff processes, considering the exponential distribution of residence times and invariable input of water in time (constant precipitation intensity with variable isotopic composition). Mean residence time was then determined based on attenuation of the seasonal variation of isotope concentration between the input water (i.e. precipitation) and water leaving the system (i.e. groundwater or stream water). The resulting mean residence time was greater than 5 years for water recharging the groundwater at the valley bottom, about 12 months for water forming the baseflow, and 4.4 months for any water contributing to the stream discharge at the catchment outlet.

Applying the same methodology to Liz, Urban (2014) estimated mean residence time of the whole catchment to be 3.46 years but at the same time concluded that water residence time is significantly uncertain because of the low isotopic variability of stream discharge.

However, the meaning of the obtained residence times is questionable. For example, it is clear that the water input inten-

sity has seasonal variations which not only cause a discrepancy between the mean isotopic composition of the precipitation and the mixed water at the output but also reduces the amplitude of the output isotopic signals. The consequence is an overestimation of the mean residence time determined. Other assumptions, such as linearity and homogeneity of the system, are violated too. Recently, Kirchner (2016a, 2016b) proposed the young water fraction as a better measure of transit times, which is more appropriate for spatially heterogeneous catchments. However, advanced analysis of the catchments' transit times is outside the scope of the present study.

Event water contribution to direct runoff

For each catchment, two significant rainfall-runoff episodes were selected with contrasting isotopic composition of the input water (rainfall or snowmelt) (Table 1). The input water was either isotopically heavy, causing increase of $\delta^{18}\text{O}$ in stream, or

isotopically light, causing decrease of $\delta^{18}\text{O}$ in stream. The isotope concentration in the stream was used to evaluate the contribution of the event water (water from the incident precipitation or snowmelt, "new water") to the catchment discharge. Plots of the isotopic composition of stream water as a function of the stream discharge illustrate the development of the "new water" relative contribution during the runoff event (Figs. 6 and 7). For this purpose, the episodes had to be clearly separated from previous runoff events and the isotopic composition of their incident rainfall had to be approximately uniform (the latter requirement is often difficult to meet). To calculate relative contribution of the "new water" to the catchment discharge presented in Table 1, the stream water was assumed to be a simple mixture of "new water" and of the water present in the catchment before the episode (pre-event water, "old water"). The isotopic composition of "old water" contributing to the outflow was assumed constant throughout the runoff episode (defined by the initial stream water isotope content).

Table 1. Characteristics of rainfall-runoff events. Symbol ϕ stands for the runoff coefficient (runoff amount divided by precipitation amount).

		Initial streamflow		Incident precipitation		Discharge		New water runoff		New water in discharge	
		disch.	$\delta^{18}\text{O}$	amt.	$\delta^{18}\text{O}$	amt.	ϕ	amt.	ϕ	max.	cumul.
		(mm/d)	(‰)	(mm)	(‰)	(mm)	(%)	(mm)	(%)	(%)	(%)
Liz	22/6–14/7 2009	0.88	-10.59	275.5	-6.93	144.7	53	38.2	14	53	30
	8/4–6/5 2013	0.92	-10.52	154.9	-12.06	73.4	47	27.2	18	66	37
Uhlirska	21/6–30/6 2013	1.01	-10.07	145.5	-12.37	96.9	67	18.9	13	41	19
	2/9–9/9 2013	0.93	-9.76	84.9	-4.56	45.1	53	19.3	23	57	43

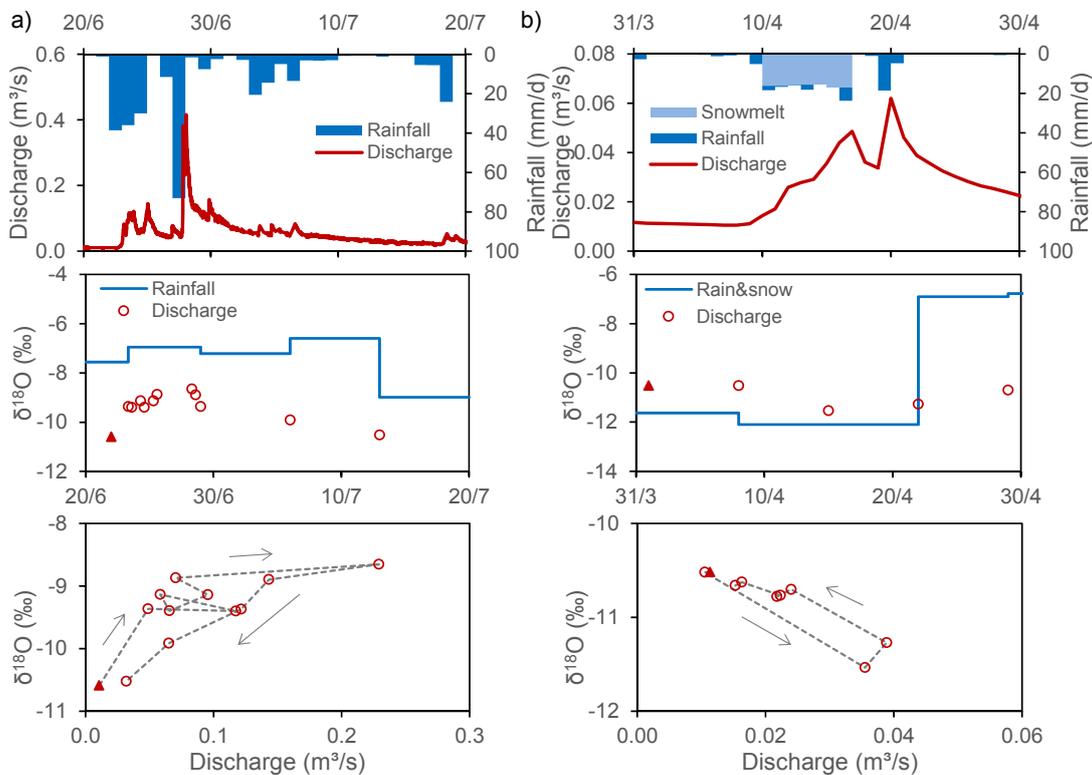


Fig. 6. Selected major runoff events at the Liz catchment induced by (a) isotopically heavy rainfall and (b) isotopically light snowmelt: incident precipitation/snowmelt intensity and stream discharge; ^{18}O concentration in precipitation/snowmelt and streamflow; streamflow isotopic composition as a function of the stream discharge. The initial (background) value of ^{18}O concentration is marked with a triangle.

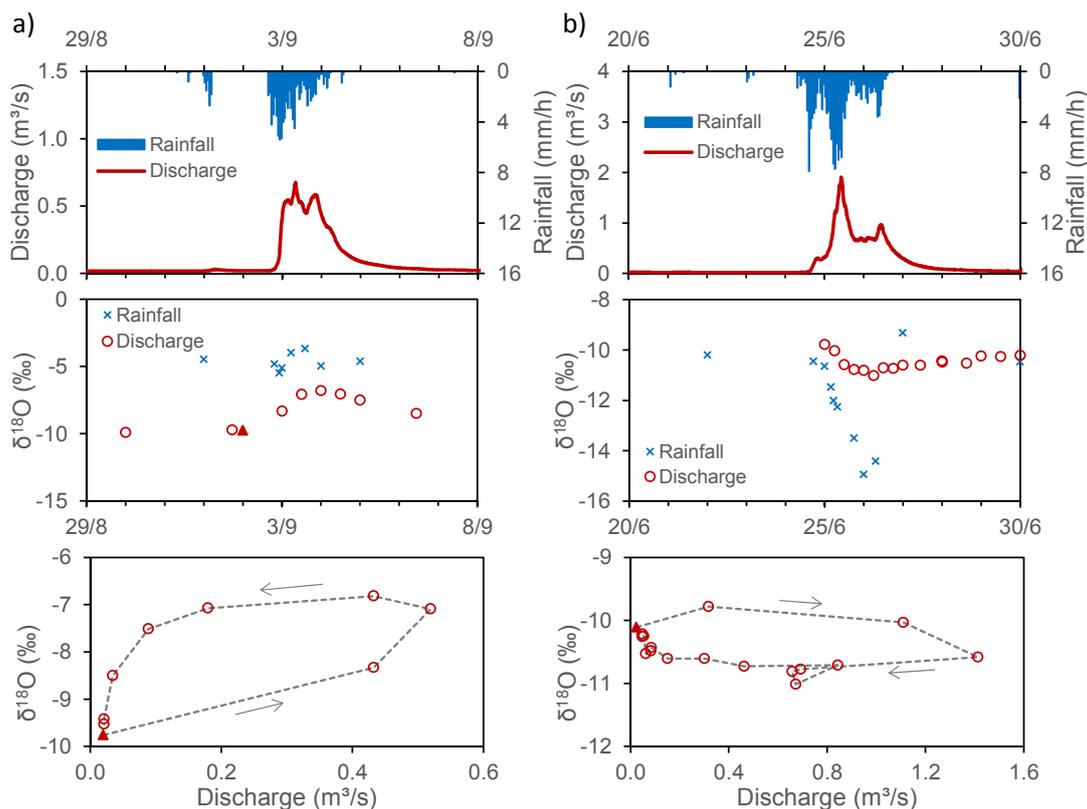


Fig. 7. Selected major runoff events at the Uhlirska catchment induced by (a) isotopically heavy rainfall and (b) isotopically light rainfall: incident precipitation intensity and stream discharge; ^{18}O concentration in precipitation and streamflow; streamflow isotopic composition as a function of the stream discharge. The initial (background) value of ^{18}O concentration is marked with a triangle.

For Liz catchment, a clockwise hysteretic relationship between the stream discharge and its isotope concentration was identified during the isotopically heavy outflow event (Fig. 6a) and a counterclockwise relationship during the isotopically light event (Fig. 6b). These results imply that the relative portion of the event water in the catchment discharge is greater during early phases of the runoff events (considering the constant isotopic composition of both the rainfall/snowmelt water and the catchment “old water”). Unfortunately, the available data do not provide more episodes suitable for this kind of analysis (weekly sampling does not capture development during standard runoff episodes).

Opposite behavior was detected at Uhlirska: a counterclockwise hysteretic relationship between the stream discharge and its isotope concentration was identified above isotopic mean and clockwise relationship below the mean (Fig. 7). Thus, the percentage of the “new water” in the catchment discharge is greater during the later stages of the runoff event, on the falling limb of the hydrograph. This behavior was identified during the majority of rainfall-runoff episodes observed at Uhlirska (for example 18 out of 20 episodes studied by Sanda et al., 2014) and thus, can be assumed characteristic. The implied reason for this behavior is, paradoxically, that the pre-event water reaction to the rainfall event is faster than the direct runoff of new water. The mechanism leading to this fast response of the pre-event water has yet to be explained.

Assuming simple mixing of water from two isotopically stable sources, an approximate separation of the event water from the baseflow can be done. The results are summarized in Table 1. The limited number of studied episodes hinders any sophisticated reasoning regarding differences between the catchments or the impact of initial conditions or incident rain-

fall/snowmelt intensity or volume. It can be argued that at both catchments only less than 25% of the rainfall/snowmelt contributed to the direct runoff. This new water represented less than 50% of the cumulative discharge of each episode (19–43%). The maximum observed an instantaneous fraction of the new water in the discharge was 66%.

Direct runoff formation mechanisms

Contrasting results for the two catchments are related to differences in their geomorphological character. The Liz catchment is formed by a hillslope with the base at the stream. The stream baseflow is supplied from an unconfined aquifer. The Uhlirska catchment is more complicated, with hillslopes separated from the stream by wetlands in the valley bottom. The stream baseflow is supplied mostly from shallow groundwater of the wetland, which is recharged partly by rainfall and direct hillslope runoff, and partly by the deeper (semi)confined aquifer.

The phenomenon of fast activation of the pre-event water in the direct runoff observed in the stream at Uhlirska has been described by Sanda et al. (2009). The geochemical composition of subsurface hillslope discharges observed in the trench at Uhlirska (Sanda et al., 2014) reveals an opposite behavior, i.e. decreasing contribution of the event water during the runoff episode (slow activation of pre-event water). This finding was related to the preferential flow in the soil profile. Sanda et al. (2014) concluded that at the scale of the catchment, preferential flow effects are overridden by displacement of pre-event water from the hillslope soil matrix.

The fact that the same behavior (slow activation of pre-event water) is observed at the Liz catchment is interesting. It implies

that the catchment direct runoff at Liz may be governed by similar processes as the episodic runoff from the soil profile observed at Uhlirška. Another similarity of the Liz catchment with the hillslope at Uhlirška can be found in the frequency of the significant direct runoff events observed.

The dominant role of the water originating at the hillslope in the stream discharge at Uhlirška was assumed based on a comparison of the dynamics and volumes of discharge observed at both scales (Sanda and Cislerova, 2009). However, the source of the pre-event water dominating the catchment outflow at the beginning of the runoff events may be different. It is possible, that the preferential flow of the event water detected in the experimental trench is characteristic of the whole hillslope and the fast pre-event water mobilization is produced within the wetland zone separating the slopes from the stream. Considering the two catchments under study, the presence/absence of riparian zone with wetlands is a marked difference that may underlie the dissimilarities in the runoff formation.

Comparison with results found at other sites

Wetlands play an important role in runoff-generation mechanism in headwater catchments around the world (e.g., Camacho Suarez et al., 2015; McCartney et al., 1998). Bullock and Acreman (2003), in their review, concluded that the impact of these regions on flood flow formation was ambiguous. They also stated that headwater wetlands tend to be saturated, thus causing quick responses of recipients to rainfall, which is in agreement with our observations at Uhlirška (faster response of the riparian zone at the Uhlirška catchment vs. more gradual response of the wetland-free catchment Liz). In our opinion, some of the ambiguous results reported for wetlands in the literature could be attributed to different local topography and soil conditions.

In the present study, similarly to Tetzlaff et al. (2009) or Hrachowitz et al. (2009), using long-term tracer data at two contrasting catchments helped to examine the relative influence of topography on runoff formation. Our finding that the pre-event water dominates the catchment streamflow discharge at the beginning of runoff events at Uhlirška is consistent with the working hypothesis of Stockinger et al. (2014) formulated for the Wüstebach catchment according to which pre-event water stored in the riparian zone gets activated fast during an event as it does not need to travel far.

CONCLUSIONS

Natural stable isotope tracer was used to study the water movement in the small experimental catchments Liz in the Bohemian Forest and Uhlirská in the Jizera Mountains, Czech Republic. Comparison of the data exposes differences in the runoff formation at these two catchments, improving our understanding of their hydrological functioning.

The two catchments exhibit different hydrological behavior. Liz is a simple hillslope-type catchment with baseflow-dominated stream discharge. At Uhlirška, hillslope parts are combined with wetlands in the valley bottom, and the stream discharge is strongly affected by rainfall-runoff events. While the baseflow discharge variations are similar in both catchments (considering the specific discharge values), the event-related stream discharge variations at the Uhlirška catchment are about five times bigger and significantly more frequent than at Liz.

The different character of the stream discharge response to rainfall events is reflected also in the different dynamics of the

stream isotopic composition variations. Considerably less variable series was obtained at the Liz catchment outlet, where the isotopic signal is almost stable, containing only a few events with contrasting isotopic composition.

Contrasting hydraulic behavior of the two catchments during the major rainfall-runoff events was disclosed using simple baseflow separation method (assuming constant isotopic composition of old water). At Uhlirška, the percentage of the catchment direct runoff formed by the event water is greater during later stages of the runoff event (on the falling limb of hydrograph) than during the initial, rising-discharge stage. In contrast, at Liz, the event water related fraction of the catchment direct runoff is greater on the rising limb of the hydrograph and then lowers. Interestingly, the Liz catchment behavior is similar to the phenomena described previously for the hillslope runoff at the Uhlirška catchment. The difference between the hillslope and stream at Uhlirška is likely related to hydraulic functioning of the riparian wetland. Summarizing findings for both catchments, only less than 25% of the rainfall/snowmelt contributed to the direct runoff and this new water represented less than 50% of the event cumulative discharge.

To further improve understanding of hydraulic functioning of the Uhlirška catchment, more information about the hydraulic communication between hillslope and riparian zone compartments is needed.

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