Estimation of the mean transit times using isotopes and hydrograph recessions

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Abschätzung der mittleren Laufzeiten mittels Isotopen- und Auslaufganglinienanalyse

Introduction

Mean transit time (MTT) is the time water spends traveling subsurface through a catchment to the stream network. It is a fundamental description of catchment hydrology, revealing information about the storage, flow pathways and sources of water in a single integrated measure (McGuire et al., 2005). Longer transit times indicate greater contact time and subsurface storage implying more time for biogeochemical reactions to occur as rainfall inputs are transported through catchments towards the stream channel (Burns et al., 2003; Scanlon et al., 2001). Thus, the estimation of the transit time distribution provides a primary description of the hydrobiogeochemical system and sensitivity to anthropogenic inputs (Turner et al., 2006). Although the topic has been studied since the 1970s, it has received a substantially increased attention in the last decade. Most of studies estimating the MTT were based on isotope studies (e.g. Maloszewski and Zuber, 1982; Holko 1995; McGuire et al. 2002; Reddy et al., 2006, Einsiedl et al., 2009). Some studies demonstrated positive correlation between basin area and MTT (DeWalle et al., 1997, McDonnell et al., 1999, Soulsby et al., 2000). Other papers showed that the basin area was not the main control of MTT (McGlynn et al., 2003, McGuire et al., 2005, Rodgers et al., 2005, Soulsby and Tetzlaff, 2008). McGuire et al. (2005) found a high correlation between catchment topography and MTT (r^2 = 0.91), while catch-

Zusammenfassung

Für drei Einzugsgebiete unterschiedlicher Größe (22, 45 und 1095 km^2) wurden die mittleren Laufzeiten (MLZ) mit Hilfe der Isotopenmethode (δ^{18}O) und mittels Auslaufganglinienanalyse berechnet. Dafür wurden Daten der Jahresreihe 2005 bis 2008 verwendet. Die MLZ-Schätzungen mittels Isotopenverfahren (Sinuskurvenverfahren) ergaben eine Dauer von 13 bis 19 Monaten, wobei der Zusammenhang zwischen MLZ und der Einzugsgebietsgröße eher auf unterschiedliche Abflussbildungsprozesse hindeutet. Die Analyse der Auslaufganglinie ergab bei kurzen Ereignissen ähnliche Ergebnisse wie die Isotopenmethode. Lang auslaufende Abflussganglinien traten jedoch selten auf und erfordern längere Beobachtungsdauern.

Schlagwörter: Laufzeit, Isotopenanalyse, Auslaufganglinie.

Summary

We have calculated mean transit times (MTT) of streamflow in three mountain catchments of different orders (areas 22, 45 and 1095 km^2, respectively) by means of isotopic method (δ^{18}O) and by the method based on hydrograph recession during the warm period of the year. Data from years 2005–2008 were used in calculations. MTTs calculated by isotopes (the sine-curve approach) varied between 13–19 months. Seeming correlation of MTT with catchment area reflects rather differences in runoff formation at different scales. Hydrograph recession provided two typical recessions. MTTs calulcated from the shorter hydrograph recessions for the two larger catchments were comparable with those given by δ^{18}O. Longer runoff data series are necessary in applying the hydrograph recession method due to the relatively small number of uninterrupted recessions in individual years.

Key words: Mean transit time, isotopes, hydrograph recession, topography.

ment area had no correlation. RODGERS et al. (2005) also observed that topography was the dominant control of MTT. SOULSBY and TETZLAFF (2008) found a strong correlation between MTT and mean catchment slope. STEWART et al. (2010) pointed out that stable isotopes biased our view on the residence time of water and processes by which water is transported through a catchment. They showed that deeper groundwater contributes more to the streamflow than estimations using stable isotopes. MCGUIRE and MCDONNELL (2006) mentioned problems related to high spatial and temporal variability of isotopic composition of water, sampling interval, range of the sampling data and selection of the distribution function. SCHWIENTEK et al. (2009) provided evidence that the theoretical distribution of transit times may be significantly altered depending on the thickness of the unsaturated zone. All these issues together with the high expense of isotopic methods have brought the need for an inexpensive calculation of the MTT. For example, SOULSBY and TETZLAF (2008) used two simplified methods. The first one was based on the ratio of precipitation to the normalised standard deviation of chlorides in streamwater, the second one was based on digital soil maps. The results were broadly comparable, although the MTTs estimated from chlorides compared better with those estimated from isotopes. An alternative approach to MTT calculation based on the analysis of hydrograph recessions has also been introduced by VITVAR et al. (2002). The objective of our study is the estimation of MTT in three mountain catchments using stable isotopes and hydrograph recession.

Description of the study area

The study was undertaken in the upper Váh river basin, north Slovakia, involving calculations of MTT for the mountainous parts of the Jalovecký creek catchment, the whole catchment of the Jalovecký creek and the Váh river basin. The basic characteristics of the studied catchments are given in Table 1.

The mountains of the Jalovecký creek catchment are covered mostly by spruce forest and dwarf pine (75%); the rest of the catchment is covered by the alpine meadows and bare rocks. Metamorphic and granitic rocks form approximately 69% of the catchment, limestone and dolomite about 7% and quaternary sediments about 24%. The main types of soil are cambisols, podzols and lithosols. Rendzinas occur on Mesozoic rocks. All soils have a high skeleton content, often reaching values of 40–50% and more (KOSTKA and HOLKO, 1997). The foothill part of the Jaloveck creek catchment is formed by flysh covered by alluvial sediments. Landuse is predominantly grasslands, agricultural land and three small urban areas.

The landuse of the upper Váh river catchment is covered by coniferous forests (47%), dwarf pine (8.7%), mixed forest (1.2%), meadows (21.6%) and arable land (16.1%). The main river valley is formed by river terraces and alluvium. Geology of the mountains surrounding the main valley of the Váh river is generally similar to that of the mountains of the Jalovecký creek catchment (with more important Mesozoic formations in the southern part of the catchment).

Methodology

Isotopic method

The variability of $\delta^{18}O$ in precipitation and streams was used to calculate the MTT of the streamflow by the means of the sine curve method. The sine curves were fitted to the $\delta^{18}O$ values in precipitation and runoff. The general equation of the sine curve is:

$$\delta_t = \delta` + A * \sin\frac{2\pi}{12} + t \tag{1}$$

where δ_t is the computed value, $\delta`$ is the mean value of $\delta^{18}O$ in precipitation or in runoff, A is amplitude and t is time in months.

Table 1: Characteristics of Jalovecký creek and Upper Váh catchment
Tabelle 1: Gebietseigenschaften der Gebiete Jalovecký creek und Obere Váh

	Jalovecký creek, mountain part	Jalovecký creek, whole catchment	Upper Váh catchment
area	22 km^2	45 km^2	1095 km^2
mean elevation	1500 m a.s.l.	1166 m a.s.l.	1090 m a.s.l.
mean annual temperature	3.1 °C	6.1°C	4.2 °C
mean annual precipitation	1562 mm	1206 mm	1046
mean annual runoff	1015 mm	714 mm	598

After fitting the sine curve to the data, the MTT was calculated using the amplitude damping (e.g. HERRMANN and STICHLER, 1981):

$$\tau_r = \frac{\sqrt{\frac{1}{f^2} - 1}}{2\pi} \qquad (2)$$

where τ_r is mean transit time in years, f is the amplitude damping B/A where A is the amplitude of $\delta^{18}O$ in precipitation, B is the amplitude of $\delta^{18}O$ in runoff (see Table 2).

Monthly composite precipitation samples in period 2005–2008 were collected in the Jalovecký creek catchment at altitude 1500 m a.s.l.. This altitude represents the mean altitude of the mountain part of the Jalovecký creek catchment. Thus, the $\delta^{18}O$ of precipitation (Figure 1) represented the input function for the mountains of the Jalovecký creek catchment. The input functions for the two other catchments were obtained by modification of the input function used for the mountains of the Jaloveck creek catchment according to the mean altitudes. Altitude gradient of $\delta^{18}O$ in precipitation given in table 2 was used for the modification. Grab runoff samples were collected at the outlets of the three catchments.

Hydrograph recession

Mean transit times calculated by $\delta^{18}O$ were compared with the results given by hydrograph recession analysis. VITVAR et al. (2002) used the analogy between hydrograph recession and a pumping test in the aquifer to calculate the MTT. M. Talbot (oral communication) noticed that the equation developed by VITVAR et al. (2002) can be transformed to a simpler form:

$$T_c = \frac{2t_r}{L} e^{\lambda} \qquad (3)$$

where T_c is the mean transit time, t_r is the total hydrograph recession time (Figure 2), L is the maximum flow path length and is the topographic index. We have used equation (3) to calculate the MTT for hydrograph recessions determined for the three studied catchments.

Hydrograph recession analysis was conducted with daily runoff data from summer periods 2005–2008 (June-September) in each of the three studied catchments. t_r was derived from the recession segments for two typical recessions (Figure 2). Flow path length L and topographic index were computed for each catchment from the digital terrain model with resolution 25 m.

Results and discussion

The values of $\delta^{18}O$ in runoff at the outlets of the studied catchments and the fitted sine curves and their amplitudes are shown in Figure 3. The amplitudes of the input functions for the mountain part of the Jalovecký creek catchment, the whole Jalovecký creek catchment and for the Váh

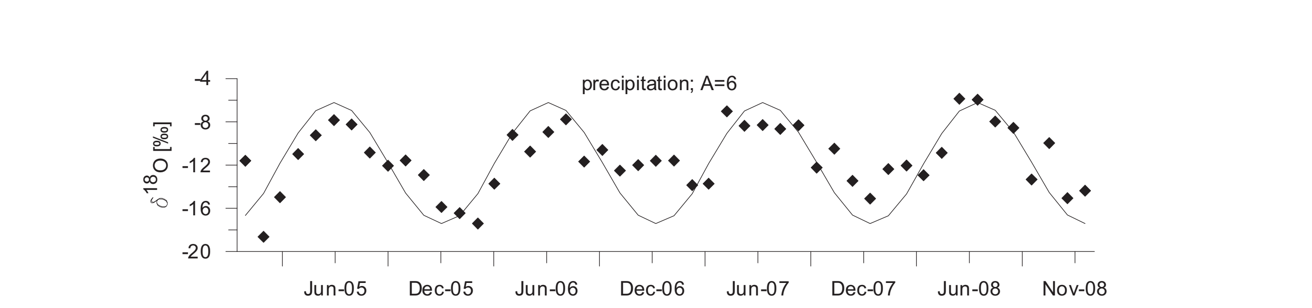

Figure 1: $\delta^{18}O$ in precipitation at 1500 m a.s.l. fitted by the sine curve – the input function for the mountain part of the Jalovecký creek catchment; A is the amplitude of the sine curve

Abbildung 1: $\delta^{18}O$-Gehalt im Niederschlag auf 1500 m. Sh. als Sinuskurve angenähert – Eingangsfunktion für das Jalovecky creek Gebiet. A entspricht der Amplitude der Sinuskurve

Table 2: Altitude gradient of δ18O in precipitation computed for Jalovecky creek catchment [‰ per 100m] (Holko 1995)

Tabelle 2: Berechneter Höhengradient des $\delta^{18}O$-Gehalts (in ‰ per 100m) im Niederschlag für das Jalovecky creek Gebiet (aus Holko, 1985)

Month	Nov.	Dec.	Jan.	Feb.	March	April	May	June	July	August	Sept.	Oct.
$\delta^{18}O$	-0.18	-0.06	-0.07	0.29	0.08	-0.11	-0.27	-0.12	-0.28	-0.25	-0.22	-0.26

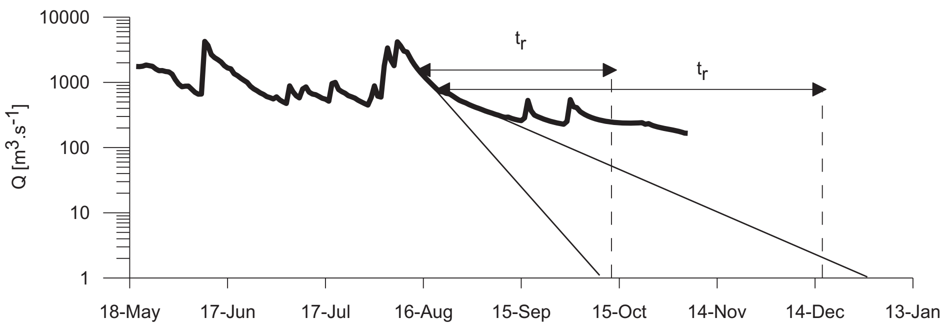

Figure 2: Estimation of the recession time t_r from the recession limb of hydrograph; the example from the Jalovecký creek mountains shows two typical recession sections – the longer and the shorter ones

Abbildung 2: Abschätzung der Auslaufzeit t_r aus der Auslaufkurve mit langer und kurzer Dauer am Beispiel Jalovecký creek

river basin were of 6.0, 5.6 and 5.5, respectively and the corresponding amplitudes of ^{18}O in runoff were 0.6, 0.7 and 0.8. The calculated mean transit times are given in Table 3. The mean transit times estimated by isotopic method range from 13 months in the largest Váh river basin to 19 months in the smallest mountain part of Jalovecký creek catchment. In our opinion the seemingly negative relationship between the calculated MTTs and catchment area reflects the differences in runoff formation in the catchments. The smallest catchment is a steep mountain catchment where the bedrock is influenced by deep weathering zones. As much of the catchment is covered by the Quaternary glaciofluvial sediments, the catchment behavior is closer to porous than fissured aquifer. We assume that the catchment as a whole contributes to runoff and therefore the flowpaths are relatively longer. The dominant topographic unit of the largest catchment is the large main river valley formed by river terraces and alluvia. Therefore the bulk of the river water probably comes from areas which are relatively close to the river. It results in a relatively shorter MTT.

The recession analysis revealed two typical hydrograph recessions. Thus, two values of MTT were calculated from hydrograph recessions for each catchment (Table 3). The longer recession could represent the MTT of baseflow. The MTTs calculated from recessions do not exhibit a relationship with the catchment area. The shortest MTTs (9 and 24 months) were calculated for the mountain part of the Jalovecký creek catchment. Compared to the MTTs calculated for this catchment using isotopes the result is completely opposite. MTTs for the Váh river basin (15 and 35 months) were between the values for mountain part of the Jalovecký creek catchment and the whole Jalovecký creek catchments.

The isotopic method was not used to calculate the MTT of baseflow. Therefore, comparisons between the results for isotopes and hydrograph recession were possible only for the MTT of streamflow (shorter hydrograph recession). Values given by the two methods (isotopes and shorter hydrographs recessions) were comparable for the two larger catchments (Table 3). MTTs calculated by isotopes and hydrograph recession for the smallest catchment differed.

Summer is the time of maximum annual precipitation in the studied region. Frequent rainfall events result in numerous runoff events. Therefore, long runoff data series should be used to obtain more hydrographs with undisturbed recessions.

Table 3: Mean transit times calculated in the 3 catchments by isotopic method and hydrograph recession.

Tabelle 3: Berechnete mittlere Laufzeit dreier Testgebiete aus Isotopenerfahren und Auslaufkurvenanalyse.

Catchment	Mean transit time [months]		
	Isotopes	Hydrograph recession - longer	Hydrograph recession – shorter
Jalovecký creek mountain area	19	24	9
Jalovecký creek - whole catchment	15	45	19
Váh river	13	35	15

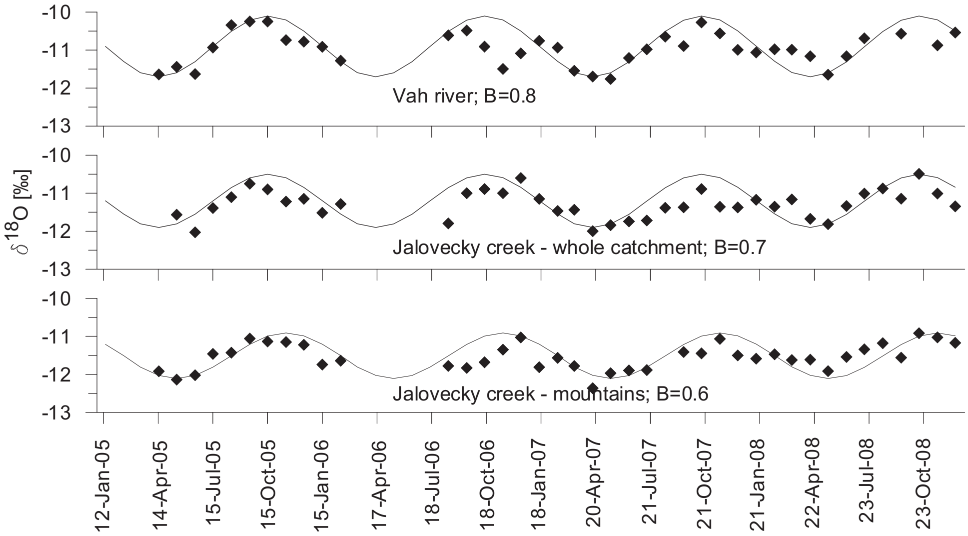

Figure 3: $\delta^{18}O$ in runoff from the studied catchments fitted by the sine curves and calculated amplitudes (B)
Abbildung 3: $\delta^{18}O$ Konzentration im Abfluss der Untersuchungsgebiete als Sinuskurve angenähert und den Amplituden (B)

Conclusions

MTT calculated by the isotopic method was comparable with that calculated from the hydrograph recession (i.e. shorter recessions) for the two larger catchments. In the small mountainous catchment, the MTT obtained from a longer recession was closer to the MTT calculated by the isotopes. The isotopic method preferably needs about 3 years of data to calculate the MTT. Because the number of undisturbed recessions in the studied area during a year is relatively small, longer data series of discharge (e.g. 10 years) are needed to obtain more representative results. Comparison of the isotopic and hydrograph recession approach to MTT estimation should be conducted in more catchments with available data.

Acknowledgement

This study was supported by the IAEA project CRP F3.30.15, MVTS IAEA and VEGA grant 2/0079/08.

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