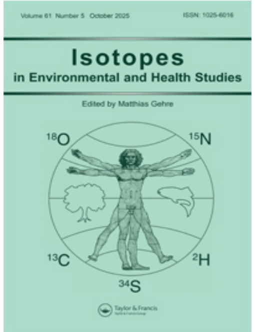

Isotopes in Environmental and Health Studies

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HYDROLOGY & HYDROGEOLOGY

Dynamics of stable isotopes in precipitation, soil water and groundwater at a Norway spruce and a European beech site at Solling, Germany

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ABSTRACT

Ongoing changes in climate alter the role of forests in the hydrologic cycle, influencing water transmission to springs and aquifers. Here we compared two forests dominated by either beech or spruce on broadly similar soils (Dystric Cambisols); we monitored the passage of natural-abundance stable isotope signals through the upper meter of soil and onward to springs. The isotopic data were similar between the sites at every time step and at every stage of transit, except at 90–100 cm depth, where the isotopic signal of the beech forest was delayed by approximately 1 month. The data were used in a lumped parameter dispersion model so that physical parameters describing transport could be determined and compared. Modeled residence times were similar between the two forests (123 (sd = 32) vs. 152 (25) days), with high precision to depths of 40 cm. According to the model, rainfall reached 1 meter depth in 200 (8) days under the spruce stand, but required 228 (37) days in the beech. The measurements below the rooting zone (90–100 cm) play a critical role in detecting site/species differences and in prediction of residence times.

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Stable isotopes; soil water movement; residence time; lumped parameter modeling; Solling forest experimental site

1. Introduction

Ongoing changes in climate conditions such as increasing air temperature and more frequent and extended dry periods [1,2] force enhanced risk to forests and the development of adapted management strategies for forest managers and ecosystem resilience are needed. Suitable management strategies adapted to cope with climate change effects at forests in Germany, which should be specific for different tree species, are still under debate [3,4]. Predicted changes of environmental conditions will affect soil water conditions, groundwater recharge patterns and overall water availability for forests. An interaction of all such changes is complex and rather difficult to predict. Unsaturated flow and

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groundwater recharge in solid rock formations, especially for forested mountainous areas, is spatially heterogeneous as well as temporally variable due to flow through preferential pathways and fractures. Interdisciplinary approaches, which are integrating forest ecological, pedological and hydrogeological knowledge, are indispensable to identify governing processes.

Stable isotope methods provide unique possibilities for characterizing water components and processes such as interception, evaporation and water movement, and have been extensively used, e.g. for soil water investigations [5–8]. Soil water stable isotope composition reflects precipitation input patterns, which are altered by interception processes depending on, e.g. forest type and structure [9–12] and soil water evaporative loss. Root water uptake and stem transport generally do not fractionate; therefore water in the stems can be compared to soil water to assess water sources [13–15]. Soil water stable isotope studies require either *in situ* sampling of soil water or water extraction methods performed on collected soil samples in the laboratory. Many different methods are discussed such as cryogenic vacuum extraction, equilibration methods, centrifugation [16–19], which are all labor-intense. Lysimeters, which collect soil water *in situ*, are less time and labor intensive once they are installed, but they sample only the mobile water fraction [18]. Time series derived from lysimeter studies therefore might differ from those derived by other methods of soil water extraction.

Multiple studies focus on models of soil water transport using stable isotope signals [7,9]. Model choice depends on the complexity of the model and the system under study, but also on the availability of system information, including climate and soil parameters that have to be measured or estimated in advance at the study site. At the forest experimental site (FES) Solling in Germany, long-term forest ecological, hydrochemical and hydrological observations are available for comparative studies of a Norway spruce and a European beech forest ecosystem [20]. Therefore, it is possible to investigate differences between forest trees using combined observational and modelling approaches.

Process-based water budget models are key tools for understanding water fluxes in forest ecosystems and forecasting the impact of climate change on drought stress and groundwater recharge. Such water budget models have been increasingly used as a tool for quantitative projections of the climate change effects and feedbacks for policy and forest management. However, with increasing model complexity there is a strong need for long-term datasets as quality control of the model evaluation and performance. The Solling FES is among the longest running intensive forest ecosystem studies worldwide. The data covers a period from 1966 to 2024. Although the measurements at Solling FES focused on soil chemistry and nutrient cycling, e.g. [20–23], model comparisons were also made with different water budget and ecosystem models [24–26].

Vegetation species differences in groundwater recharge have been assessed before, but mostly focused on woody rather than non-woody vegetation [27]. Woody vegetation is reported to draw more frequently on deep soil water, and even groundwater, relative to the grasses and shrubs around it [28]. A more focused study compared water use by two tree species, European beech versus Norway spruce, the same species studied here [29]. The spruce was much more dependent on soil surface water, which was treated as recent precipitation, relative to the deeper-rooted beech. The study used simple lumped parameter modelling to describe pronounced differences in mean residence times of the water in the soil profiles under the two species, but did not attempt to quantify groundwater recharge. Our study uses the same two species, but here we estimate residence times and compare them to water from nearby aquifers.

The objectives of this work are to use seasonal patterns in water stable isotope composition in different compartments of the hydrological flowpath to evaluate possible isotopic fractionation during interception and soil water evaporation, water uptake depths as well as residence times within the soil and to nearby springs. The observations are compared with the outcome of a simple dispersion model.

2. Study site and methods

The Solling FES is located in central Germany, 80 km southwest of Hannover at the northern edge of the Central German low mountain ranges (51°46′ N, 09°34′ E) at an elevation of 500–510 m above sea level (m asl) (Figure 1) [30]. The FES was established in 1966 as part of the International Biological Program (IBP) with two major study plots covered by monocultures of Norway spruce (*Picea abies* Karst L.) and European beech (*Fagus sylcvatica* L.) stands [31]. Later the plots were included into the Lower Saxonian Soil Protection Program as permanent soil monitoring plots as well as part of the Pan-European ICP Forests Level II network [32]. Further, FES is included in the Long-Term Ecological Research (LTER) network [20]. Meesenburg et al. [30] describe the current instrumentation of the site and the long-term monitoring infrastructure in more detail.

The mean annual precipitation is around 1100 mm (1146 mm for the period of 1990–2020 and 1078 mm for 2018–2023) of which 15–20 % falls as snow [20,30,33]. Highest annual precipitation in the study period was recorded for 2023 with 1558 mm and lowest years were 2022 with 826 mm and 2018 with 886 mm. The long-term average temperature is given as 7.3 °C [20] and between 2018 and 2023 a mean of 8.3 °C was

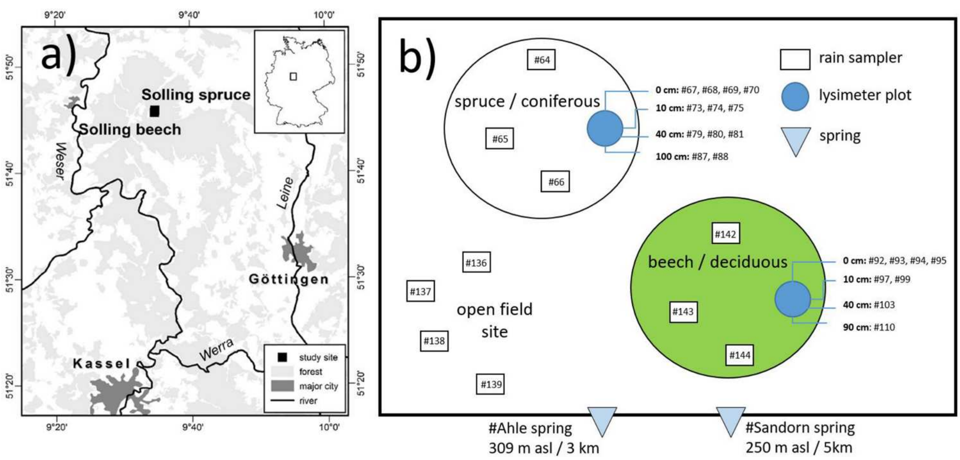

Figure 1. (a) Location of the Solling forest experimental site (FES) close to Göttingen in Germany with the beech and spruce forest plots, (b) sketch of stable isotope sampling infrastructure and installed probes at the study site, where labels of probes refer to those given in text and figures.

Table 1. Characteristics of spruce and beech plots at the Solling FES, Germany.

	Solling spruce	Solling beech
Altitude (m asl)	504	508
Slope (°)	0–1	0–2
Aspect	East	South
Forest stand species	Norway spruce	European beech
Stand age in 2023 (years)	142	177
Quadratic mean diameter of the mean basal area tree 2023 (cm)	40.7	39.1
Stand height of the mean basal area tree 2023 (m)	32.3	27.7
Basal area (m^2/ha)	30.7	26.1
Stand density (N/ha)	236	218
Solid volume over bark in 2023 (m^3/ha)	438	407
Geology	Sandstone with loess cover	Sandstone with loess cover
Soil type according to WRB	Albic Endoprotostagnic Podzol	Dystric Cambisol
Humus type	morlike moder	typical moder
Precipitation 2018–2023 (mm/year)	1078	
Precipitation May-October 2018–2023 (mm/year)	455	
Mean temperature 2018–2023 (°C)	8.3	
Mean temperature May-October 2018–2023 (°C)	13.7	

observed. The warmest years measured in this period were 2022 and 2023 with 8.6 °C and 2018 and 2020 with 8.5 °C. In both stands, some sanitary fellings have been necessary in recent years due to pathogenic fungi (beech plot) and bark-beetle outbreaks (spruce plot).

The geology at the FES consists of Triassic sandstone which is covered with 60–80 cm thick solifluction layers of loess material. Soils are mainly developed from the acid and nutrient poor loess material and are described as Dystric Cambisols or Stagnic Podzols. At both sites, the base saturation is < 5 % and the pH($CaCl_2$) < 4 in most horizons of the upper 100 cm [34]. The soil is covered by a sparse herb layer, dominated by *Oxalis acetosella* and *Luzula luzuloides* [30]. The natural vegetation at the study site is an oligotrophic beech forest. The two major monitoring sites comprise a European beech (*Fagus sylvatica* L.) stand which is 176 years old and a Norway spruce (*Picea abies* Karst L.) stand of 141 years age (2024, Table 1). Whereas the deciduous beech stand is close to the natural vegetation of the Solling plateau, the coniferous spruce stand represents a major productive forest type of the region.

2.1. Monitoring and sampling methods

Meteorological data (precipitation, air temperature, humidity, global radiation and wind speed) were obtained from observations at a clearing in the open field site. For gap filling, observational data from climate and precipitation stations of the German Meteorological Service (Deutscher Wetterdienst, DWD) were used. The regionalization to the study sites was performed using the methods described by Ahrends et al. [35]. A statistical bias correction using empirical quantile mapping for daily regionalized climate data for gap filling was performed with the R package hyfo [36].

Precipitation amounts were collected every 2 weeks as totals at four rain samplers at an open plot (samplers # 136, 137, 138, 139) in about 500 m distance north of the beech and 100 m west of the spruce plot. Because we wanted to describe the amount and isotopic composition of water that reached the forest floor in more detail, below the canopy 15 collectors at each forest plot were installed (Figure 2). Three composite samples (beech:

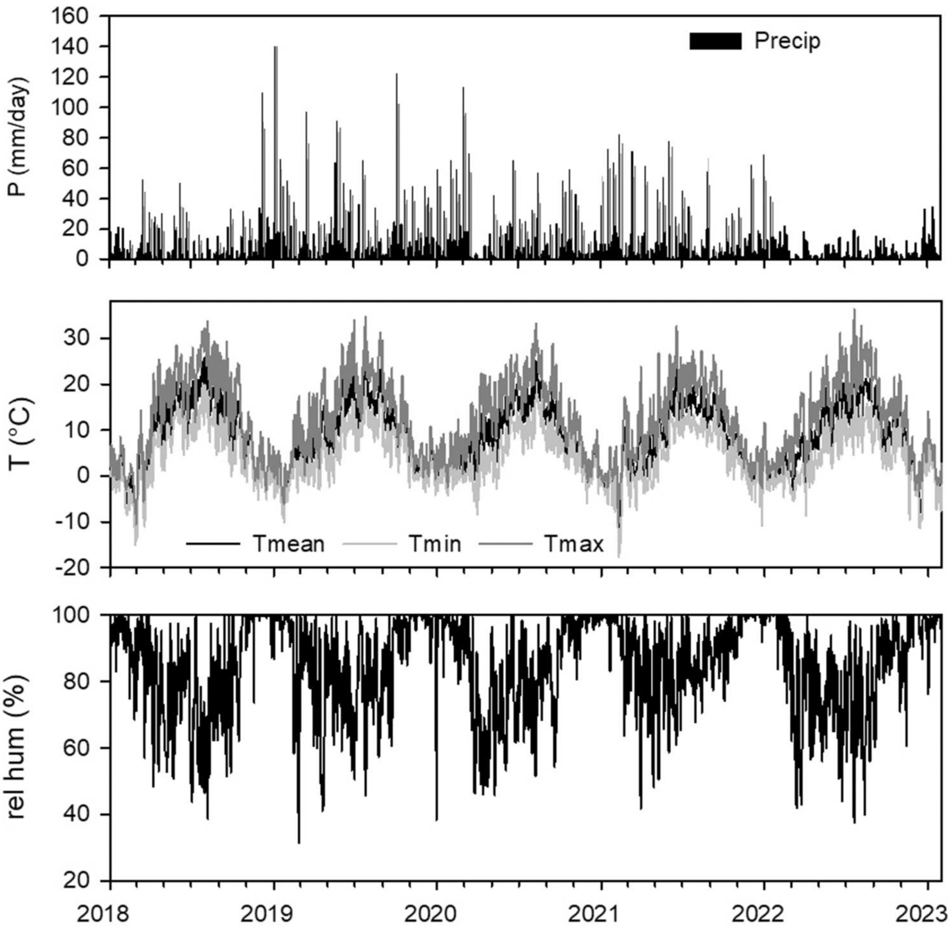

Figure 2. Climate conditions (precipitation *P*, temperature *T* and relative humidity) during the study period from 2018 to 2022.

142, 143, 144; spruce: # 64, 65, 66) were obtained from the 15 collectors. The collectors are placed at the beech and spruce plots, respectively, to cover the spatial variation in throughfall [37,38]. Mean volume weighted values were calculated for the open field, beech and spruce plot.

At each forest plot, suction lysimeters collected soil water at different depths with three to four replicates according to the standards of ICP Forests [39,40]. At the spruce plot, soil water was collected bi-weekly from February 2018 to October 2022 at depths of 0, 10, 40 and 100 cm and at the beech plot at 0, 10, 40 and 90 cm. The 0-cm depth describes the interface between the forest floor and the mineral soil. Samples underwent hydrochemical, isotopic and volume analyses.

Groundwater samples were collected bi-weekly as grab samples at two sites, the Ahle spring (51°43′ N, 9°30′ E, 309 m asl, mean discharge MQ = 1.3 m^3/s, approximate catchment size of 143 km^2) and at a local water supply (Sandborn). 30 ml brown glass bottles with tight seals were used to prevent evaporation out of the bottles and growth of microorganisms during storage.

2.2. Laboratory methods

All samples were analyzed for stable isotope composition at the Federal Institute for Geosciences and Natural Resources (BGR) in Hannover, Germany, measuring δ^2H and $\delta^{18}O$ simultaneously using a Picarro L2130-i cavity ring down laser spectrometer after vaporization (VAP 214 vaporizer). All samples were measured at least four times and the reported value is the mean value. All values are given in standard delta notation in per mil (‰) versus VSMOW.

Raw data were corrected for memory effects and excluded if necessary. The data sets were corrected for machine drift during the run and normalized to the VSMOW/SLAP scale by assigning a value of 0 and −428 ‰ (δ^2H)/−55.5 ‰ ($\delta^{18}O$) to VSMOW and SLAP, respectively. For normalization, two laboratory standards, which were calibrated directly against VSMOW and SLAP, were measured in each run. External reproducibility – defined as standard deviation of a control standard during all runs – was better than 0.8 and 0.20 ‰ for δ^2H and $\delta^{18}O$, respectively.

2.3. Modeling

A lump parameter model using analytical equations built within R-software was applied. Theory and application of lumped parameter models for environmental tracers in groundwater systems are described by Maloszewski and Zuber [41]. The models are characterized by residence time distribution functions of tracer (e.g. δ^2H) between inflow (recharge) and outflow (e.g. discharge). The functions are adjusted according to the hydrological system knowledge [42]. Input time series for δ^2H in precipitation for soil water models were calculated using bi-weekly samples of precipitation from the Solling FES (2018–2022) (Figure 2). Data gaps were filled by linear interpolation between neighboring values. For the models of spring water, the bi-weekly samples from the Solling site were aggregated to precipitation-weighted monthly averages and for prior years monthly values from the German Isotope Network (GIN) stations Wasserkuppe (140 km away from the study site), Bad Salzuflen (65 km) and Hannover (75 km) for the period of 2008–2017 were used.

The time-dependent input function $C_{in}(t_i)$ of δ^2H in precipitation was calculated according to Maloszewski et al. [43]:

$$C_{in}(t_i) = \frac{[N\alpha_i P_i(C_i - C_{mean})]}{\sum_{i=1}^{N}(\alpha_i P_i) + C_{mean}}, \tag{1}$$

where N is the number of time steps, a_i is the infiltration coefficient for time step i, P_i is the amount of precipitation for time step i, C_i is the δ^2H value, C_{mean} is the mean δ^2H in precipitation of the entire modeling period. The models were fitted to the observed δ^2H time series in soil water of both sites at all lysimeter depths as well as for water of the Ahle and Sandborn springs. Model fitting and parameter uncertainty were estimated using a Bayesian approach. Bayesian analysis is a combination of the data likelihood and the prior distribution using the Bayes theorem [44] using the log-likelihood of a simulation given the observations and standard deviations at each model realization. The *a posteriori* parameter distribution was estimated using the Differential Evolution Markov Chain Monte-Carlo (DE-MC) algorithm with three sub-chains [44] implemented in the R package

BayesianTools [45]. The number of iterations was 9000 for each individual fitting to ensure a Gelman–Rubin reduction factor < 1.1. We assumed mixing of water in soil and hence applied a simple dispersion model for δ^2H values in soil water. Fitting parameters were therefore residence time *t* and the dispersion parameter PD as well as *α* and an arbitrary value to compensate for the different weighted δ^2H value averages between input and observation point.

For δ^2H values in spring water either dispersion, exponential or linear models were possible due to the assumed geometry of the aquifer. The dispersion and exponential model functions gave unsatisfactory fitting results (not shown). Therefore, we applied only the linear model assuming an unconfined aquifer with constantly increasing thickness from recharge to discharge area. The estimation of *α* for the catchment area of the Ahle spring followed the method according to Grabczak et al. [46], which uses the stable isotope compositions of the precipitation in the summer months and winter months, respectively; and mean isotopic composition of local groundwater. An arbitrary value to compensate for the differently weighted δ^2H averages between input and observation point was also applied. From all accepted model runs, 108 were randomly selected at each individual location to evaluate average model results and standard deviations of the fitted parameters.

3. Results

3.1. Stable isotope composition of precipitation and throughfall

Stable isotopes composition of precipitation was observed in the open field and in a beech and spruce plot within a few hundred meters distance. Time series of stable isotope composition from the beginning of 2018 to end of 2022 are shown in Figure 3 (upper part) together with monthly precipitation amounts over the 5-year period. In comparison to precipitation at the open site, throughfall from both spruce and beech tends to be enriched by approximately 0.1–0.2 ‰ for $\delta^{18}O$ and 1 ‰ for δ^2H. This enrichment was more pronounced for the beech than for the spruce site. Stable isotope mean values for the months October to March are generally more depleted than those from April to September and deuterium excess values ($d = \delta^2H - 8*\delta^{18}O$) for the summer months are lower than those for winter months (see Table 2). The values of the beech site are most enriched during months April to September, whereas the months of October to March, when the beech is leafless, are close to open field site precipitation. For the colder period, the spruce forest has more enriched values than the open and beech sites. The local meteoric water line (LMWL) calculated for Solling ($y = 7.51x + 7.33$, $R^2 = 0.97$) is close to that of Hannover ($y = 7.31x + 3.38$, $R^2 = 0.97$) and shown in comparison to the global meteoric water line (GMWL, $y = 8x + 10$) in Figure 4.

Observed and long-term mean stable isotope values for precipitation and throughfall are shown in Figure 4 and listed in Table 2.

3.2. Stable isotope composition of soil solution

Soil water isotopes collected from lysimeters installed at depths of 0 cm (below forest floor), 10, 40 and 90 cm (beech)/100 cm (spruce) below mineral soil surface are shown in Figures 4(b) and 5. In Figure 4, mean values of all respective soil solution samples of each horizon are plotted in δ^2H versus $\delta^{18}O$ space. Figure 5 shows mean values of δ^2H

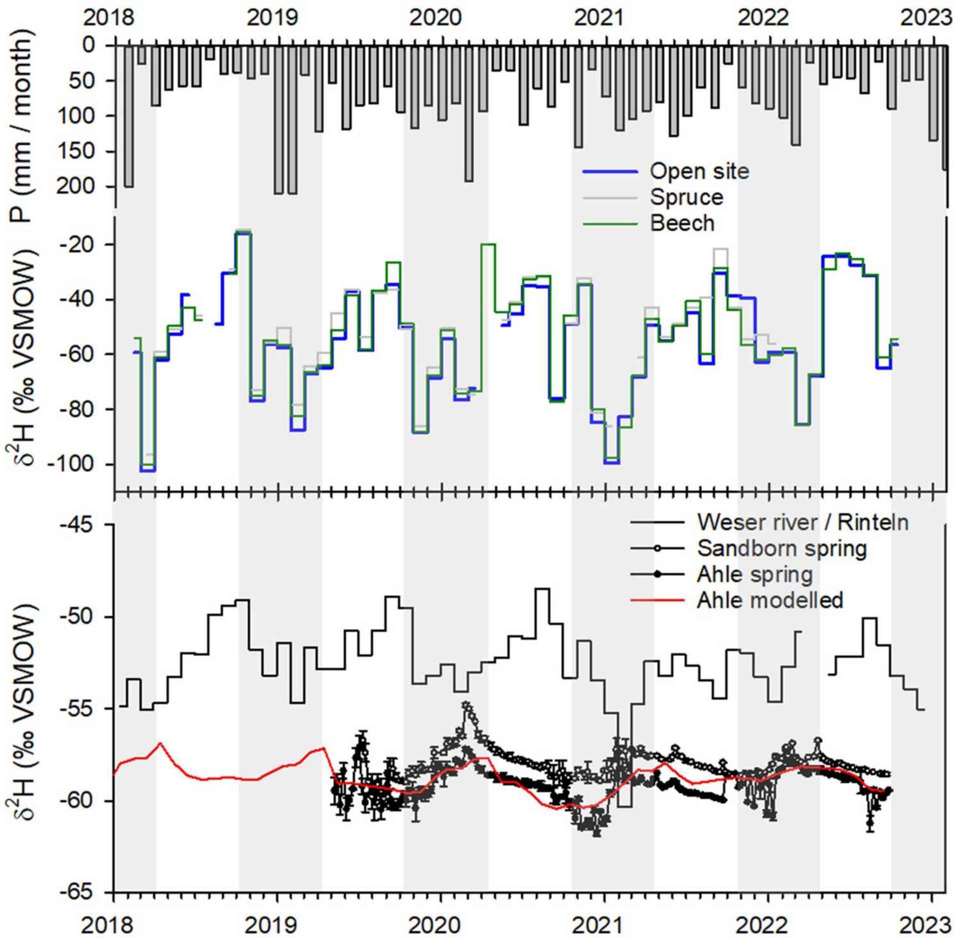

Figure 3. (top) Precipitation in mm per month and bi-weekly δ^2H composition of precipitation at the open (blue color) and throughfall sites in the spruce (black color) and beech forest (green color) and (bottom) δ^2H composition of water at Sandborn (white symbol) and Ahle springs (black symbol) with standard deviations for replicate measurements. A lumped parameter model fitted to the Ahle spring values is given as red line. Grey-shaded areas indicate months of October to March. For reference, also monthly values of the Weser River at Rinteln are included.

Table 2. Long-term (2018–2022) mean stable isotope and deuterium excess (*d*) values and standard deviation (sd) of precipitation and throughfall at the Solling FES, Germany. *n* indicates the number of mean values calculated per plot (in brackets the total number of samples analyzed for each plot).

		n	$\delta^{18}O$ (‰)	sd	δ^2H (‰)	sd	*d* (‰)	sd
Mean	Open field	107 (275)	−8.11	2.80	−53.6	21.3	11	4
	Spruce throughfall	89 (190)	−8.01	2.59	−51.6	20.4	12	4
	Beech throughfall	112 (212)	−7.91	2.71	−51.5	20.9	12	3
Apr–Sep	Open field	59 (141)	−7.14	2.19	−46.5	16.4	10	3
	Spruce throughfall	44 (88)	−6.99	2.07	−44.2	15.7	11	4
	Beech throughfall	63 (111)	−6.89	2.20	−41.1	16.5	11	3
Oct–Mar	Open field	48 (134)	−9.24	2.86	−61.7	22.5	12	4
	Spruce throughfall	45 (102)	−9.04	2.62	−58.9	21.7	13	3
	Beech throughfall	49 (101)	−9.13	2.65	−60.0	21.9	13	3

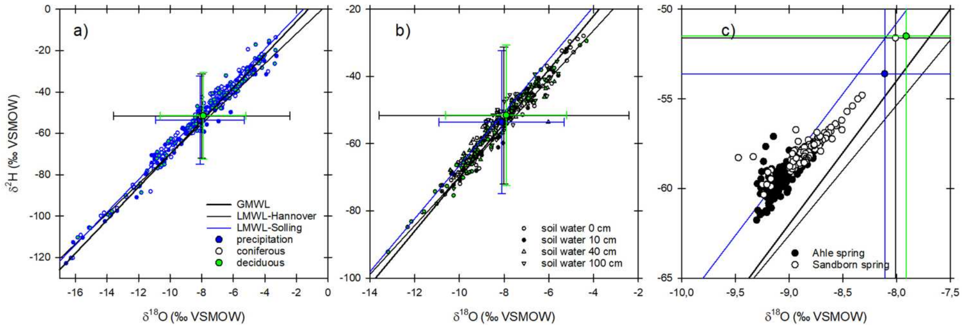

Figure 4. δ^2H versus $\delta^{18}O$ plot of (a) precipitation, (b) soil water and (c) springs (groundwater) collected at the Solling experimental forest site (FES). Cross symbols indicate long-term mean values with amplitudes for precipitation at the open site (blue), spruce forest (black) and beech forest (green) (given as reference in each plot) as well as global (GMWL) and local (LMWL) meteoric water lines calculated for Solling and Hannover precipitation.

as time series together with the respective values of each lysimeter to interpret soil or infiltration inhomogeneity. Soil solution isotope composition shows seasonal patterns reflecting precipitation input with increased damping with depth (Figure 5(a–d)). There are only small differences in the upper soil (0 and 10 cm depth) between beech and spruce. With increasing depth, there seems to be higher variability in the beech plot and larger differences between both forest plots (Table 3). The mean stable isotope values at the spruce plot indicate more positive values in the upper layers, whereas at the beech plot mean values do not vary with soil depth.

3.3. Spring water isotope composition

Spring water isotope composition is shown in Figure 3 (lower part). The time series of the observed δ^2H values for the two springs Ahle and Sandborn are in bi-weekly resolution and monthly values of the Weser River at Rinteln are shown for comparison. The mean values for Ahle spring are about 0.2 and 1.3 ‰ more negative than those for Sandborn spring for $\delta^{18}O$ and δ^2H, respectively (Table 3), indicating a slightly higher mean catchment elevation for the latter. A clear seasonality is visible for both springs and for the Weser River at Rinteln. δ^2H values of spring water are more negative (−9.0 and −58 for $\delta^{18}O$ and δ^2H, respectively) than those of soil water (Table 3), and spring water values are closer to those of winter precipitation (Table 2).

3.4. Stable isotope modelling

Modeled values are included in Figure 3 for the Ahle spring and Figure 5 for the different soil depths at the spruce and beech plots. The seasonal stable isotope signal of precipitation is transferred to lower soil layers and groundwater with an increasing time delay and amplitude dampening. The fitting parameters used for the lumped parameter model are shown in Table 4. The δ^2H time series in the soils can be explained with a dispersion model. Only the data on the beech plot at a depth of 90 cm differs, but is adequately explained by a combination of two dispersion models. This model can be used

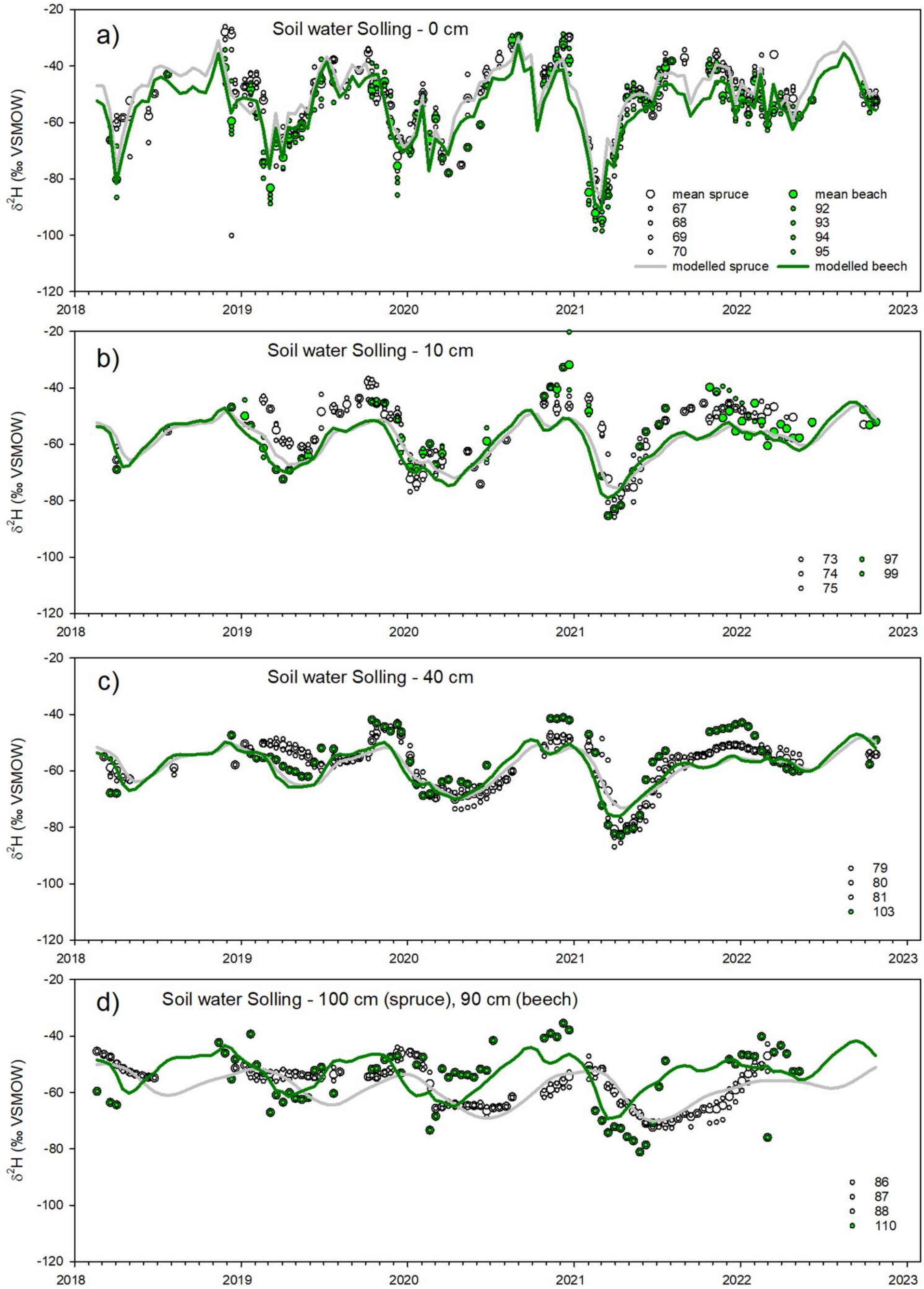

Figure 5. Measured and mean values of δ^2H from each soil water probe (probe numbers according to overview map Figure 1) of the lysimeter plots at the spruce (black symbols) and beech forest (green symbols) collected in soil depths of (a) 0 cm, (b) 10 cm, (c) 40 cm and (d) 100 cm (90 cm for the beech plot). Grey and green lines indicate modeled results for spruce and beech respectively.

Table 3. Long-term mean (2018–2022) stable isotope, deuterium excess (*d*) values and standard deviation (sd) for soil water samples and springs at the Solling FES, Germany. *n* indicates the number of mean values calculated per depth (in brackets the total number of samples taken at each depth).

		Depth (cm)	*n*	$\delta^{18}O$ (‰)	sd	$\delta^{2}H$ (‰)	sd	*d* (‰)	sd
Soil lysimeter	Spruce	0	77 (266)	−7.88	1.73	−51.4	12.7	12	3
		10	63 (124)	−8.43	1.46	−55.8	10.8	12	3
		40	89 (249)	−8.86	1.16	−58.1	8.5	13	2
		100	84 (154)	−8.80	0.93	−57.8	7.3	13	3
	Beech	0	74 (251)	−8.55	1.87	−56.4	14.1	12	3
		10	56 (65)	−8.53	1.69	−56.5	12.7	12	3
		40	67	−8.64	1.52	−56.9	11.1	12	3
		90	69	−8.41	1.52	−55.3	11.2	12	2
Spring water	Ahle		176	−9.03	0.14	−59.2	0.9	13	1
	Sandborn		149	−8.85	0.17	−57.9	0.8	13	1

to interpret a fast and a slow flow component, whereby 25 ± 14 % of the water volume (p) can be assigned to the slow component. The residence time (*t*) generally increase with depth and the dispersion (progressive mixing) (PD) of the infiltrating water with the soil water generally decrease with depth. An exception is again the beech plot at a depth of 90 cm, where the residence times deviate from this trend. However, the strength of the mixing at this point is probable: longer flow paths mean stronger mixing. Overall, the PD values are probable and up to a depth of 40 cm in the same order of magnitude for both plots. For the beech plot at a depth of 90 cm, the mixing for both components is comparatively higher, whereas on the spruce plot the mixing does not increase further from 40 cm to a depth of 100 cm. The infiltration coefficient (*α*) for the soil models is around 60 ± 10 %. Both efficiency measures, the Nash–Sutcliffe efficiency (NSE) and the Kling–Gupta efficiency (KGE) are predominantly above 0.5 (Figure 6).

The $\delta^{2}H$ time series of the Ahle spring is well explained with a linear model. The derived residence time of about 990 days is probable in comparison to that of the soil (Table 4). The linear model represents an unconfined aquifer whose thickness increases from the catchment area to the sampling point. This assumption is probable for the sandstone aquifer in question. The model efficiency is sufficient with values > 0.5.

4. Discussion

Seasonal differences of stable isotope concentrations in precipitation can be used for an interpretation of soil water transport and residence times as was shown in earlier works [5,7,9,47]. In winter, due to lower temperatures and snow formation, δ-values of precipitation are more negative and show a higher *d*-excess. During summer months, the temperature effect as well as enhanced loss of water by interception and evaporation causes more positive δ-values and lower values of *d*-excess (Table 2). Precipitation isotope variability between spruce and beech sites at FES was lower than expected. Both spruce and beech showed slightly higher mean isotope values than open field precipitation (Figure 4). Throughfall was not enriched as described, for example, in Brodersen et al. [10] for a site with spruce and beech stands in southern Germany. Likewise, snow enrichment caused by snowmelt and throughfall, which were reported by Koeniger et al. [11] for dense (spruce) forest during winter in Idaho, USA, were not observed here. This might be

Table 4. Black box model parameters (residence time *t* in days, dispersion parameter PD, infiltration coefficient *α*, fraction *p*, Nash–Sutcliffe efficiency (NSE), Kling–Gupta efficiency (KGE) and regression coefficient R^2) for δ^2H values of soil water from spruce and beech plots at Solling FES and Ahle spring.

			Depth (cm)	*t* (days)	sd (days)	PD (–)	sd (–)	*α* (–)	sd (–)	*p* (–)	sd (–)	NSE (–)	KGE (–)	R^2 (–)
Soil lysimeter	Spruce	(DM)	0	32	0.4	0.87	0.09	0.61	0.11	–	–	0.69	0.78	0.70
			10	129	32	0.43	0.20	0.62	0.12	–	–	0.48	0.61	0.71
			40	152	25	0.35	0.13	0.58	0.11	–	–	0.65	0.67	0.69
			100	200	8	0.14	0.03	0.60	0.11	–	–	0.66	0.76	0.69
	Beech	(DM)	0	36	8	0.72	0.16	0.60	0.11	–	–	0.82	0.79	0.83
			10	115	35	0.60	0.23	0.58	0.12	–	–	0.56	0.65	0.76
			40	123	32	0.41	0.21	0.61	0.10	–	–	0.56	0.60	0.69
		(2DM)	90	96	22	0.34	0.10	–	–	0.75	–	0.43	0.47	0.44
				625	132	0.22	0.16	–	–	0.25	0.14			
Spring water	Ahle	(LM)		990	9	–	–			–	–	0.54	0.78	

DM = dispersion model, LM = linear Model, 2DM = two linear combined DMs.

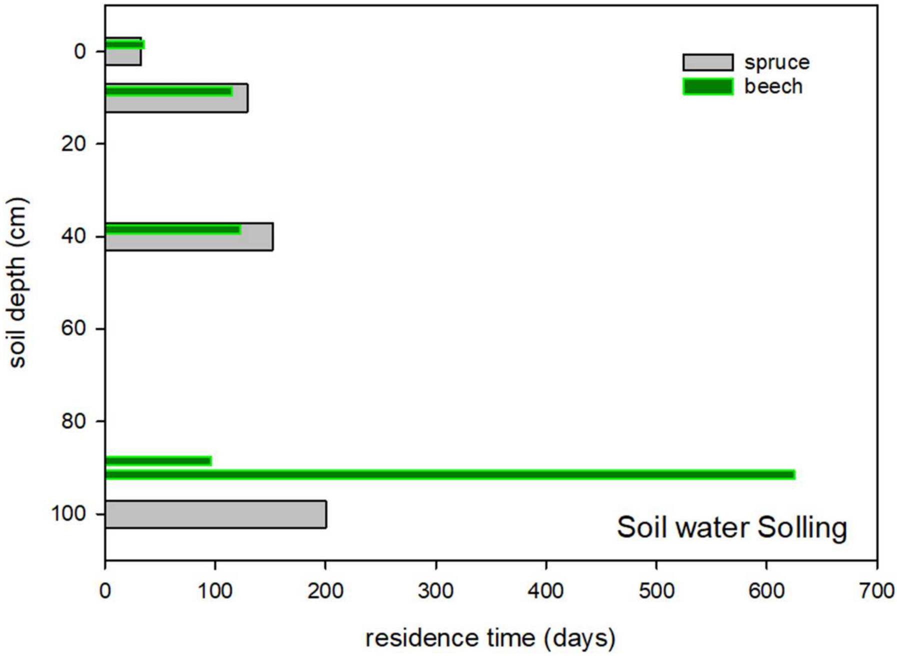

Figure 6. Comparison of residence times (days) derived for different soil depths (cm) at spruce and beech forest of the Solling experimental forest site (FES).

due to less frequent sampling and snow campaigns with higher spatial resolution during snowmelt might be necessary to detect such signals. In Canada, Snelgrove et al. [48] reported recently no consistent evidence of isotopic enrichment of throughfall and stemflow relative to gross rainfall or of stemflow relative to throughfall for red oak or eastern hemlock but found enrichment for white pine [48,49].

Temporal trends of observed isotopic composition correlate well with climate patterns, especially temperature, e.g. the lowest δ^2H signal in February and March 2021 coincides with lowest mean daily and minimal daily temperatures (Figure 2). This isotope signal is transferred to deeper soil layers during the summer season 2021. The phase shift and damping of this pattern is well represented by modeled time series (see Figure 5, and discussion below). The highest δ^2H signal was observed in rain during October 2019 (however, it did not cause significant changes in soil water signals) which might have been caused by other large precipitation events during that time.

Soil water stable isotope composition is surprisingly homogeneous within each plot as indicated by replicate samples. In Figure 5, δ^2H values from all lysimeters indicate good replicability with only some outlier values, e.g. for December 2018 and August 2020 for the uppermost (0 cm) layer in the spruce plot (black symbols), and in July and December 2020 in the 10 cm layer for the beech plot (green symbols). However, there is a clear variability between the plots, and it increases with depth. The biggest difference was observed in the deepest layers for the spruce and beech sites. This may be important because these layers are most likely to contribute to deep recharge.

Less soil water was collected during the summer months (June to September), when the soil water content is low due to transpiration. This may be regarded as a disadvantage of field sampling via lysimeters. Extraction methods would have enabled sampling of soil water during summer as well, because it is possible to collect soil water also at lower soil water contents [19,50]. However, pore water collected during dry soil conditions is of limited value as this soil water fraction would contribute little to recharge.

A lumped parameter model approach (dispersion model) was used to fit observed soil water isotopic composition (Figure 5). For model input we used time series from Solling precipitation. For extrapolation to longer time span four nearby precipitation stations were added (Hannover, Wasserkuppe, Braunschweig and Bad Lippspringe, stations of the German isotope network, GIN). The precipitation signal, which is transferred to soil and springs, was derived by using the parameterization given in Table 4. The mixing in the soil is in relation to the flow length (extraction depth) of the leachate, the residence times are within an expected range at given soil properties (relatively high effective field capacity) and the climatic boundary conditions (amount of precipitation) (Figure 6). Only for the beech plot at a depth of 90 cm, the results are less convincing. Although the slow component with a retention time of 625 days has a small share of only 25 % of the total water volume; this is very uncertain with a standard deviation of 14 %. The deviation of observations at different depths of the spruce and beech plots potentially have various reasons. On the one hand, the installation of the sampling system can cause differences. On the other hand, it may be due to effects caused by soil heterogeneity, e.g. preferential flow paths in combination with particularly impermeable areas. The comparison with the residence time of the water in the Ahle spring and the associated catchment area size makes the long residence time at 90 cm improbable. The probability of the model combination with regard to the underlying flow processes in the soil should therefore first be questioned and the quantification by the model should be substantiated or refuted with further investigations, data or progress in the future. More detailed modeling with Hydrus-1D [51] and Brook90 [52,53] will implement this data set and other experimental results in future work. The simulations fit best for the uppermost layers (0 and 10 cm depths), while performance is less accurate for the deeper layers 90/100 cm (see Table 4). Most likely transport processes such as macro pore flow (preferential flow paths) are not adequately described by the current lumped parameter approach [54].

In general, there are only minor differences in isotope patterns between the two forest types in the upper soil layers. Throughfall input shows only minor differences. However, soil water of the deepest monitored layer (100 cm for spruce and 90 cm for beech) differs significantly. For beech only one suction lysimeter was available and for spruce there were three replicates. Additional replicates at the beech plot would have been useful. However, the modeling results indicate that the mean residence time (*t*) for the soil water at 90–100 cm depth is more than 28 days shorter in the spruce forest (200, sd = 8 days) than in the beech forest (228, sd = 37 days). The higher uncertainty in the beech forest resulted from the need to fit two flow components: a major component, with 75 % of the flow, had residence time 96 days and a minor component, with 25 % of the flow, had residence time 625 days (Table 4). The need to split the flow into two components and the higher uncertainty that resulted might be related to (localized) heterogeneities in the beech forest [55,56]. The differences observed between the two sites could be due to the soil at the beech forest site being 10 cm shallower. However, mean residence times are not always higher with higher soil thickness [57]. Stumpp et al. [58] showed the relevant effects of soil texture, precipitation intensity, vegetation, etc. with respect to preferential flow, which may alter the calculated results. However, many studies are conducted in sandy soils or Karst due to the relevance of preferential flow [59–62], which is not expected to significantly influence the results in Solling, so they are not directly comparable. Ma et al. [63] show that $\delta^{18}O$ and $\delta^{2}H$ values from the upper 40 cm may be enriched due to evaporation processes in periods with low soil water content. This was not really the case in Solling: $\delta^{18}O$ and $\delta^{2}H$ increased in the spruce stand and only marginally decreased in beech (see Tables 2 and 3) and this may be attributed to generally high soil moisture. The difference in $\delta^{18}O$ and $\delta^{2}H$ values of the two sites could also reflect variable influence of interception and root water uptake.

5. Conclusion

For a 5-year observation period (from 2018 to 2022) and during the extraordinary dry years of 2018 and 2022 stable isotope time series for precipitation, soil water and springs were compiled for the first time at the Solling FES in central Germany. Solling FES is a long-term ecological research site with excellent meteorological and forest ecological monitoring infrastructure and serve as a reference site for large areas of German forests. Transport mechanisms and residence times of soil water and springs were studied using stable isotopes as environmental tracers. Soil lysimeters were used to collect mobile water from several depths up to 1 meter for a period of 5 years. The derived seasonal signals were damped with depth and interpreted using lumped parameter dispersion models to derive residence times and dispersion parameters. We found that water is infiltrating with a time delay of approximately 200 days to a depth of one meter. Residence times for a spring site (Ahle) showed a time delay of 33 months (990 days) and water from a supply well (Sandborn) show similar behavior. The difference of precipitation isotope input between an open site, spruce and beech forest was slight and soil water isotope composition was less heterogeneous than expected for the observed period.

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