Spatial and temporal variability of stable water isotopes in snow related hydrological processes

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Raumzeitliche Variabilität stabiler Wasserisotope bei schneebeeinflussten hydrologischen Prozessen

1 Introduction

Stable water isotopes (^{18}O, ^{2}H) have been measured and applied in snow hydrology since the 1970s. They are used to identify water sources, separate hydrograph components and estimate the mean transit time of water in a catchment or an aquifer (e.g. Dóša et al., 2011). Recent technological progress in laser spectroscopy has paved the road for cheaper and simultaneous analyses of both δ^{18}O and δ^{2}H. The hydrological community has thus the possibility to obtain longer data series with higher resolution that could lead to an improved understanding of water movement in the hydrological cycle (Lyon et al., 2009). The objective of this article is to report the main results of detailed monitoring of the variability of stable water isotopes in the snow-related part of hydrological cycle. We studied the isotopic composition of snowfall, snow cover, snowmelt, soil, ground- and stream waters in the mountain environment of northern Slovakia in the two contrasting winters of 2011 and 2012.

Zusammenfassung

Es wurde die Variabilität der δ^{18}O- and δ^{2}H-Isotope an schneebezogenen Wasserbilanzkomponenten (Schneeniederschlag, Schneedecke, Schmelzwasser, Bodenwasser, Grundwasser und Oberflächenabfluss) in gebirgigen Einzugsgebieten der Nordslowakei im Winter 2011 und 2012 gemessen. Unerwarteterweise wurden negative Höhengradienten der δ^{18}O- und δ^{2}H-Konzentration im Schneeniederschlag gefunden. Der Isotopenanteil in der Schneedecke zeigte höhere räumliche Variabilität bei schneearmen Wintern. Leichtes Schneewasser war im Boden bis in den Juni hinein nachweisbar. Die erfasste Isotopenkonzentration des Schmelzwassers zeigte eine Abhängigkeit vom gewählten Entnahmegerät. Die Isotopenkonzentration in den Flüssen zeigte in Abhängigkeit zur Ordnungszahl den Einfluss unterschiedlicher Schmelzprozesse im Berg- und Talbereich.

Schlagworte: Schneehydrologie, δ^{18}O und δ^{2}H.

Summary

We monitored variability of δ^{18}O and δ^{2}H in the snow-related part of a hydrological cycle (snowfall, snow cover, snowmelt, soil water, groundwater and streams) in mountain catchments of northern Slovakia in winters 2011 and 2012. Unexpected negative altitude gradients of δ^{18}O and δ^{2}H were found for almost all snowfalls. The isotopic composition of snow cover during a snow-poor winter was spatially more variable than during a snow-rich winter. Light snow water was visible in the soils (at depths of 51–71 cm) at least until the middle of June. Isotopic signals of snowmelt water significantly depended on the device used to collect the water samples. The isotopic composition of streams of different orders during snowmelt periods pointed out the different regimes of the snowmelt in the main river valley and in the mountains.

Key words: Snow hydrology, δ^{18}O and δ^{2}H, mountains.

2 Study area and data

Stable water isotopes in precipitation, snow cover, streams, springs and soil water were monitored in the upper Váh River basin in northern Slovakia. The study area is composed of two contrasting landscapes – a large river valley surrounded by small mountain catchments. The river valley is situated at altitudes of 570–900 m a.s.l. Altitudes of the small mountain catchments range approximately between 800 and 2500 m a.s.l. Winters 2011 and 2012 were significantly different. Winter 2011 was extremely snow-poor. Snow cover melted more than a month earlier than usually even at the highest altitudes. Winter 2012 had much more snow. The first significant snowmelt occurred in March 2012 when the snow in the main river valley disappeared, while still a lot of snow remained in the mountains (Fig. 2).

Precipitation was measured by standard rain gauges with orifices of 500 cm^2 at altitudes of 570, 750 and 1500 m a.s.l. The samples were collected once a week. Snow cover was measured and sampled by snow tubes at altitudes varying between 570 and 1900 m a.s.l. The isotopic composition of snowmelt water was sampled by means of extended funnel gauges (EARMAN et al., 2006), small tin snow lysimeters laid on the ground before the first snowfall and passive capillary samplers (FRISBEE et al., 2010). Soil water samples were collected by soil suction cups at seven locations (570 to 1500 m a.s.l.). Stream water samples were collected at the outlet of the mountain part of the Jalovecký creek catchment (catchment area 22 km^2, mean altitude 1500 m a.s.l.),

near the outlets of the whole Jalovecký creek catchment (area 45 km^2, mean altitude 1166 m a.s.l.) and the upper Váh river basin (catchment area 1095 km^2, mean altitude 1090 m a.s.l.). Groundwater samples were collected from two springs situated in the Jalovecký creek basin at altitudes of 700 m a.sl. (alluvium of the Jalovecký creek) and 850 m a.s.l. (mountain part of the Jalovecký creek catchment).

All collected samples were analysed for $\delta^{18}O$ and δ^2H by the OA-ICOS laser spectrometer at CTU in Prague. Samples that deviated from the meteoric water line were excluded from further processing.

3 Results and discussion

3.1 Isotopic composition of snowfall

At weekly time intervals, there were only 10 weeks when precipitation occurred simultaneously as snowfall at three different altitudes in winters 2011 and 2012. The isotopic composition of these snowfalls is shown in Fig. 1. With one exception, all of them exhibited negative altitude effect, i.e. precipitation at the highest altitude was isotopically heavier than at the lower ones. Unlike at 570 m a.s.l. with daily attendance of the gauge, precipitation at 750 and 1500 m a.s.l. was measured just once per week. As a result of this, the snow stayed in the gauges for 1–7 days after the snowfall. It is possible that isotopic exchanges with the atmosphere or direct evaporation may have changed the isotopic composi-
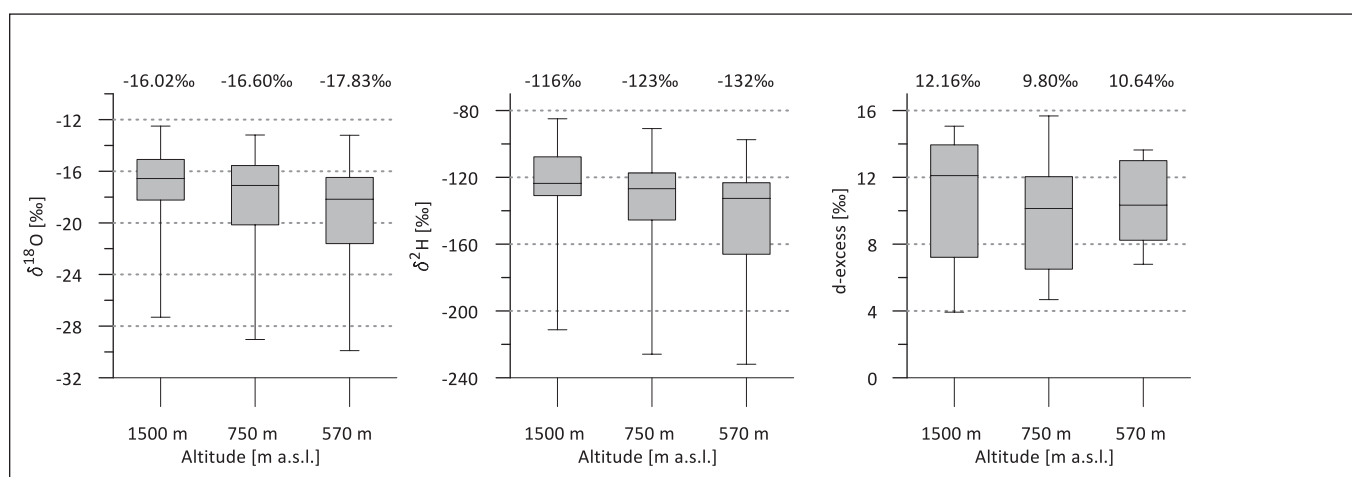

Figure 1: Box-whiskers plots of isotopic composition of solid precipitation at different altitudes in winters 2011 and 2012 (10 weeks); each graph shows maximum, 75-quartile, median, 25-quartile and minimum; mean values (weighted by precipitation amounts) are written above the graphs

Abbildung 1: Boxplot der Isotopenkonzentration des festen Niederschlags in verschiedenen Höhen des Winters 2011/12 (10 Wochen). Dargestellt sind Maximum, 75-Quartile, Median, 25-Quartile und Minimum. Gewichtete Mittelwerte sind als Zahlenwerte dargestellt

tion of the original snowfall. Additional measurements will be performed in winter 2013 to verify this option.

3.2 Isotopic composition of snow cover

Condensed information on the evolution of snow cover and on its isotopic composition in winters 2011 and 2012 is shown in Fig. 2. The isotopic composition of snow cover during the snow-poor winter 2011 exhibited a very large spatial variability. Ranges of $\delta^{18}O$ and δ^2H at the time of maximum snow water equivalent (in mountains) reached about 4 ‰ and 28 ‰, respectively. The isotopic composition of snow cover during the snow-rich winter 2012 exhibited smaller spatial variability and in lower parts of the catchments even an altitude gradient. The ranges of $\delta^{18}O$ and δ^2H reached about 2–3 ‰ and 21–23 ‰, respectively. The altitude effect was about 0.2–0.4 ‰/100 m for $\delta^{18}O$ and 1.4–2.6 ‰ for δ^2H. Higher altitude gradients occurred before the thawing episodes. Fig. 2 also documents the gradual enrichment of snow cover during the season. We discovered significant small-scale variability of isotopic composition snow cover when three samples were collected at the same snow course (right bottom part of Fig. 2). Snow cover in the forest was isotopically significantly heavier than in the nearby open area.

3.3 Isotopic composition of snowmelt water

Comparative measurements in the mountains (altitudes 1420 and 1500 m a.s.l.) showed that different sampling devices provided different isotopic signatures of snowmelt water (Figs. 3 and 4).

Snow cores from the entire snowpack were isotopically lighter than snowmelt water sampled by other devices (Fig. 3).

Snowmelt water samples collected from the extended funnel gauge in the open area were isotopically heavier than the ones collected from the tin lysimeters (Fig. 3) or passive capillary samplers. The extended funnel gauge was made from the standard (metallic) rain gauge of the meteorological service placed on the ground. A container under the gauge collected snowmelt water. The snow metamorphosis over the winter transformed the snow in the gauge into ice. Thus, despite the large diameter of the gauge (25.2 cm) and its placement on the ground, the snow structure in the gauge was significantly different from the surrounding snow cover. Ice formation in the extended funnel gauge situated in the forest was not so pronounced, but all snow collected in the gauge melted about a week earlier than the surrounding snow cover. Although the extended funnel gauges situated at different altitudes provided varying isotopic signals (both in time and space), this device was not considered useful in our study.
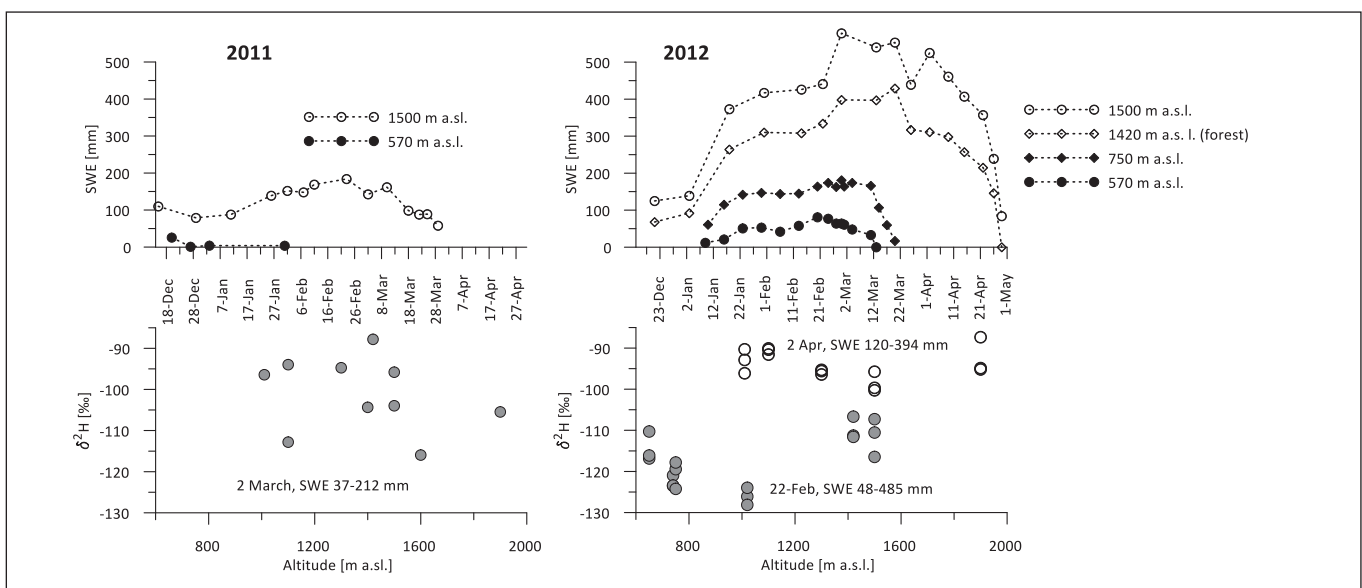

Figure 2: Snow water equivalents (upper panels) and δ^2H in the snow cover (lower panels) in winters 2011 and 2012
Abbildung 2: Schneewasseräquivalent (oben) und δ^2H Konzentration (unten) der Winter 2011 und 2012

Snowmelt water sampled by tin lysimeters was generally isotopically heavier than that sampled by the passive capillary samplers (by 0.3–1 ‰ for $\delta^{18}O$ and 2–5 ‰ δ^2H). Snowpack dominantly melts from its surface. Therefore, we wanted to test the idea if sampling of the upper (most active) snow layer could provide values comparable with the isotopic composition of snowmelt water sampled at the soil surface (bottom of snowpack). This idea was not true in the forest with shallow snowpack (about 40 cm of snow at the beginning of intensive melting). In the open area – snow depth at the beginning of intensive melting was about 65 cm – the isotopic composition of the upper 10 cm of snow was within the range of values provided by tin snow lysimeters (Fig. 4).

Small-scale variability of isotopic composition of snowmelt water is not negligible (see points representing snowmelt water from the same device situated at the same altitude in Figs. 3 and 4). Isotopic composition of water from two tin lysimeters in April 2012 in the open area that were located just about 15 m apart differed in $\delta^{18}O$ by 0.1–1.8 ‰ and in δ^2H by 1–13 ‰ (Fig. 4).

The isotopic composition of snowmelt in different parts of the catchment in spring 2012 is shown in Fig. 5. The variability of isotopic composition of snowmelt water during snowmelt in the main river valley was very high while in the mountains it was lower. The figure shows that δ^2H of snowmelt water ranged from about –140 ‰ at the beginning of the snowmelt to about –70 ‰ at its end.
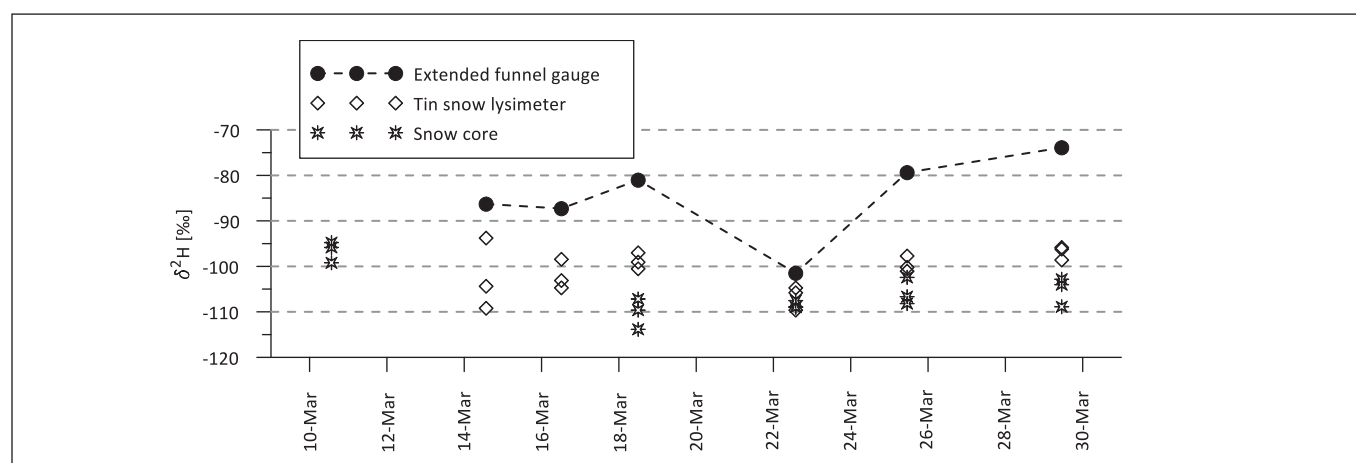

Figure 3: δ^2H of snowmelt water sampled in spring 2011 in the open area (1500 m a.s.l.) by the extended funnel gauge and three tin snow lysimeters; δ^2H values of snow cover at three points located at the same site are shown as well

Abbildung 3: δ^2H-Konzentration des Schmelzwassers im Frühjahr 2011 an der Freifläche (1500 m Sh.) gemessen mit Sammeltrichter und drei Schneelysimeter sowie aus Proben der Schneedecke
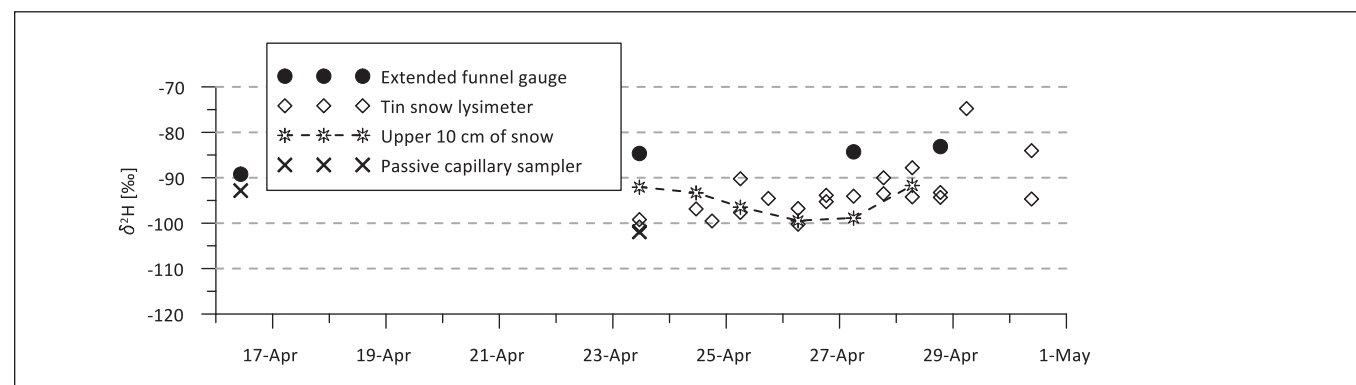

Figure 4: δ^2H of snowmelt water sampled in spring 2012 in the open area (1500 m a.s.l.) by the extended funnel gauge, two tin snow lysimeters, upper 10 cm of snow and passive capillary sampler (only two values were obtained before the snow above the capillary sampler melted)

Abbildung 4: δ^2H-Konzentration des Schmelzwassers im Frühjahr 2012 an der Freifläche (1500 m Sh.) gemessen mit Sammeltrichter, zwei Schneelysimetern, Proben der Schneedecke (obere 10 cm) und Kapillarsammler (2 Werte)
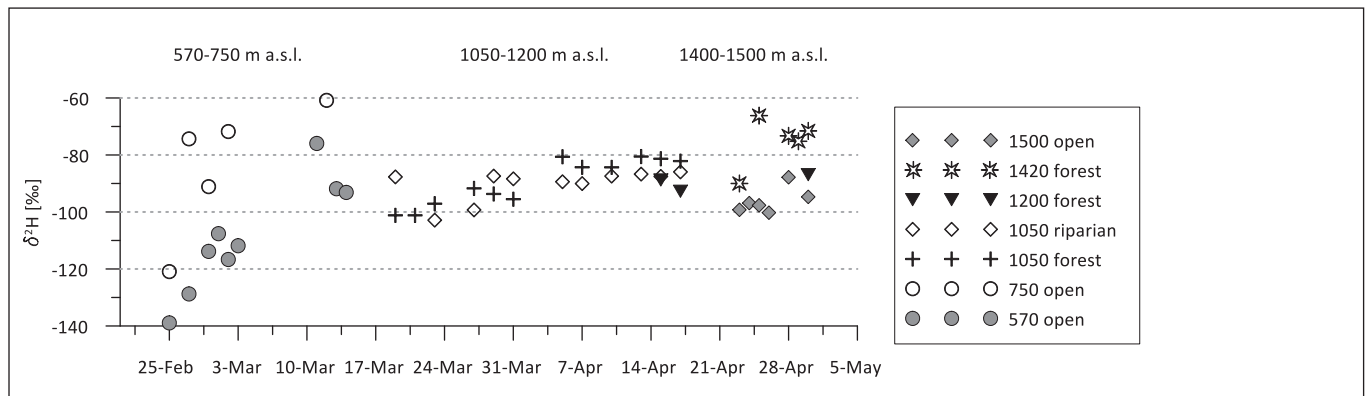
Figure 5:   Variability of δ²H of snowmelt water in spring 2012 in different parts of the catchment as given by tin snow lysimeters
Abbildung 5: Variabilität der δ²H-Konzentration im Schmelzwasser im Frühjahr 2012 an den verschiedenen Standorten der Schneelysimeter

3.4 Isotopic composition of soil water, springs and streams

The sampling of soil water by suction cups was not possible in winter not only due to unwanted disturbance of snow cover, but also due to the freezing of water in the tubing above the soil surface. Yet, we could determine the time when the light snowmelt water was fully replaced by heavier water from rainfalls at certain depths in the soil. A clear increase of δ¹⁸O and δ²H of soil water at depths of 50–70 cm occurred at altitudes of 570–1400 m a.s.l. in the middle of June. Since the snowmelt at higher altitudes started later than in the main river valley, this means that higher altitudes had a bigger turnover of water. It corresponds to higher precipitation and smaller evapotranspiration at higher altitudes. Groundwater samples indicated the displacement of older (isotopically heavier water) during the snowmelt. Owing to very little snow in winter 2011, only one event with a high contribution of snowmelt occurred in the

Jalovecký creek catchment. δ²H of the creek at the outlet of mountains decreased by 5‰ (from –81‰ to –86‰). After the event it raised by 3‰ (to about –83‰). The change of δ²H at the downstream profile which also collects water from the foothill part of the catchment was smaller. δ²H decreased by 3‰ (from –79‰ to –82‰). After the event it raised by 2‰ (to about –80‰).

In spring season 2012 we could compare the isotopic composition of streams from different subcatchments as well as short-time variability of isotopic composition of stream water during the snowmelt. Fig. 6 shows that the differences in δ²H of stream water before and after the snowmelt were almost the same; i.e. about 2‰ between the main river Váh and its tributary Jalovecký creek and about 1‰ between the mouth of the Jalovecký creek and the outlet of its mountain part. When the snowmelt in the lowest part of the catchment started, water in the main river became isotopically close to that at the mouth of its mountain tributary (the Jalovecký creek). This indicates the con-
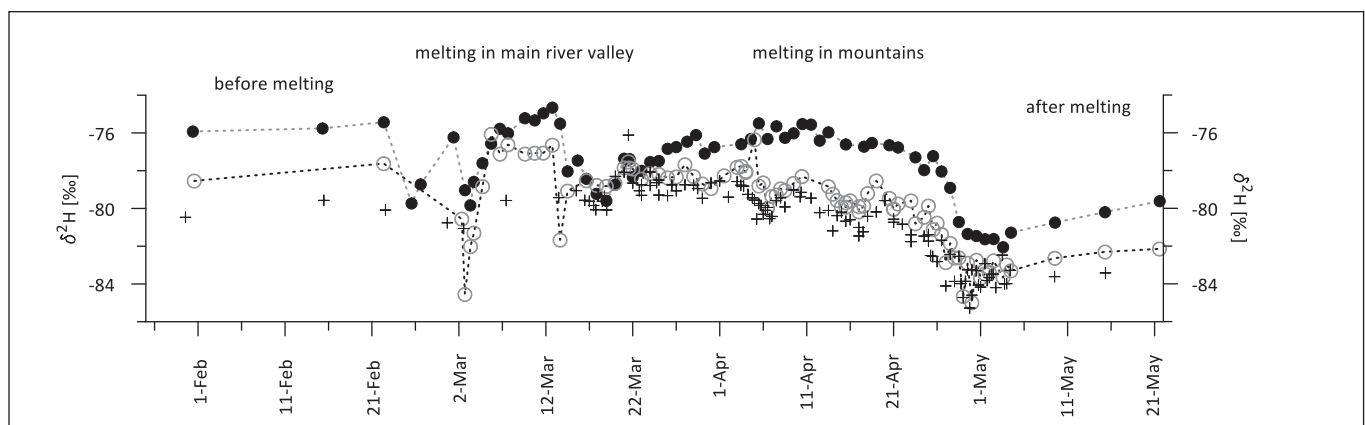

Figure 6:   Variability of δ²H of streams in snowmelt season 2012
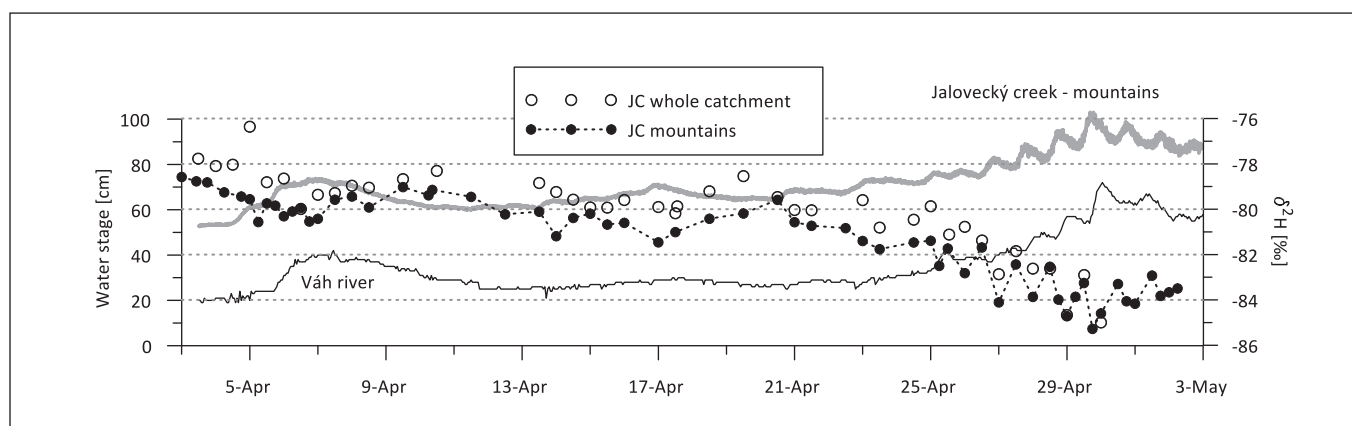Abbildung 6: Variabilität der δ²H-Konzentration in den Flüssen in der Schmelzperiode 2012

Figure 7:   Short-term variability of δ^2H in the Jalovecký creek at two profiles (outlet of mountains and of the whole catchment); hourly water levels in the main river (Váh) and 10-minutes water levels in its tributary (the Jalovecký creek) in April 2012

Abbildung 7: Kurzfristige Variabilität der δ^2H Konzentration im Jalovecký-Fluss an zwei Profilen (Gebirgsauslass und Gesamtgebietsauslass). Stundenwerte des Wasserstands am Vah-Fluss und 10-Minuten-Werte am Jalovecký-Fluss für April 2012

tribution of snowmelt water from areas close to the river network. When the snow in the main river valley melted, the main river became again isotopically different from its tributary, i.e. water from reservoirs with longer residence times became dominant. Gradual snowmelt in the mountains (Fig. 2) resulted in the slow decrease of δ^2H in all streams (approximately between about 11–20 April), the main river being already clearly heavier than the Jalovecký creek. However, only intensive snowmelt in the mountains at the end of April caused a significant decrease of δ^2H in all streams (by about 4‰).

More detailed information on the short-time variability of isotopic composition of streams is shown in Fig. 7. Runoff responses of the river Váh and its mountain tributary Jalovecký creek were very similar. Water samples from the Jalovecký creek were collected every 6–24 hours. The isotopic composition of water during the mixed rainfall-snowmelt event that occurred on 5–11 April changed only gradually. On the other hand, its temporal variability during typical runoff oscillation caused by intensive snowmelt due to dial air temperature variation at the end of April responded to runoff variability. A sampling frequency of 12 hours seems to be appropriate for a suitable monitoring of the isotopic composition of water during snowmelt in the studied area.

4 Conclusions

A significant change of the ranges of $\delta^{18}O$ and δ^2H occurs in the snow-related part of the hydrological cycle. While snowfalls and snow cover are isotopically significantly different from the rivers, the isotopic composition of snowmelt water at the end of the melting season is very close to that of the rivers. The isotopic composition of winter precipitation (snowfalls) and snow cover may not be good indicators of the isotopic signal that enters a catchment. However, even sampling of the snowmelt in mountain catchments may provide different values depending on the device used to collect the samples. Thus, the application of stable water isotopes to trace the snow water in the hydrological cycle should be based on a number of spatially and temporally distributed measurements in various parts of the catchments.

Acknowledgement

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