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Seasonal subsurface water contributions to baseflow in the mountainous Uhlířská catchment (Czech Republic)

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Abstract: Nine years of seasonal $\delta^{18}O$ values in precipitation, soilwater and groundwater were evaluated in the Uhlířská catchment between 2008 and 2016 and recharge winter/summer ratios were calculated using $\delta^{18}O$ values. The longterm average ^{18}O content in groundwater is lower than the mean weighted ^{18}O content in precipitation. This is explained by more than 50% of winter- and snowmelt- induced groundwater recharge that occurs in all years except of 2010 and 2013. The recharge of the peat organic soil water is balanced between summer and winter, whereas the mineral hillslope soil is dominantly recharged by summer precipitation. The 67% portion of baseflow, dominantly generated in the winter season, is composed of groundwater and peat organic soil water, according to the hydrochemical distribution of runoff components. Isotopic mass balance of individual winters shows that precipitation in warmer winters is entirely transformed into outflow until the end of the winter season, generating no significant water storage for potential drought periods.

Keywords: ^{18}O isotope; Precipitation; Soil water and groundwater; Snowmelt/recharge ratios; Winter; Summer.

INTRODUCTION

The relation between snowmelt and groundwater recharge in catchments remains poorly understood. The role of groundwater in runoff generation (Sayama et al., 2011) and baseflow (Fenicia et al., 2006) is generally recognized and assessed in terms of temporally invariable tracer-derived groundwater residence times (McDonnell et al., 2010) and their links to spatial distribution of various geological, topographical and landscape characteristics (Cody Hale and McDonnell, 2016; Dóša et al., 2011; Soulsby et al., 2010). However, little has been carried out to understand the role of snowmelt in the groundwater recharge and, conversely, in the hydrological drought. This topic has become more popular in the hydrological research over the past years, being widely recognized crucial in the context of climate-induced shifts of the hydrological cycle and groundwater recharge (Van Loon and Laaha, 2015).

Despite these efforts, the spatial and temporal variability of snowmelt-induced groundwater recharge remains poorly understood. One of the reasons is that the simultaneous monitoring of snowmelt, runoff and groundwater and its isotopic or other tracer characteristics in catchments has been rare. The vast majority of catchment studies has considered the isotopic average content in streamwater as a catchment-average value, that is nearly equal to annual isotopic average content in precipitation and presumably also to the average isotopic content in groundwater. These assumptions are, however, rarely met; instead, the isotopic variations in streamwater often indicate catchment water residence times (Hrachowitz et al., 2009; Pfister et al., 2017) biased toward the faster runoff components, poorly addressing the residence time of the groundwater components (Kirchner, 2016).

The difference between average isotopic values of precipitation, streamwaters and groundwaters is very variable in time and space. It is widely accepted that groundwater recharge in temperate regions is generally stronger towards winter and snowmelt periods. Various studies (Earman et al., 2006; Penna et al., 2014) have revealed that more than 50% of recharge is generated by snowmelt. The strong contribution of snowmelt to groundwater in cold-temperate catchments has been also highlighted in stable isotope applications over the past decades to intuitively explain groundwaters depleted in ^{18}O and ^{2}H (Maulé et al., 1994; O'Driscoll et al., 2005; Šanda et al., 2014). In turn, the isotopically depleted groundwater recharge in tropical regions is typically explained by isotopic amount effect (Demlie et al., 2007; Lapworth et al., 2013) or paleoclimatic conditions (Jasechko et al., 2015). In an arid catchment, Turner et al. (1987) observed that the average stable isotope values in groundwater match the average values in streamwater. Reddy et al. (2006) have identified various site-specific relations between average isotopic values in streamwater and groundwater that were linked to various direct interactions between streamwater and groundwater. Darling et al. (2003) identified a winter-dominant groundwater recharge in sandstones, resulting in a depleted average isotopic content on groundwater compared to streamwater. In contrast, chalk aquifers did not show any winter groundwater recharge bias, presumably due to limited percolation of winter precipitation and snowmelt-induced water to recharge.

To assess the winter-summer groundwater recharge variations, Jasechko et al. (2014) have analyzed the long-term average spatial distribution of the isotope-derived groundwater recharge rates over a large set of Canadian and some selected worldwide catchments. They have proven that the isotopic groundwater depletion in the majority of temperate-humid catchments was dominantly associated with recharge of winter precipitation. However, little understanding exists of the temporal (annual and decadal) changes in the snowmelt induced groundwater recharge. This paper therefore explains, using readily available isotopic data in precipitation and groundwater, the seasonality of groundwater recharge in the well-instrumented mountainous catchment Uhlířská, over the 9-year period 2008–2016. The study is also part of the trinational initiative aimed at the snowmelt-recharge-drought assessment (Zappa et al., 2015).

STUDY SITE

The Uhlířská catchment is located in the Jizera Mountains near the northern border of the Czech Republic. Focus in this study is given to its subcatchment at the Porsche gauge profile (Fig. 1). It is a small (1,18 km^2) forested granitic headwater catchment with average altitude 822 m a.s.l. in cold humid climate, characterized by mean annual precipitation amount of 1300mm and mean annual temperature 4.7°C (Hrnčíř et al., 2010). Mineral soil hillslopes cover approximately 90% of the catchment area and their 0.6 - 0.9 m thick soil profile consists of highly permeable Dystric Cambisols, Podzols or Cryptopodzols (Nikodem et al., 2013). Wetlands along the stream course are formed by Histosol soil types. They are up to 3 m deep, with permeability values substantially lower as compared to the soils on the hillslopes (Šanda et al., 2014). Wetlands are located on a layer of sediments deposited in the catchment valley with a various depth reaching up to 50 m proven by geoelectrical resistivity measurements along the valley bottom and in perpendicular hillslope profiling. A more detailed recent description of the Uhlířská catchment can be also found in Šanda et al. (2014), Vitvar et al. (2016), Votrubova et al. (2017) and Jankovec et al. (2017).

Studies at Uhlířská using long term stable isotopes measurements (^{18}O) along with analysis of diluted SiO_2 proved that the wetland is predominantly groundwater-supplied, as its SiO_2 concentration is close to the range of SiO_2 concentration in the perennial groundwater (Šanda et al., 2014). Water in stream is partly supplied also with the event water component (direct flow), which is quickly transferred via upslope saturated soil-weathered bedrock interface. Recent works at Uhlířská revealed that the BFLOW approach to separate runoff components delivered about 67% of baseflow (Šanda et al, 2014), which corresponds with the inverse hydrochemical modelling approach NETPATH (Vitvar et al., 2016). This approach was employed in three scenarios on the October 2015 dataset, characterizing hydrological conditions close to the average discharge of about 38 l/s at the Porsche gauge profile. Carbon, sodium and ^{18}O were selected as model constraints in the mixing of initial waters (rain, mineral soils, peat soils, and wetland groundwater) towards the streamflow. The most reliable scenario distributed the runoff contributions among the wetland groundwater (28%), peat (42%) and mineral soil (23%) water and 7% rainfall. The sum of wetland groundwater and peatwater (about 70%) can be therefore considered as baseflow amount, corresponding to the 67% obtained by the discharge data approach BFLOW (Šanda et al., 2014; Vitvar et al., 2016).

MATERIAL AND METHODS

This study used ^{18}O data measured between the hydrological years 2008 and 2016 in precipitation, hillslope pore soil water (Cambisols, Podzols and Cryptopodzols) (further denoted as mineral soil water), valley peat pore soil water (Histosols) (further denoted as peatwater), shallow groundwater and streamwater. Soil water and groundwater is manually sampled in 1–2 month interval throughout the whole year, whereas streamwater is sampled weekly manually in winter period excluding snowmelt time (November–February/March). Streamflow is sampled once a day at midnight at low flows or every 6 hours (4times a day) during high flows (summer stormflow and snowmelt period, i.e. February/March–October) by carousel samplers at the Porsche profile (Fig. 1). Downslope Histosols and upslope Cambisols/Podzols in young and mature forest are instrumented with total of4pairs of suction cups (each pair of 30 and 60 cm depth), at two sites each (Fig. 1 shows pore water and ground water in one symbol due to their vicinity). The suction cups are emptied (vacuum of 600-700 mbar is applied for 24 hours) and closed. At the sampling time, they are depressurized and accumulated water sample are collected. Four shallow boreholes (2.4-5.2 m deep) of 40-50 mm in diameter are sampled is sediments below the Histosols. Boreholes are close to each other (distance below 50 m) along the mild hillslope transect covered by Histosols. Due to their low yield, the boreholes are fully emptied by peristaltic vacuum pump (maximum of 5 minute pumping) and left for 24 hours to refill. They are finally sampled with the same vacuum pump.

Monthly liquid total precipitation samples are collected manually by means of 24 cm wide funnel directed to 50 liter container located partly in the soil subsurface. A thin film of light oil is applied to prevent evaporation of collected precipitation. Solid precipitation is sampled manually in two replicates as weekly and monthly sample in two 10 cm wide and 100 cm long cylinders raised to 3 m height above the soil surface. The monthly ^{18}O contents in precipitation and streamwater are included in the global monitoring databases of stable isotopes in precipitation GNIP (IAEA/WMO, 2017) and in rivers GNIR (IAEA, 2017). The $\delta^{18}O$ values in water samples were obtained by means of the Czech Technical University in Prague (CTU) laser water isotope analyzer.

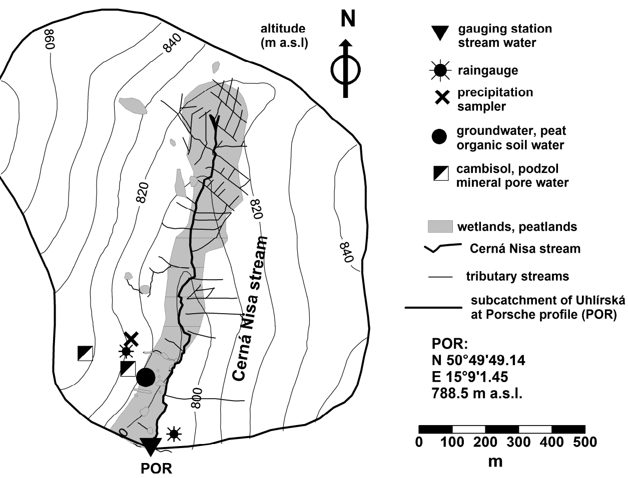

Fig. 1. The Uhlířská-Porsche catchment with location of sampling stations.

The isotope sampling in the Uhlířská catchment is supported by a wide hydrometeorological monitoring that was established in the 1980´s. The runoff gauge Porsche is gauging 2/3 of whole Uhlířská catchment (i.e. 1.18 km^2) and it is equipped with 120 degree open V-notch sensed by pressure transducer in 10 minute interval.

The $\delta^{18}O$ data interpretation was based on seasonal grouping of monthly $\delta^{18}O$ values from the principal compartments. The recharge index (after Jasechko et al., 2014) is expressed as

$$\frac{\left(R/P\right)_{winter}}{\left(R/P\right)_{summer}} = \frac{\left(\dfrac{\delta_{terrestrial\,(annual)} - \delta_{precip.(summer)}}{\delta_{precip.(annual)} - \delta_{precip.(summer)}}\right)}{\left(\dfrac{\delta_{terrestrial\,(annual)} - \delta_{precip.(winter)}}{\delta_{precip.(annual)} - \delta_{precip.(winter)}}\right)} \tag{1}$$

where *P* is precipitation, *R* is runoff, *terrestrial* is consecutively used for groundwater, mineral soil pore water or peat organic pore water, and *summer* and *winter* are average values for the months May–October and November–April, respectively. We are aware that this approach does not consider intra-seasonal isotopic differences such as isotopic content of melting snow during various phases of the snowmelt process.

The baseflow amount at the Porsche profile for the period 2008–2016 was obtained by three approaches: BFLOW tool (digital filter approach), the monthly minimum approach and the Kliner-Kněžek approach. The approach BFLOW (Arnold et al., 1995) analyses the frequency spectrum of daily hydrographs, associating long waves with baseflow and high-frequency variability with direct run-off. The Kliner-Kněžek approach (Kliner and Kněžek, 1974) applies the relationship between stream discharge and groundwater level in the nearby borehole P20 (2 m deep). The baseflow amount was computed in absolute volume values for a 6 month-period and not in percentages of daily total flow. We are aware that the seasonal stream baseflow amount is not necessarily equal to seasonal groundwater recharge amount. In this study we consider baseflow as seasonally generated mixture of subsurface water components. It should be also noted that the three selected baseflow separation methods represent different approaches (Holko and Španková, 2014): digital filter, simple statistics and more physically-based Kliner-Kněžek method, which all deliver non identical baseflow results. The eq. 1 was therefore applied for winter/summer recharge ratios, where R is the mean baseflow value of the three baseflow separation methods, accompanied by a corresponding band width of two sigma-values of standard deviations of the three methods.

The relations between the seasonal isotopic content of various groundwater compartments were also explored by the use of summation curves (isotopic mass curves). They sum up (over the winter period) the weighted isotopic content of precipitation, streamwater and groundwater, weighted by the respective runoff amount. The summation curves of precipitation sum the monthly precipitation amounts multiplied by the respective isotopic content, the streamflow summation curves sum the hourly runoff amounts multiplied by the respective streamwater isotopic content, (where weekly, daily or 6-hourly values of isotopes are linearly interpolated for respective streamflow data) and the baseflow summation curves sum the hourly runoff amounts multiplied by the respective groundwater isotopic content as its average for a given hydrological year. The latter therefore creates a summation curve of a hypothetical runoff formed only by groundwater. This concept is widely analogous to the typology of post-winter droughts developed by Van Loon et al. (2014), in our case presented through summation curves and additional isotope mass balance.

RESULTS AND DISCUSSION

Isotopic records in precipitation and groundwater

Table 1 presents the seasonal and annual precipitation, runoff and air temperature parameters for the period 2008–2016. It shows that although the winter precipitation (577 mm in average) contributes by less than 50% to the total annual precipitation (1318 mm on average), the winter precipitation is more sustainable and contributes substantially to runoff through subsurface water components. Three winter seasons (2008, 2009 and 2012) provide more than 650 mm of precipitation and can be therefore considered wet. Winter air temperature in the catchment is typically near the freezing point, however three warm winters (2008, 2014 and 2016) showed mean winter season air temperature values around 1 centigrade.

Table 1 also shows higher runoff coefficients in winter season (0.96) than in summer season (0.58). This reveals that groundwater storage and release are dominant in the winter season (in absence of winter evapotranspiration).

Average groundwater $\delta^{18}O$ values (–10.34‰) are overall more depleted in comparison to the downhill peat water (–9.96‰), uphill mineral soil water (–9.47‰) and the weighted precipitation (–10.06‰) (Fig. 2). It is assumed that this is caused by the groundwater recharge supplied dominantly from winter precipitation and snowmelt. Isotopically depleted winter precipitation in 2010 and 2011, however, cause that the average values of peat water and groundwater in 2011 are nearly identical (see also Table 2).

Table 1. Hydrological and climatic paramaters of hydrological years 2008–2016.

hydrological year	precipitation annual (mm)	precipitation winter (mm)	precipitation summer (mm)	precipitation winter (%)	precipitation summer (%)	day of max.snow water equivalent	max.snow water equivalent (mm)	runoff annual (mm)	runoff winter (mm)	runoff summer (mm)	runoff coef. annual	runoff coef. winter	runoff coef. summer	air terperature annual	air temperature winter	air temperature summer
2008	1256	685	572	0.54	0.46	1.2.	196	917	673	244	0.73	0.98	0.43	6.52	1.75	11.29
2009	1390	658	732	0.47	0.53	27.2.	486	1090	603	487	0.78	0.92	0.66	5.15	–0.49	10.79
2010	1643	472	1171	0.29	0.71	19.3.	274	1224	459	765	0.74	0.97	0.65	4.59	–1.50	10.69
2011	1465	573	892	0.39	0.61	18.4.	169	1149	585	564	0.78	1.02	0.63	5.38	–0.78	11.55
2012	1384	777	607	0.56	0.44	29.2.	462	1025	712	314	0.74	0.92	0.52	5.52	–0.52	11.56
2013	1630	629	1001	0.39	0.61	2.4.	310	1295	570	725	0.79	0.91	0.72	4.92	–1.49	11.33
2014	996	404	592	0.41	0.59	27.3.	78	767	413	354	0.77	1.02	0.60	5.87	1.39	10.35
2015	803	439	364	0.55	0.45	15.1.	196	575	414	161	0.72	0.94	0.44	6.06	0.29	11.84
2016	1294	557	737	0.43	0.57	17.2.	127	912	518	393	0.70	0.93	0.53	6.32	0.93	11.71
average	**1318**	**577**	**741**	**0.45**	**0.55**		**255**	**995**	**550**	**445**	**0.75**	**0.96**	**0.58**	**5.59**	**–0.05**	**11.23**

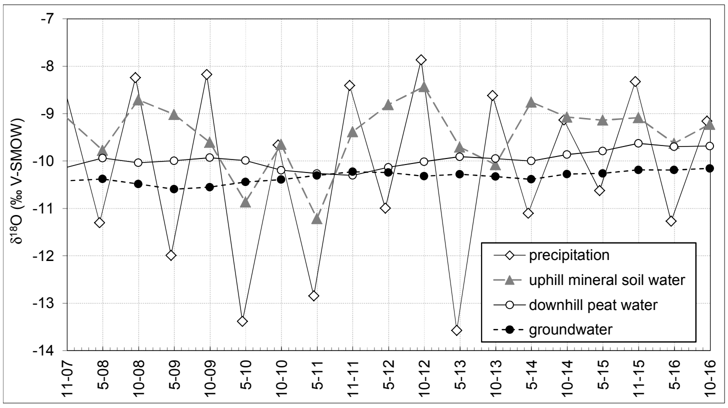

Fig. 2. Stable isotopes of oxygen in various catchment compartments (6-month averages).

Table 2. Isotope signatures of precipitation, groundwater, mineral soil pore water, organic-peat pore water, of hydrological years 2008–2016.

hydrological year	δ^{18}O precipitation annual (‰ V-SMOW)	δ^{18}O precipitation winter (‰ V-SMOW)	δ^{18}O precipitation summer (‰ V-SMOW)	δ^{18}O groundwater annual (‰ V-SMOW)	δ^{18}O groundwater winter (‰ V-SMOW)	δ^{18}O groundwater summer (‰ V-SMOW)	δ^{18}O mineral soil pore water annual (‰ V-SMOW)	δ^{18}O organic peat water annual (‰ V-SMOW)
2008	–9.91	–11.30	–8.24	–10.43	–10.38	–10.49	–9.24	–9.98
2009	–9.98	–11.99	–8.18	–10.57	–10.59	–10.55	–9.40	–9.96
2010	–10.73	–13.38	–9.66	–10.42	–10.44	–10.39	–10.31	–10.08
2011	–10.14	–12.85	–8.41	–10.26	–10.30	–10.23	–10.28	–10.28
2012	–9.62	–11.00	–7.86	–10.28	–10.24	–10.32	–8.66	–10.08
2013	–10.53	–13.57	–8.62	–10.31	–10.28	–10.33	–9.93	–9.93
2014	–9.93	–11.10	–9.14	–10.33	–10.39	–10.28	–8.86	–9.92
2015	–9.58	–10.62	–8.32	–10.22	–10.26	–10.19	–9.11	–9.71
2016	–10.07	–11.27	–9.16	–10.17	–10.19	–10.16	–9.43	–9.69
average	**–10.06**	**–11.86**	**–8.60**	**–10.34**	**–10.35**	**–10.33**	**–9.47**	**–9.96**

Fig. 3 reveals the differences in the isotopic composition of precipitation in relation to their signal in the subsurface water components. A decrease of the isotopic content of summer precipitation and an increase of the isotopic content of winter precipitation can be observed. This may cause the general isotopic enrichment of all subsurface water components over the 9-year period. The difference in the isotopic composition of summer and winter uphill soil water in the years 2010 and 2011 is caused by the abundant summer precipitation in 2010 followed by isotopically very depleted winter precipitation. These two winters were the only cases within the entire 9 year-period where uphill soil water was isotopically more depleted than groundwater (Fig. 3a). These effects led to the differences in 2010 and 2011 (Fig. 3b), whereas the overall low isotopic values in the peat water in 2011 seem to be the consequence of the mixing of these isotopically depleted waters in the deeper peat horizon (Fig. 3c). In turn, the groundwater carries also isotopic signals of longer memories, which may explain the low values in 2009 that have no obvious background in the recent-to-date precipitation values.

Seasonal and annual isotopic differences and ratios

Table 2 provides seasonal δ^{18}O values of groundwater, mineral soil water, peat water and precipitation. Based on these data, Fig. 4 exhibits the difference between summer and winter precipitation isotopic compositions from the 9 winters. The difference between summer (April to September) and winter (October to March) δ^{18}O values is between 2 and 5‰ V-SMOW from the annual mean and it is negatively correlated with the amount-weighted δ^{18}O values in precipitation (annual). Jasechko et al. (2014) found similar differences for a worldwide set of catchments, stating that the difference around 5‰ V-SMOW in between summer and winter δ^{18}O values in precipitation is typical for isotopically depleted precipitation in the extratropics, whereas the difference around 2‰ V-SMOW is typical for tropical areas. Our study shows, however, that a catchment can exhibit the full spectrum of winter-summer differences within a decade. The difference between summer (May to October) and winter (November to April) δ^{18}O is about 5‰ for the coldest years with most depleted annual precipitation, and about 2‰ V-SMOW for months with isotopically more enriched precipitation.

No correlation was found between the annual groundwater - precipitation isotopic difference and shallow groundwater (Fig. 5). This difference is typically negative, showing that for most of the time the mean isotopic content in groundwater is lower than in precipitation. This occured in seven out of nine years where the isotopic content of groundwater oscilled between –10.1‰ and –10.6‰ V-SMOW. It shows the dominance of the groundwater winter isotopic content regardless of the isotopic composition of groundwater in particular years. Similar trend can be observed in the peatwater, highlighting that the isotopic differences between peatwater and precipitation do not depend on the annual mean isotope average. In contrast, the difference mineral soil water - precipitation is related (R^2 = 0.63) to the annual isotopic content of the mineral soil water, revealing that the mineral soilwater can be used as proxy for the annual long-term amount-weighted isotopic composition of precipitation in the Uhlířská catchment.

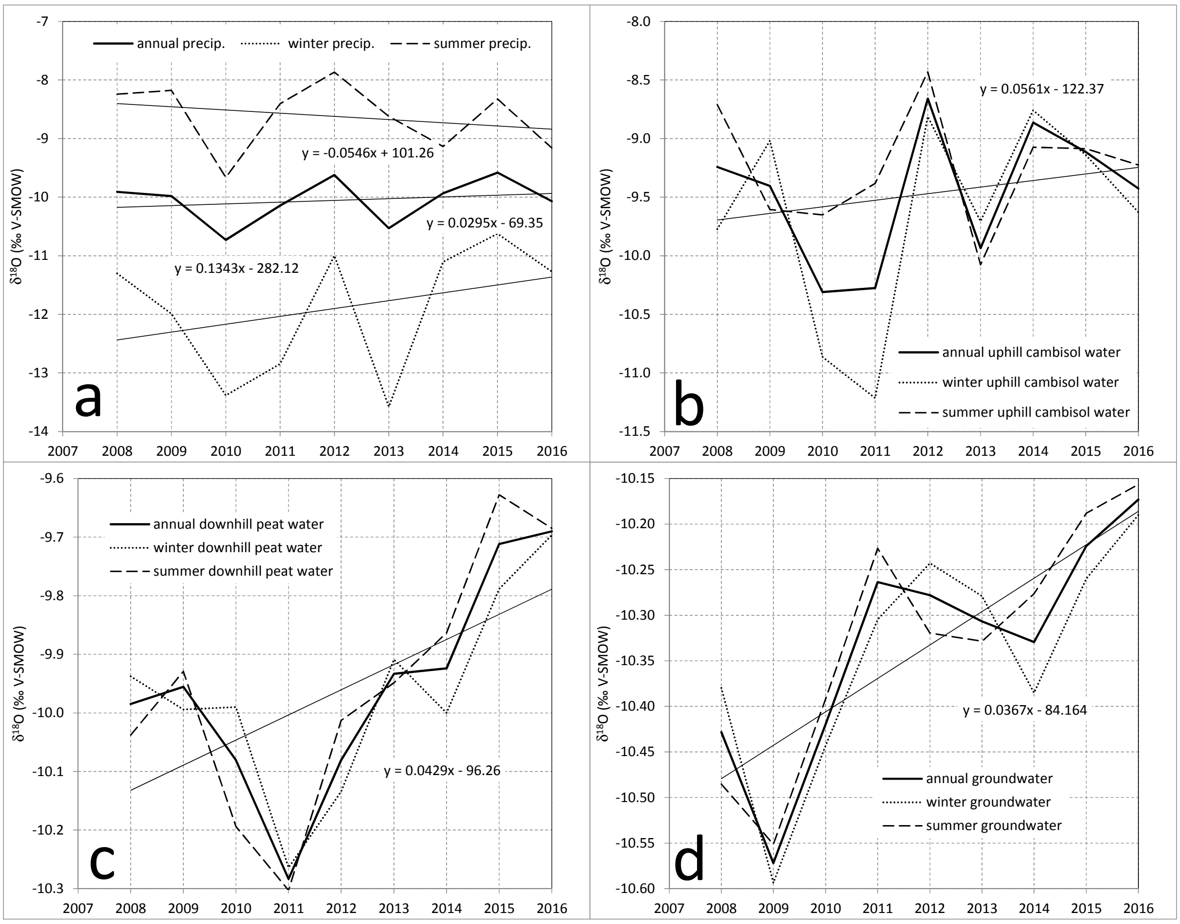

Fig. 3. abcd (from top left to bottom right) – Stable isotopes of oxygen in precipitation (a), uphill mineral soil (Cambisol or Podzol) water (b), downhill peat water (c) and shallow groundwater (d) (6-month averages: summer: May–Oct, winter: Nov–Apr and 12 months averages Nov–Oct of hydrological year). Note the different scales on the y-axes.

Table 3. Recharge ratios by isotope and hydrological hydrograph separation methods of hydrological years 2008–2016. Groundwater represents average of four shallow wells (2.7–5.2 m deep) according to fig. 1 in the valley, where groundwater discharges from the aquifer, sampled in 1-2 month intervals and averaged for 12 months (or 6 summer/6 winter months, thus average of maximum of 48 values or 24 values respectively).

hydrological year	recharge/precipitation in winter/summer ratio for groundwater by isotopes (–)	recharge/precipitation in winter/summer ratio for organic soil pore water by isotopes (–)	recharge/precipitation in winter/summer ratio for mineral soil pore water by isotopes (–)	recharge/precipitation in winter/summer ratio for baseflow by hydrograph separation: average of 3 methods (–)	recharge/precipitation in winter/summer ratio for baseflow by hydrograph separation: average of 3 methods - 1σ interval (–)	recharge/precipitation in winter/summer ratio for baseflow by hydrograph separation: average of 3 methods + 1σ interval (–)
2008	2.09	1.11	0.41	1.89	1.36	2.37
2009	1.88	0.97	0.53	1.25	0.97	1.44
2010	0.63	0.31	0.52	1.05	0.92	1.14
2011	1.12	1.14	1.13	1.28	1.07	1.42
2012	2.62	1.89	0.27	1.64	1.09	2.03
2013	0.82	0.58	0.58	0.93	0.86	0.97
2014	2.26	0.98	–0.18	1.30	1.07	1.45
2015	3.94	1.26	0.43	1.52	1.29	1.68
2016	1.22	0.19	0.19	1.28	1.01	1.44
average	**1.84**	**0.94**	**0.43**	**1.35**	**1.07**	**1.55**

Table 3 also shows the relative winter/summer recharge index calculated using Eq. (1) for the groundwater, peat water and hillslope water through the period 2008–2016. It reveals that the winter groundwater recharge was always greater than the summer recharge (index greater than 1), except for the years 2010 and 2013 with highly abundant summer precipitation (more than 1000 mm). This result (Fig. 6a) therefore underlines the overall winter dominance of isotopically depleted groundwater recharge, as reported by Jasechko et al. (2014) in non-tropical areas. Other catchment compartments show a more (hillslope mineral soil water, summer groundwater recharge bias in 8 years out of 9) or less (peat soil water, summer groundwater recharge bias in 5 years out of 9) substantial tendency to dominant summer recharge. Fig. 6a also shows the winter/summer recharge ratio in form of a winter/summer relation of baseflow volumes averaged from three approaches

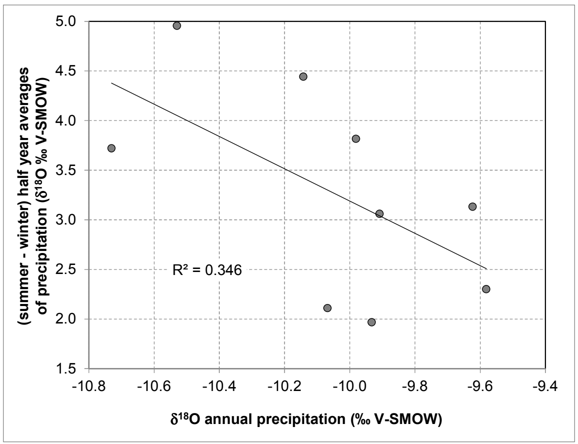

Fig. 4. Absolute value of difference in between precipitation-weighted $\delta^{18}O$ differences of summer and winter half years (May–October and November–April) for the period of 2008–2016.

(BFLOW, monthly minima and Kliner-Kněžek). This relation is almost entirely greater than 1, indicating the winter dominance of groundwater on baseflow. Fig. 6b compares the winter/summer baseflow ratio from Fig. 6a with a combined winter/summer recharge ratio, composed by a combination of three isotopic winter/summer recharge ratios calculated using Eq. (1) – wetland groundwater, peat organic soil water and mineral soil water. Best combination of these three isotopic winter/summer recharge ratios was identified, that delivered the baseflow R value in Eq. 1 as close as possible to the mean winter/summer baseflow ratios determined by the three separation methods and also to the 2σ intervals of three annual baseflow ratios obtained by the same approach. This procedure was employed each year (Table 3). It is obvious that the annual winter/summer ratios of the baseflow indicating the mean and 2σ intervals are not symmetric to the mean, because those ratios are determined independently for each year. The resulting contributions yield 29% (25%–34% as 2σ interval of three baseflow separation methods) ofthe isotopic content of groundwater, 50% of peat organic soil water (41%–63% as 2σ) and 22% (3%–33% as 2σ) of hillslope mineral soil water. As described in Vitvar et al. (2016), the NETPATH approach distributed the runoff contributions among the groundwater (28%), peat water (42%) and mineral hillslope soil with rainfall (30%) (combination of mineral soil hillslope water (23%) and rainfall (7%)) (Vitvar et al., 2016).

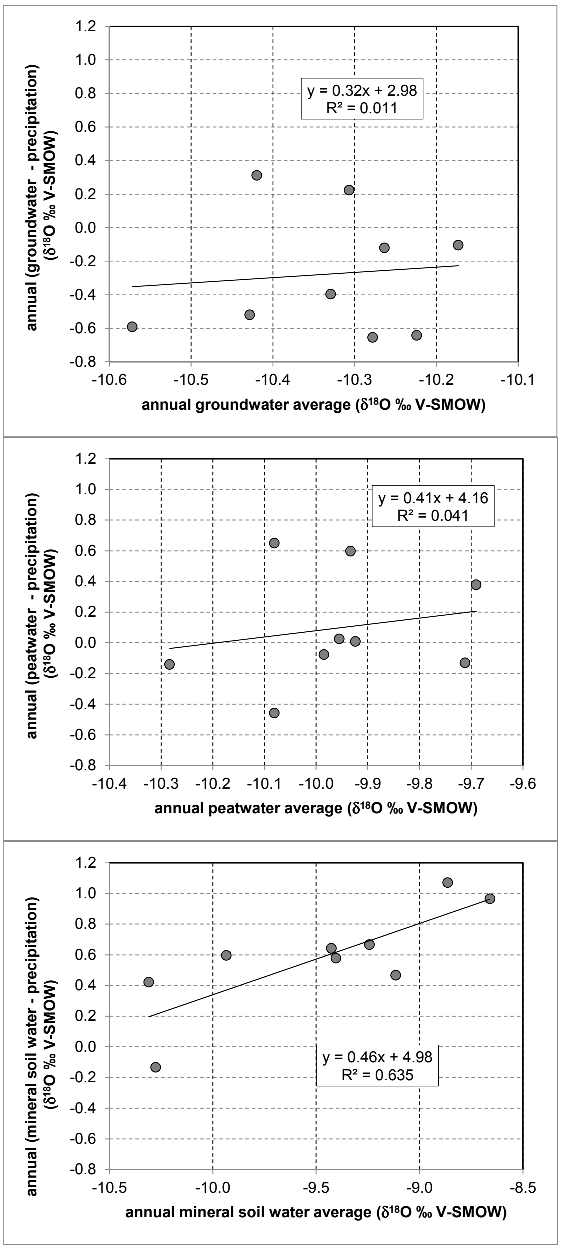

Fig. 5. Difference in the isotopic composition of groundwater, peatwater and mineral soil water and the amount-weighted precipitation for the years 2008–2016.

Isotopic summation curves

Fig. 7 depicts nine occasions of the snowmelt-runoff-recharge relationship, characterized by summation curves (isotopic mass curves) of precipitation, streamflow and baseflow. The computed summation curves show that all nine winters are grouped along the relative criteria Wetter, Drier, Colder, Warmer. Colder winters show rapid increase of the isotopic mass balance of streamflow caused by the onset of one or two distinct snowmelt periods (mid-March 2010, end of December 2012 and begin of April 2013, and end of February 2012). Milder and drier winters (for example, 2013/2014) exhibit largely parallel summation curves of precipitation and streamflow, indicating that the accumulated isotopic mass flows out in the same winter. Colder and wetter winters also show greater difference between the sum of isotopic masses in baseflow and in precipitation at the end of the winter (for example, 2011/2012), due to the accumulated isotopic mass in precipitation. The accumulated isotopic mass in precipitation is typically greater than the accumulated mass in streamwater. This shows that the winter precipitation discharged into the stream not only during, but also after snowmelt periods. The accumulation of isotopic mass in baseflow in all types of winters is sustainable and does not show any particular differences. In contrast, in a mild winter with low precipitation amounts such as 2013/2014 the isotopic mass balance at the end of the winter is closed, revealing that the winter precipitation is completely transformed into outflow during the same winter period.

CONCLUSIONS

The study has demonstrated that the nearly 10-year isotope monitoring in the Uhlířská catchment delivers significant information on how different amounts and temporal distributions of winter accumulation and release affect the subsurface water transition and storage in mineral soil, peat and ground-

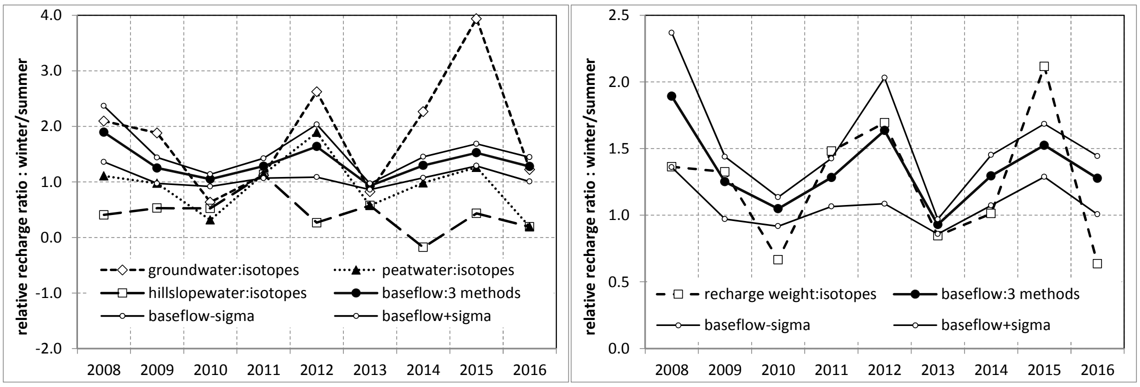

Fig. 6. a) (left) Annual relative ^{18}O- recharge ratios winter/summer in groundwater, peatwater and hillslope soilwater. Also included are the stream baseflow winter/summer ratios obtained as average of three methods: separation software BFLOW, monthly minimum approach and Kliner-Kněžek approach b) (right) Stream baseflow winter/summer ratios obtained by the three abovementioned approaches and stream baseflow winter/summer recharge ratios obtained by weighting the baseflow components (hillslope, peatwater and groundwater) by the identified in the isotopic approach. Plus a minus sigma denote the annual relative recharge ratios winter/summer standard deviations from the mean value of the three baseflow separation methods.

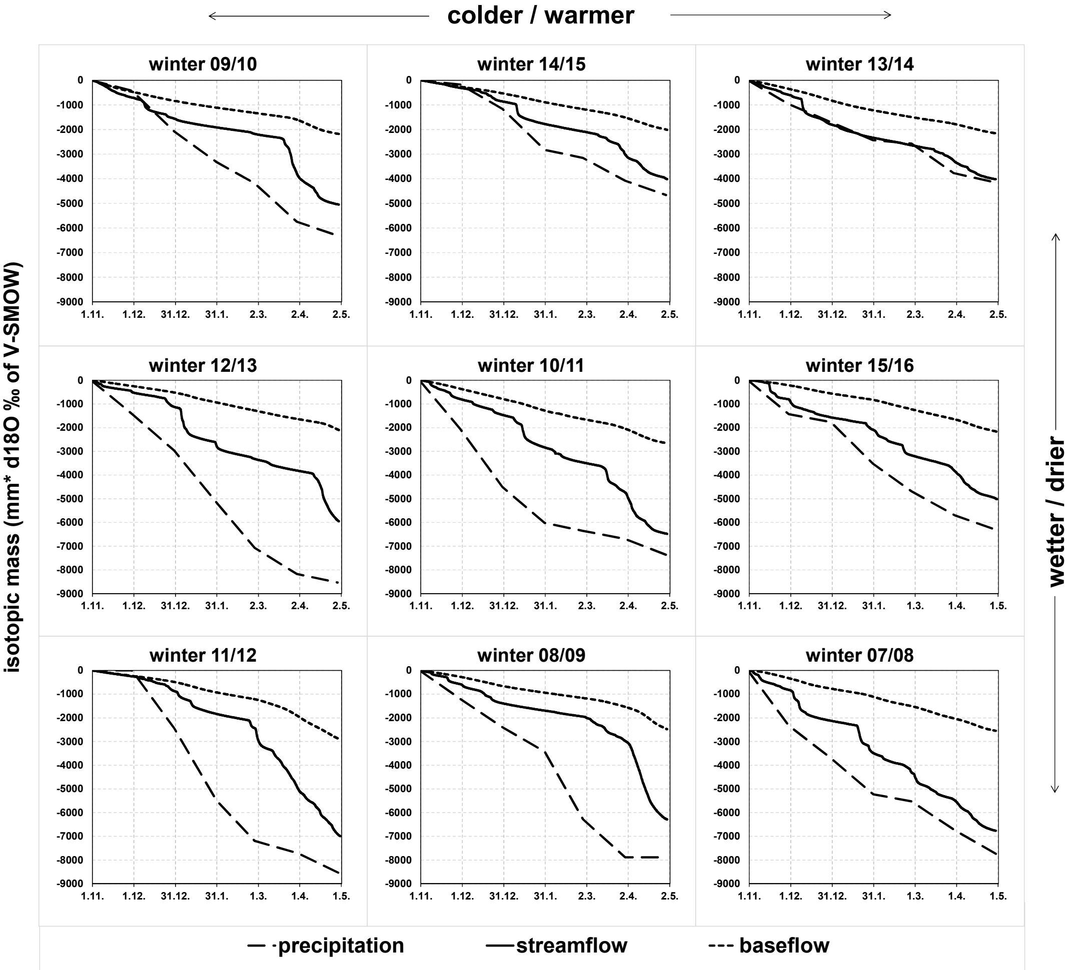

Fig. 7. Summation curves of isotopic mass across the winter season (November – April) for precipitation, streamflow and baseflow.

water. It also showed that the readily available approaches such as recharge ratios or baseflow separation can explain not only the spatial, but also the seasonal distribution of recharge patterns in a catchment. These approaches also explain why the average ^{18}O content in groundwater at Uhlířská remains below the ^{18}O content in streamwater. Although the overall isotopic composition tendency highlights the winter precipitation accumulation as the principal origin of the baseflow, a detailed examination of nine winters reveals several types of winters characterized by individual isotopic patterns and potential water storage for summer drought periods. Because the applied approaches require a monthly isotopic monitoring of various types of subsurface waters, they can be presently used only in a limited number of catchments.

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