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Research papers

Tracer sampling frequency influences estimates of young water fraction and streamwater transit time distribution

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A B S T R A C T

The streamwater transit time distribution (TTD) of a catchment is used to derive insights into the movement of precipitation water via various flow paths to the catchment's stream. Typically, TTDs are estimated by using the convolution integral to model a weekly tracer signal measured in streamflow. Another approach for evaluating the transit time of water to the catchment stream is the fraction of young water (F_{yw}) in streamflow that is younger than a certain threshold age, which also relies on tracer data. However, few studies used tracer data with a higher sampling frequency than weekly. To investigate the influence of the sampling frequency of tracer data on estimates of TTD and F_{yw}, we estimated both indicators for a humid, mesoscale catchment in Germany using tracer data of weekly and higher sampling frequency. We made use of a 1.5 year long time series of daily to sub-daily precipitation and streamwater isotope measurements, which were aggregated to create the weekly resolution data set. We found that a higher sampling frequency improved the stream isotope simulation compared to a weekly one (0.35 vs. 0.24 Nash-Sutcliffe Efficiency) and showed more pronounced short-term dynamics in the simulation result. The TTD based on the high temporal resolution data was considerably different from the weekly one with a shift towards faster transit times, while its corresponding mean transit time of water particles was approximately reduced by half (from 9.5 to 5 years). Similar to this, F_{yw} almost doubled when applying high resolution data compared to weekly one. Thus, the different approaches yield similar results and strongly support each other. This indicates that weekly isotope tracer data lack information about faster water transport mechanisms in the catchment. Thus, we conclude that a higher than weekly sampling frequency should be preferred when investigating a catchment's water transport characteristics. When comparing TTDs or F_{yw} of different catchments, the temporal resolution of the used datasets needs to be considered.

1. Introduction

Many studies of catchment transit time distributions (TTDs), representing the different flow paths taken by precipitation water during catchment passage, and of the mean transit time (MTT), the average time a water parcels needs to exit the catchment after entering it as precipitation, used weekly sampling intervals for chemical (Hrachowitz et al., 2009; Molenat et al., 2013) or isotopic tracer data (Rodgers et al., 2005; Stockinger et al., 2014; Tetzlaff et al., 2007; Viville et al., 2006). Only few studies applied data with a higher sampling frequency (Kirchner et al., 2000; Roa-Garcia and Weiler, 2010). For example, using a sub-daily sampling frequency for several events, Roa-Garcia and Weiler (2010) found evidence of time-variable MTTs when looking at event and base flow conditions. Birkel et al. (2012) refined this knowledge by estimating TTDs of a one year long time series using daily precipitation and weekly, daily and 4 h (during two events) streamflow stable isotope data ($\delta^{18}O$ and $\delta^{2}H$), respectively. They found evidence for time-variable TTDs with summer and winter runoff events differing in MTTs. Consequently, Birkel et al. (2012) argue for the value of high-frequency sampling to evaluate the feasibility of MTTs derived with data sets of e.g., weekly sampling intervals. This argument is supported by findings of Berman et al. (2009), who found fine-scale changes in the isotopic composition of precipitation measuring up to 90 samples per day. Additionally, the need for high-resolution tracer data to move forward in the hydrological

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sciences was recently emphasized (McDonnell and Beven, 2014), while Kirchner et al. (2004) pointed out the importance of high-frequency chemical data for a better understanding of catchment hydrology.

The effect of sampling frequency of tracer data on estimates of MTTs was investigated by Hrachowitz et al. (2011). They used weekly precipitation and stream isotope data to estimate MTTs of a Scottish catchment and found increasing errors in MTTs while increasing the sampling interval up to 8 weeks. They argue that internal catchment processes will be misrepresented when using a reduced sampling frequency.

More recently, the study of Timbe et al. (2015) of a tropical montane cloud forest catchment compared different sampling frequencies of stable isotope data ranging from daily to bimonthly and found that it affected estimates of TTDs for soil and stream water. However, in their study the case of daily sampling intervals was based on daily precipitation data only, while the stream was sampled weekly. Additionally, modeling focused on baseflow conditions, as samples of several rainfall-runoff events were discarded, potentially missing faster flow conditions in their analysis.

The effect of using long-term isotope tracer data of streamwater and precipitation with a daily or sub-daily sampling frequency on estimated TTDs and MTTs has not yet been studied. Considering the argument of Hrachowitz et al. (2011) that high-resolution data can potentially better represent internal catchment processes, the hydrological community faces the risk of acquiring a biased understanding of catchment runoff generation processes when using low temporal resolution data. Furthermore, the comparison of TTDs of different catchments derived from data sets with different sampling frequencies may lead to ambiguous results (e.g., the study of Heidbüchel et al. (2012) using fortnightly isotope tracer data for one catchment, while using daily isotope tracer data for a different catchment).

Many of the prior studies used the convolution integral approach to derive the TTD and MTT from tracer data. Recently, Kirchner (2016a) and Kirchner (2016b) tested a similar approach by fitting sine waves to the tracer signal of precipitation and streamflow and derived the MTT using the change in amplitude and the occurring phase shift. Both studies show that the sine wave method is not able to derive correct MTTs under the condition of spatial heterogeneity (Kirchner, 2016a) and non-stationarity (Kirchner, 2016b). As every catchment is heterogeneous and non-stationary to some degree, the sine wave fitting method is not suitable to derive TTDs and MTTs. Accordingly, a new measure was proposed which could be correctly estimated, which is the fraction of young water, F_{yw} (Kirchner, 2016a). F_{yw} represents the fraction of water that is younger than a certain threshold age. It remains a topic of future studies to test whether the convolution integral suffers from equal aggregation bias errors as the sine wave method.

In this study, we investigated the hypotheses that (1) a higher sampling frequency improves the quality of stable isotope modeling of streamwater in terms of an objective function metric, and (2) the TTD is a function of sampling frequency. To this end, we estimated TTDs using the convolution integral approach. As Kirchner (2016a) showed the potential of aggregation bias error when using the convolution integral, which would result in a highly uncertain understanding of the impact of sampling frequency on a catchment's water transport characteristics, we additionally investigated an independent proof-of-concept metric with the hypothesis that (3) F_{yw} is a function of sampling frequency.

The data for this study consisted of stable isotope data ($\delta^{18}O$) with a temporal resolution of 0.5 day for precipitation and daily and 4 h for streamflow under baseflow and event conditions, which were mathematically aggregated to a weekly temporal resolution.

2. Methods

2.1. Study site

The Erkensruhr catchment (41.7 km^2) is located in the western part of Germany at an altitude between 286 m asl. in the northern to 631 m asl. in the southern part (Fig. 1). The catchment's climate is humid with a distinct precipitation gradient (annual precipitation increases from 740 mm in the eastern part to 1150 mm in the western part). The mean annual temperature ranges from 7.6 °C for higher to 10.0 °C for lower altitudes. The catchment is part of the national park Eifel and dominantly covered by coniferous forest in the south and deciduous forest and grassland in the north (Fig. 1, Table 1). Soils in the catchment primarily are cambisols with the exception of river valleys where gleysols and planosols can be found. The base rock is Devonian clay shale with sandstone intrusions (Stoltidis and Krapp, 1980).

2.2. Measured data

We used hydrological and isotopic data to estimate TTDs and F_{yw} for the time period of 3rd October 2012 to 8th March 2014. Additionally, data from 24th November 2010 to 2nd October 2012 was used to spin up the model that was applied to estimate TTDs (Fig. 2, Fig. S1 in Supplemental Material).

Precipitation amount data (1 h resolution, 0.1 mm increment) was acquired from the Schöneseiffen meteorological station (620 m asl.) located at the southeastern border of the catchment (Fig. 1). To account for the catchment's precipitation gradient we used precipitation radar data from the Neuheilenbach station (585 m asl., German Weather Service, DWD). Radar pixel sizes varied between 0.95 and 2.1 km^2 and precipitation was determined in five minute intervals. A global rescaling factor was applied to the precipitation amounts of each pixel so that the value of the pixel to which the Schöneseiffen station belongs equals '1'. We then calculated the arithmetic mean of the pixel values within the Erkensruhr catchment to represent the catchment's average areal precipitation amounts in comparison to Schöneseiffen. Finally, the Schöneseiffen precipitation time series was multiplied with this value to rescale it to the Erkensruhr precipitation input. Additionally, snow data acquired from the meteorological station Kalterherberg (German Weather Service, station number 80115, 535 m asl.) located approximately 9 km to the west of the Erkensruhr catchment was used to account for snow blanket buildup in hydrological modeling.

Stream stage data (15 min resolution, 1 mm increment) is available from 2001 to the present (courtesy of the local water board, Wasserverband Eifel-Rur) and was converted to runoff using a polynomial regression to the 4th power (R^2 = 0.99, not shown). Situated in the south of the Erkensruhr catchment lies the well-studied Wüstebach sub-catchment which is one of the Terrestrial Environmental Observatories (TERENO) test sites (Bogena et al., 2015; Zacharias et al., 2011). Soil water content (SWC) data from this location was used to aid in estimating TTDs of the Erkensruhr.

As about 55% of the catchment is forest-covered and canopy interception influences the estimates of TTDs (Stockinger et al., 2015), different kinds of precipitation $\delta^{18}O$ samples were taken at three different locations throughout the catchment: (1) throughfall (TF) samples of a deciduous forest (Im Brand, IB) in weekly resolution; (2) TF samples of a coniferous forest (Wüstebach, WU) in weekly resolution; and (3) open land (OP) samples at the Schöneseiffen meteorological station in 0.5 day resolution. We could not sample the location Im Brand from 6th November 2012 to 17th May 2013 due to administrative issues. While TF was sampled using RS200 samplers that were already successfully applied in