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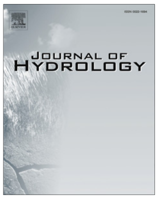

Research papers

Accounting for seasonal isotopic patterns of forest canopy intercepted precipitation in streamflow modeling

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ABSTRACT

Forest canopy interception alters the isotopic tracer signal of precipitation leading to significant isotopic differences between open precipitation (δOP) and throughfall (δTF). This has important consequences for the tracer-based modeling of streamwater transit times. Some studies have suggested using a simple static correction to δOP by uniformly increasing it because δTF is rarely available for hydrological modeling. Here, we used data from a 38.5 ha spruce forested headwater catchment where three years of δOP and δTF were available to develop a data driven method that accounts for canopy effects on δOP. Changes in isotopic composition, defined as the difference δTF-δOP, varied seasonally with higher values during winter and lower values during summer. We used this pattern to derive a corrected δOP time series and analyzed the impact of using (1) δOP, (2) reference throughfall data (δTF_{ref}) and (3) the corrected δOP time series (δOP_{Sine}) in estimating the fraction of young water (F_{yw}), i.e., the percentage of streamflow younger than two to three months. We found that F_{yw} derived from δOP_{Sine} came closer to δTF_{ref} in comparison to δOP. Thus, a seasonally-varying correction for δOP can be successfully used to infer δTF where it is not available and is superior to the method of using a fixed correction factor. Seasonal isotopic enrichment patterns should be accounted for when estimating F_{yw} and more generally in catchment hydrology studies using other tracer methods to reduce uncertainty.

1. Introduction

Forest canopy interception increases the time for precipitation to reach the forest floor and reduces rainfall amounts due to evaporation. Additionally, evaporation also changes the isotopic composition of precipitation by isotopic fractionation, usually enriching the remaining water (Cappa et al., 2003, Dewalle and Swistock, 1994). A recent review summarized 24 interception studies and found a mean enrichment of around 0.2‰ for oxygen-18, with several studies exceeding mean enrichments of 0.5‰ (Allen et al., 2016). Although seldom, even isotopic depletion of throughfall was observed. These studies did not find temporal stability of interception-induced isotopic changes (Allen et al., 2014; Brodersen et al., 2000).

The isotopic difference of precipitation above (open precipitation, OP) and below the canopy (throughfall, TF) becomes important when using the stable isotopes of water (δ^2H and $\delta^{18}O$) of OP (δOP) as input data to hydrological models assuming strictly conservative behavior. So far many studies focused on describing stable isotope patterns of TF (δTF) (Ikawa et al., 2011; Pichon et al., 1996; Xu et al., 2014), but only few used δTF in hydrological modeling (Gibson et al., 2000; Fitzgerald et al., 2003; Liu et al., 2015). However, previous studies on hydrograph separation (Kubota and Tsuboyama, 2003) and on transit time distribution estimation (Stockinger et al., 2015) have revealed significant differences when using δOP or δTF for forested locations. Both studies demonstrate that the use of biased input data can lead to misinterpretation of catchment runoff generation processes. A skewed estimate of the amount and timing of the arriving water may impact the prediction of nutrient and dissolved organic matter transport to groundwater and streams (Bachmair et al., 2009; Gottselig et al., 2014).

δTF is seldom available at a specific location due to technical, administrative and/or financial restrictions. Therefore, several correction methods were presented in literature to quantify the effect of canopy interception on δOP. Stockinger et al. (2014) and Calderon and Uhlenbrook (2014) proposed a constant correction factor of 0.5‰ and 1.4‰, respectively. A more complex approach of weighing measured open precipitation, deciduous forest and coniferous forest throughfall isotope data based on land use percentages was suggested by Stockinger et al. (2016). However, a simple shift of isotopic data to account for enrichment might not

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be adequate because temporal differences in the δOP to δTF relationship may occur on different timescales, e.g. annual, seasonal or event.

One emerging tool where interception effects could have important effects is the fraction of young water (F_{yw}). F_{yw} has been proposed as a measure for characterizing the fast flow component of water transport through a catchment (Kirchner, 2016). It represents the percentage of water in streamflow that is younger than a certain threshold age τ_{yw} and is derived from tracer data. Interception effects on F_{yw} cannot be corrected with the constant correction factor applied in previous studies, as it uniformly shifts all data points towards more positive values. This in turn will not change the parameters necessary to calculate F_{yw} (the amplitude and phase shift of a fitted sine wave; see also Section 2 of this study).

In the present study we analyzed temporal δ^{18}O patterns of a three-year time series of OP and TF in a coniferous and a deciduous forest. Our results suggest that a seasonally variable correction of δOP data is needed and we therefore developed a respective correction method. We calculated F_{yw} using the corrected δOP and compared this to F_{yw} derived from δTF (the reference) and the uncorrected δOP. F_{yw} results were compared to test if our correction improves F_{yw} results towards the reference.

2. Methods

2.1. Study site

Coniferous forest TF and OP data was obtained from the Wüstebach headwater catchment (38.5 ha) of the Erkensruhr River, Germany, which is part of the Lower Rhine/Eifel Observatory of the Terrestrial Environmental Observatories (TERENO) network (Zacharias et al., 2011). Elevation ranges from 595 to 628 m asl., with the climate being humid temperate with mean annual precipitation of 1107 mm (1961–1990) and a mean annual temperature of 7 °C (Zacharias et al., 2011). The bedrock consists of Devonian shale with sporadic inclusions of sandstone (Richter, 2008). Soils are up to 2 m deep with an average depth of 1.6 m (Graf et al., 2014). Soil types of cambisol and planosol/cambisol are found on hillslopes, whereas gleysols, histosols and planosols are found in the riparian zone. During the time of our investigation most of the catchment was homogeneously covered with Norway spruce (*Picea abies*) and Sitka spruce (*Picea sitchensis*) (Etmann, 2009), while 8 ha (~21%) was clear-cut approximately at the start of the time series.

Deciduous forest TF was obtained from the station "Im Brand" which is a natural forest reserve. The station is located at 480 m a.s.l. in the Erkensruhr catchment (Fig. 1) and lies about 7.5 km north of the Wüstebach catchment. The site is covered by 65–80 years old beech trees. The climate, soil and bedrock characteristics are comparable to the Wüstebach site. More detailed descriptions of the Erkensruhr catchment can be found in (Stockinger et al., 2016) and (Cornelissen et al., 2016).

2.2. Measured data

Weekly isotope data (δ^{18}O) relative to Vienna Standard Mean Ocean Water (VSMOW) (Brand et al., 2014) and volume data of TF and OP were collected from April 12, 2013 to March 5, 2016 (Supplement Fig. S1). Due to collinearity, only δ^{18}O was used in the analysis but no δ^{2}H. At each location TF was collected with six samplers (RS200, UMS GmbH, Germany) while OP was collected at Wüstebach with two samplers of the same design. The samplers consisted of 1.80 m vertical pipes which were buried approximately 30 cm in soil in a distance of 2 m to each other and 2 m from tree trunks. A mesh-protected funnel with a diameter of 20 cm was installed on top which led precipitation water via an approximately 2 cm diameter plastic tube to a collection bottle which was placed inside the samplers. Those measures were taken in order to prevent evaporative loss and thus isotopic fractionation of the collected water. The system was already shown to be reliable in this context as well as representative for the forested Wüstebach area (Stockinger et al., 2015). The TF and OP samples were volume-weighed on a weekly basis to create a TF and OP precipitation input time series, respectively. The TF data of Wüstebach used in this study partly contains the TF data already presented by Stockinger et al. (2015) and in comparison doubles the time series length from 1.5 to 3 years.

In addition, we used rain- and snowfall data from the meteorological station Kalterherberg (German Weather Service, station number 80115, 535 m asl.) which is located nine km northwest of Wüstebach. Rainfall data of 1 h intervals in 0.1 mm increments was used to volume-weigh isotope values during the calculation of F_{yw}. Finally, we used temperature data of the meteorological station Schöneseiffen (620 m asl., 3 km to the northeast) to further analyze isotopic Oxygen-18 enrichment patterns.

F_{yw} was calculated time-weighed by further using weekly isotope data from stream water grab samples taken at the Wüstebach runoff gauging station (Fig. 1). The grab samples were volume-weighed according to runoff at the moment of sample collection. They are mostly representative of base flow conditions.

Water isotopic analysis was carried out using laser-based cavity ringdown spectrometers (models L2120-i and L2130-i, Picarro). Internal standards calibrated against VSMOW, Standard Light Antarctic Precipitation (SLAP2) and Greenland Ice Sheet Precipitation (GISP) were used for calibration and to ensure long-term stability of analyses. The precision of the analytical system was ≤0.1 ‰ for δ^{18}O.

2.3. Pattern analysis and young water fractions

The isotopic change Δδ due to forest canopy interception in Wüstebach was calculated as the difference δTF-δOP. We assumed that the δOP measurements at this location were representative for the whole Erkensruhr catchment (Fig. 1). However, due to small scale isotopic differences the calculation of Δδ for station "Im Brand" was not possible.

Upon visual inspection a seasonal pattern in Δδ was apparent which was then fitted to a sine wave function (Fig. 2, Eq. (1)). By adding the respective values of this sine wave to each δOP data point we derived $\delta\text{OP}_{\text{Sine}}$ which better represents δTF. To verify this, we calculated a reference F_{yw} and compared it to F_{yw} results based on δOP (assumed to give less similar results to the reference) and $\delta\text{OP}_{\text{Sine}}$ (assumed to give more similar results to the reference). The reference F_{yw} was derived by weighing δTF and δOP according to land-use percentages (forested: 79%, deforested: 21%, Fig. 1), which will from now on be referred to as $\delta\text{TF}_{\text{ref}}$.

In the following, we briefly explain the calculation of F_{yw} (for a detailed description we refer to Kirchner (2016)). The method assumes a conservative tracer passing through the catchment, i.e., the only change the tracer undergoes from input to output solely happens due to hydrological processes connected with water flow. Usually, precipitation (input) and streamflow (output) are used as their stable water isotopes show an annual sinusoidal signal.

We used multiple linear regressions with the sine and cosine components as the independent variables to fit sine waves to the tracer input and output signals (Eq. (1)). The respective amplitudes (A_p and A_s) and phase shifts (φ_P and φ_S) were subsequently calculated (Eq. (2)) (Kirchner, 2016; Stockinger et al., 2016):

$$C_P(t) = a_P\cos(2\pi ft) + b_P\sin(2\pi ft) + k_P,$$