

ORIGINAL RESEARCH ARTICLE

Wavelet analysis of soil water state variables for identification of lateral subsurface flow: Lysimeter vs. field data

Annelie Ehrhardt¹  | Jannis Groh^{1,2}  | Horst H. Gerke¹ 

¹ Leibniz Centre for Agricultural Landscape Research (ZALF), Research Area 1 “Landscape Functioning”, Working Group “Hydropedology” Eberswalder Straße 84, Müncheberg 15374, Germany

² Forschungszentrum Jülich, Agrosphere, Institute of Bio- and Geoscience IBG-3, Jülich, Germany

Correspondence

Annelie Ehrhardt, Leibniz Centre for Agricultural Landscape Research (ZALF), Research Area 1 “Landscape Functioning” Working Group “Hydropedology” Eberswalder Straße 84, 15374 Müncheberg, Germany.
Email: Annelie.Ehrhardt@zalf.de

Assigned to Associate Editor Majdi Abou Najm.

Abstract

Preferential and lateral subsurface flow (LSF) may be responsible for the accelerated transport of water and solutes in sloping agricultural landscapes; however, the process is difficult to observe. One idea is to compare time series of soil moisture observations in the field with those in lysimeters, where flow is vertically oriented. This study aims at identifying periods of deviations in soil water contents and pressure heads measured in the field and in a weighing lysimeter with the same soil profile. Wavelet coherency analysis (WCA) was applied to time series of hourly soil water content and pressure head data (15-, 32-, 60-, 80-, and 140-cm depths) from Colluvic Regosol soil profiles. The phase shifts and periodicities indicated by the WCA plots reflected the response times to rain events in the same depth of lysimeter and field soil. For many rain events and depths, pressure and moisture sensors installed in the field soil responded earlier than those in the lysimeter. This could be explained by either vertical preferential flow or LSF from upper hillslope positions. Vice versa, a faster response in the lysimeter soil could be indicative for vertical preferential flow effects. Dry weather conditions and data gaps limited the number of periods with elevated soil moisture in 2016–2018, in which LSF was likely to occur. The WCA plots comprise all temporal patterns of time shifts and correlations between larger data time series in a condensed form to identify potentially relevant periods for more detailed analyses of subsurface flow dynamics.

1 | INTRODUCTION

Lateral subsurface flow (LSF) or funnel flow describes the lateral redirection and funneling of water caused by textural boundaries in the soil (Gerke, 2006; Guo & Lin, 2018; Hendrickx & Flury, 2001). In agricultural landscapes, this phenomenon can potentially be responsible for accelerated

nutrient and pesticide transport from fields into adjacent water bodies like streams and kettleholes leading to a pollution of these ecosystems (Julich et al., 2017; Kahl et al., 2008). In mountainous regions, LSF is also known to promote the development of landslides (Wienhöfer et al., 2011). The LSF process has been studied; for example, in the Shale Hills Catchment (Guo et al., 2018) in a hummocky ground moraine in northeast Germany (Gerke et al., 2010; Filipović et al., 2018), in a soil cover over waste rock (Hopp et al., 2011), in forested hillslopes (Laine-Kaulio et al., 2014), and in an alpine region (Wienhöfer & Zehe, 2014).

Abbreviations: COI, cone of influence; FDR, frequency domain reflectometry; LSF, lateral subsurface flow; SWC, soil water content; Vol-%, unit of the volumetric soil water content in volume percentage; WCA, wavelet coherency analysis; WTC, wavelet coherency spectrum.

This is an open access article under the terms of the [Creative Commons Attribution-NonCommercial](https://creativecommons.org/licenses/by-nc/4.0/) License, which permits use, distribution and reproduction in any medium, provided the original work is properly cited and is not used for commercial purposes.

© 2021 The Authors. *Vadose Zone Journal* published by Wiley Periodicals LLC on behalf of Soil Science Society of America

The conditions for LSF are inclined soil layers with contrasting hydraulic properties and water saturation in the upper, more permeable soil layer (Laine-Kaulio et al., 2014; Liu & Lin, 2015). Lateral subsurface flow is occurring especially during periods of high soil moisture—for example, those induced by snowmelt (Wilcox et al., 1997). In unsaturated soils, water flow is mainly vertical as predicted by simulations based on the Richards equation (Filipović et al., 2018). Only if the soil water pressure head approaches a value of zero and capillary forces become negligible—for example, near impeding layers and less conductive soil horizons—the gravitational-driven LSF may occur (Lu et al., 2011; Lv et al., 2013). However, a vanishing of capillary forces does not necessarily mean that all soil pores are water saturated. The relation between pressure head and water content (i.e., water retention function) is not a unique and single function; it is hysteretic and changing with time due to local nonequilibrium processes (Hannes et al., 2016; Herbrich & Gerke, 2017), and it is affected by the spatial heterogeneity of local or pore scale and macroscopic soil properties at pedon and larger spatial scales (Filipović et al., 2019; Guo & Lin, 2018; Lin & Zhou, 2008). These effects may also occur in combination (Dasgupta et al., 2006); for instance, during vertical preferential flow through macropores, local nonequilibrium conditions in the pressure head between macropores and matrix can develop (Gerke, 2006). In such cases, water-saturated pore regions can occur locally where the macropore flow hits an impeding layer and from where lateral flow can be initiated (Newman et al., 2004). These authors also observed that LSF was starting from root macropores in the clay-enriched illuvial subsoil horizon after macropore-centred saturation. Earlier, Sidle et al. (2001) suggested from observations in sloping forest soils that vertical and lateral subsurface preferential flow paths are connected by a network of macropores forming the basis for lateral preferential flow in such sites.

In soil columns and lysimeters, lateral flow is restricted due to the limited size and fixed boundaries at the sides such that macroscopic flow is assumed to be predominantly vertical (Bravo et al., 2020; Wittenberg et al., 2019, 2020). Although macropore-centred saturation (Newman et al., 2004) due to vertical preferential flow can also occur in an intact soil monolith of a lysimeter, lateral water movement remains local and may occasionally lead to water movement along the interface between the soil and the sidewall of the lysimeter (Corwin, 2000). As indicated by two-dimensional flow simulations (Filipović et al., 2018), water dynamics in a sloping field soil may be assumed to start deviating from that in the same depth of a lysimeter if the soil is approaching pore water saturation at some point in the flow domain. It is likely to assume that with the beginning of lateral flow in the field, the pressure head increase will be limited at uphill positions while the increase in soil water content (SWC) will continue at downhill positions during a flow

Core Ideas

- Soil water content time series in weighing lysimeters are compared with those of field soil.
- Identification of lateral subsurface flow in sloping hummocky soil landscape.
- Deviations of lysimeter from field data depending on infiltration events.
- Wavelet coherency analysis to quantitatively describe temporal patterns of time shifts.

event. In contrast, the SWC in the lysimeter soil will increase faster above impeding horizons than in the field, where lateral downhill movement can reduce the pressure head buildup.

The observation of LSF and especially the detection of the beginning of LSF in the field soil is still a challenge (Lamb et al., 2019; Xie et al., 2019). Preferential flow was identified by comparing soil moisture – depth differences of larger time series according to response sequences (Graham & Lin, 2011; Wiekenkamp et al., 2016). Both vertical and lateral preferential flow pathways have been experimentally studied by various techniques including dye staining, using compounds such as uranine, brilliant blue FCF, or methylene blue (Alaoui et al., 2011; Luo et al., 2019). The dyes can be sprinkled onto the soil surface (Gerke et al., 2015) or injected during infiltration experiments (Nyquist et al., 2018). However, an adequate observation of deep dye patterns requires sectioning the soil along different vertical or horizontal planes, which necessitates extensive effort and destroys the soil in the process. More recently, geophysics techniques (e.g., electrical resistivity tomography [ERT] and ground penetrating radar [GPR]) were also adopted to investigate subsurface flow processes (Guo et al., 2020; Lamb et al., 2019). Although most techniques are either destructive or technically demanding, available data from common and field measurements (Pütz et al., 2016; Sommer et al., 2016), such as SWCs and pressure heads, could provide information on temporal dynamics of LSF.

Thus, we hypothesize that differences in the soil moisture dynamics between the field soil and the soil with a similar horizon sequence in the lysimeter will be indicative for the beginning of deviations from vertical flow in the field. We are aware that the possible occurrences of LSF and vertical preferential flow can only be indirectly determined with this approach; furthermore, data interpretation is affected by soil spatial heterogeneity and differences in plant and root distributions (Luo et al., 2019). The data analysis requires the evaluation and comparison of larger time series of water contents and pressure heads in order to capture a wide range of conditions that include both water saturated and unsaturated soil condition. In regions with relatively low annual

precipitation, such as in northeastern Germany (Herbrich & Gerke, 2017; Rieckh et al., 2012), transient near-saturated soil moisture conditions in subsurface horizons occur only infrequently.

One major challenge when analysing two time series of the SWC or the pressure head is to find possible correlations in these often nonstationary datasets (Ritter et al., 2009). Classical correlation analyses fail for datasets that include periodicities and trends (Biswas & Si, 2011). Temporal and scale variabilities in the relationship between two time series cannot be specified if an overall correlation coefficient over the entire period is calculated (Bravo et al., 2020; Hu & Si, 2013). Time series of soil water state variables underlie periodic fluctuations like diurnal, seasonal, and annual cycles (Herbrich & Gerke, 2017; Liu et al., 2017; Rahmati et al., 2020).

Time series analysis of periodic signals is based on wavelet transform (Torrence & Compo, 1998; Grinsted et al., 2004). The transfer from the time domain into the frequency domain is achieved by comparing the original signal with a set of template functions of known frequency (Farge, 1992). The wavelet analysis can be used to determine the correlation between two time series, even if they are shifted in time, by calculating the coherency between two wavelet spectra (Grinsted et al., 2004). Wavelet coherence is a statistical tool to determine the similarity between two time series. It can be compared with R^2 in regression analysis and varies between zero and one (Si, 2008).

Wavelet coherency analysis (WCA) has been applied to detect spatial and temporal variations of soil hydraulic properties along a transect in the loess plateau of China (Yang et al., 2018) and differences in the moisture dynamics inside and outside of lysimeters for volcanic ash soils in southern Chile (Bravo et al., 2020). Earlier, Yang et al. (2016) compared the temporal stability of the soil matric potential of grassland and cropland with WCA and found stronger temporal variations in shallower than in greater depths. In their analysis of a 16-yr SWC record, Wu et al. (2002) determined the time shift in the SWC response to precipitation with depth. Lee and Kim (2019) used WCA for identifying vertical preferential flow events from the time shift in depth-dependent SWC responses between closer and more distant soil horizons.

The objective of this study is to identify deviations between field and lysimeter time series of SWC and pressure head for the analysis of the possible occurrence of LSF. The deviations are separately interpreted for specific rain infiltration events in all four seasons by assuming that flow in the lysimeter soil is forced to be vertical. For the WCA, wavelet, cross wavelet, and wavelet coherency spectra are analyzed that are obtained from a unique dataset of time series of SWC and pressure heads in a colluvial soil profile of an arable soil landscape for the 2016–2018 period.

2 | MATERIALS AND METHODS

2.1 | Site and soil description

The datasets are from sensors installed in an intact soil monolith of a lysimeter and in the field at the monolith extraction pit. The field site is located in a hummocky ground moraine soil landscape at the CarboZalf-D experimental field of the Leibniz-Centre for Agricultural Landscape Research (ZALF), Müncheberg (Sommer et al., 2016) where the occurrence of LSF has been assumed (Filipović et al., 2018; Gerke et al., 2010). The site is located close to the village of Holzen-dorf, near Dedelow, northeast Germany (53°23' N, 13°47' E; 50–60 m asl). The average annual values of precipitation (495 mm), potential evapotranspiration (633 mm), and the annual mean air temperature (8.6 °C) were recorded from 1992 to 2016 at the Lysimeter Experimental Field Station Dedelow (53°22'2.45 N, 13°48'10.91 E) maintained by the ZALF (www.zalf.de). More information on the soils and hummocky arable soil landscape can be found elsewhere (Herbrich et al., 2017; Rieckh et al., 2012; Rieckh et al., 2014).

The 2-m-deep colluvial soil profile is from a toe slope position (Figure 1) where the slope angle was about 4%. The intact soil monolith was extracted at the location “field” (Figure 2) of the experimental site CarboZALF-D (53°22'43'' N, 13°47'01'' E in October 2012). The soil can be classified as Endogleyic Colluvic Regosol (IUSS, 2006) and consists of colluvial material down to about 70-cm depth (Figure 1) covering a former Luvisol soil profile with gleyic features at the bottom. The soil properties (Table 1) were determined from bulk and 300-cm³ core samples taken directly at the soil profile during the excavation of the soil monolith. Lateral flow could be expected to occur in the topsoil (Ap-horizon) above the plough pan and in the Ahb horizon above the relatively dense Btg horizon.

The unsaturated soil hydraulic conductivity, K , was determined by throughflow experiments with tension disc infiltrometers for core samples extracted in vertical, K_v , and horizontal, K_h , direction (Table 2). The K values at a pressure head, h , close to full water saturation ($h = -1$ cm) decreased about 20-fold from K_h of about 24 cm d⁻¹ towards a value of 1.0 cm d⁻¹ for the Btg-horizon. The values were higher in horizontal as compared to vertical direction (Table 2) for the Apb, Ahb, and Btg-horizons and the values of anisotropy ratios K_v/K_h are ranging between 0.4 and 0.7.

The soil monolith extraction, the lysimeter setup, and the installation of the sensors in the lysimeter soil and of the field soil profile was carried out by the company Umwelt-Geräte-Technik (UGT). A special soil cutting device was used that allowed for minimal disturbance during the extraction of the intact soil monolith and the surrounding field soil profile. The extracted soil monolith was fitted in a stainless steel cylinder

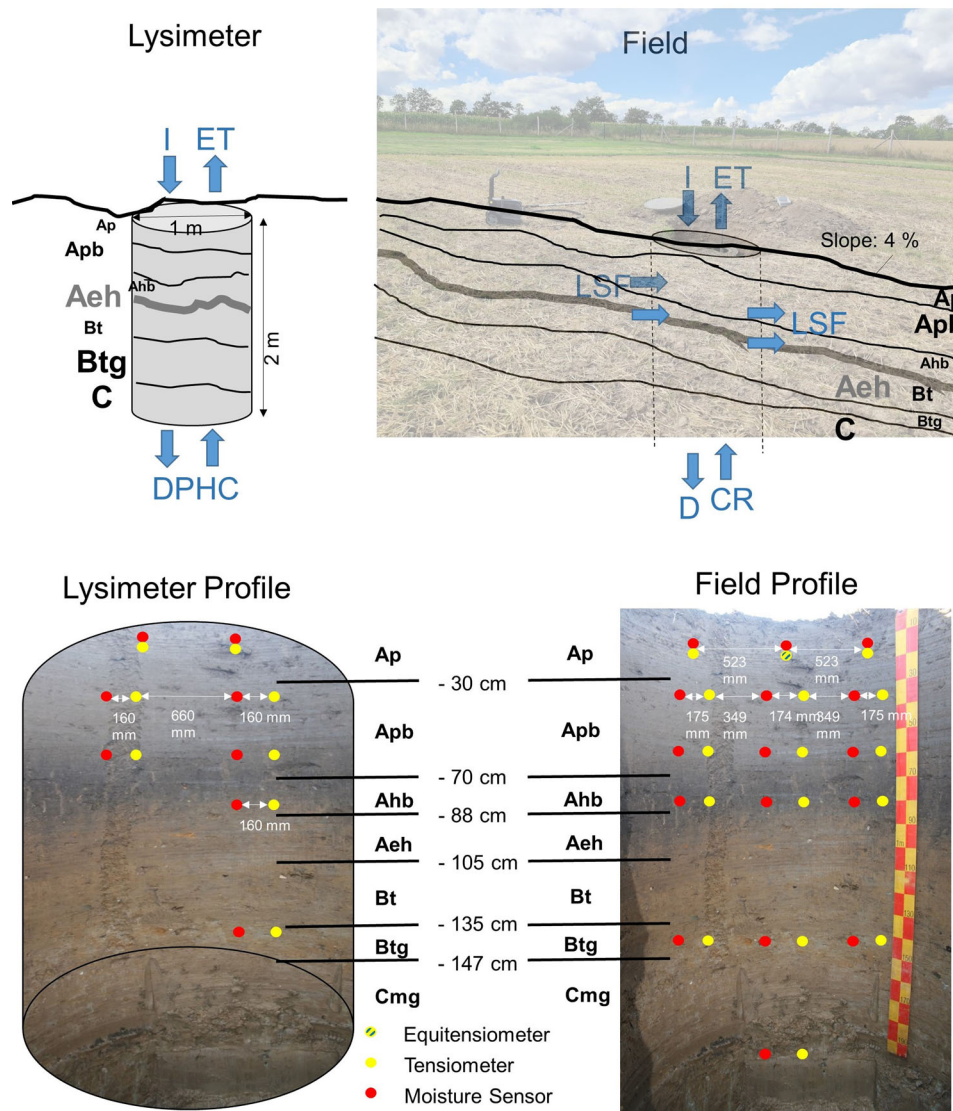


FIGURE 1 The lysimeter-field system with soil horizons and boundary conditions for the lysimeter (left) and the field (right) situation; upper two schemes: infiltration (I), evapotranspiration (ET), drainage (D), capillary rise from the water table (CR), dynamic pressure head control by soil water pressure head measured in the field (DPHC), lateral subsurface flow (LSF). Bottom pictures show the Endogleyic Colluvic Regosol soil profile after the extraction of the lysimeter and the location of the sensor installations of frequency domain reflectometry (red dots) and tensiometers (yellow dots) in the lysimeter (left) and the field (right). Soil horizons were classified according to IUSS (2006)

of 1-m² surface and 2-m height and moved to a lysimeter station located about 80 m northeast (53°23'21" N, 13°47'6" E) of the "field" extraction site (Figure 2). Here, the soil monolith lysimeter was placed in a larger polyethylene-casing box that was recessed into the ground such that the surfaces of the soil in the lysimeters and the surrounding soil were at the same level. A detailed description of the lysimeter equipment can be found elsewhere (Umwelt-Geräte-Technik, 2013). At the lysimeter bottom, the flux out of or into the lysimeter soil is controlled by filter panels that allow for conditions in the lysimeter soil that correspond with pressure head values measured in the field in a depth of 190 cm. By this dynamic pressure head control of the lysimeter's bottom boundary it was

intended to match the soil water dynamics according to that of the field soil. The idea was to mimic field conditions of both downward flow during times with a relatively shallow water table in the field and upward capillary water flow from deeper soil regions to avoid drier conditions and more reactive responses of the SWC on precipitation in the lysimeter as compared to the field soil (Groh et al., 2016).

At the monolith extraction site ("field" in Figure 2), a cylindrical plastic tube was inserted in the 2-m-deep hole to stabilize the profile walls and to be able to cover it later with topsoil after the installation was completed. From the inside of this 1-m² tube, the frequency domain reflectometry (FDR) sensors and tensiometers were horizontally inserted into the



FIGURE 2 Aerial image (capture date range: 30 June 2010 to 19 Sept. 2016) and map of the experimental field site (CarboZalf-D) located in northeastern Germany; the locations of the rain gauges and the “field” soil profile and “lysimeter” station. Locations of rain gauges for measuring precipitation are numbered (1–5), and instrument types are described (Table A2)

TABLE 1 Soil physical and chemical characteristics of the Endogleyic Colluvic Regosol (Figure 1): classification of soil horizons according to IUSS (2006) and KA5 (Ad-hoc-Arbeitsgruppe Boden, 2006); the organic C content (C_{org}), and the pH value (pH_{CaCl2}); and equivalent particle size of organic C-free and carbonate-free sieved (<2 mm) soil for sand (2–0.063 mm), silt (0.063–0.002 mm), and clay (<0.002 mm) (Michael Sommer, ZALF, personal communication, July 2020)

Horizon (IUSS, 2006)	Horizon (KA5)	Depth	Sand	Silt	Clay	C_{org}	pH_{CaCl2}
		cm	g kg ⁻¹				
Ap ^a	Ap	0–30	630	260	100	0.90	5.05
Apb ^a	M	30–70	590	310	110	0.44	5.87
Ahb ^b	fAh	70–88	570	280	150	0.56	6.39
AEh	fAh-Al	88–105	580	260	170	0.34	6.66
Bt	Bt-sGo	105–135	560	240	190	0.22	7.01
Btg	Bt-sGro	135–147	570	240	190	0.12	7.27
Cmg	elCc-Gor	>147	580	290	140	0.01	7.69

^aGray topsoil: sandy material from the eroded parts of the upper slope (E horizons).

^bFormer topsoil (dark color) with light colored filled earthworm burrows.

TABLE 2 Soil bulk density (ρ_b), soil hydraulic conductivity in vertical (K_v) and horizontal (K_h) direction measured at pressure head of $h = -1$ cm, and anisotropy ratio (K_v/K_h). Mean values, SD, and SE from five replicates are shown

Horizon	ρ_b		K_h			K_v			K_v/K_h
	Mean	SD	Mean	SD	SE	Mean	SD	SE	
	g cm ⁻³		cm d ⁻¹						
Apb	1.65	0.06	14.94	10.96	5.48	6.59	4.39	1.97	0.44
Ahb	1.63	0.03	23.72	22.32	9.98	14.38	13.28	5.94	0.61
Btg	1.82	0.07	1.02	1.13	0.51	0.70	0.15	0.07	0.68

surrounding soil at the same profile locations as in the lysimeter (Figure 1). Data from the field and the lysimeter were monitored in hourly intervals by data loggers outside the managed field plot connected with subsurface data cables. The plastic tube at the “field” was then closed and covered by about 35 cm of soil such that soil cultivation including plowing, seedbed preparation, crop management, and harvesting (Table A1 in the Appendix) could be carried out uniformly for the whole plot. The soil and crop management of the lysimeter was carried out manually, thus trying to imitate the management of the field plot.

Both soil profiles (i.e., “field” and “lysimeter”) were equipped with sensors for measuring SWC and soil water pressure head (Figure 1). The SWC was measured with FDR sensors (SM300, after August 2018: SMT-100, UGT) in up to three replicates per depths. The soil water pressure head was measured with tensiometers (Tensio160, UGT) and an Equi-tensiometer (EQ15, ECOMATIK) with a measurement range of up to $-1,500$ kPa and an accuracy of ± 10 kPa. The sensors were installed in 15-, 32-, 60-, 85-, 140-, and 190-cm depths in the lysimeter and in 15-, 32-, 55-, 80-, 140-, and 195-cm depths in the field. In the lysimeter, two sensors of each type were inserted down to 60-cm soil depth sensors and a single one in the depths below. In the field soil profile, three sensors of each type were inserted per depth level, except for 195-cm depth, where only one tensiometer and FDR-sensor were installed and in 15-cm depth, where one Tensio160 was replaced by the EQ15 (Figure 1). Data were recorded since August 2013 in uniform intervals of 1 h with data logger DL-2000 (UGT).

Precipitation was recorded by different types of rain gauges (Appendix, Table A2) at five locations distributed at the experimental field (Figure 2). The time-resolved precipitation data were aggregated to hourly sums and manually corrected for outliers. For the analysis, the arithmetic mean of corrected data of the available sensors was used. Here, field and lysimeter sensor data of the relatively wet year 2017 (656 mm yr^{-1}) were compared with those of the relatively dry years 2016 (385 mm yr^{-1}) and 2018 (303 mm yr^{-1}).

2.2 | Time series data gap filling procedure

The application of the WCA requires continuous time series without data gaps of a period that covers as much of the temporal variation as possible (e.g., Bravo et al., 2020, analyzed a period of several years); however, shorter periods have also been studied (Lee & Kim, 2019). Thus, a data gap filling procedure was used (see Appendix A3 for more details) to obtain consistent time series of comparable quality. Still, logger failures for a period of more than one day led to missing data that could not be reconstructed. Thus, only complete periods without data gaps in the time series were selected for the present

analysis. Data processing was carried out with the software R 3.6.2 (R Core Team, 2019).

2.3 | Wavelet analysis and WCA

The complex Morlet wavelet (wavenumber $k_0 = 6$) was applied here because it provided a balance between time and frequency resolution (Grinsted et al., 2004) and information about phase and amplitude of a signal (Torrence & Compo, 1998). Wavelet coherence (ρ^2) was calculated (Torrence & Webster, 1999) as

$$\rho_{X,Y}^2 = \frac{\bar{S}_{X,Y}^2}{\bar{S}_{X,X} \bar{S}_{Y,Y}} \quad (1)$$

where $\bar{S}_{X,Y}^2$ is the smoothed cross-wavelet transform of the time series X and Y , and $\bar{S}_{X,X}$ and $\bar{S}_{Y,Y}$ are the smoothed wavelet spectra of the time series X and Y . The cone of influence (COI) is the part of the plot of the wavelet coherency spectrum (WTC) where edge effects due to padding of the time series with zeroes to a length of 2^n time steps can be ignored. According to Grinsted et al. (2004), the COI is here calculated as the area in which the wavelet power caused by a discontinuity at the edge has dropped to e^{-2} of the value at the edge.

Statistical significance was tested to detect whether the wavelet spectra differed from a “red noise” background power spectrum modeled by a first order autoregressive (AR1) process. For the wavelet coherence, statistical significance was calculated by a Monte Carlo method. A number of 300 surrogate dataset pairs was used for the Monte Carlo estimation of the significance level. A 5% significance level against red noise was chosen. Further details can be found in Si and Zeleke (2005) and Grinsted et al. (2004). Calculations of the wavelet spectra, cross wavelet spectra, and wavelet coherency spectra were carried out in Matlab (2019b) with the code provided by B. Si and W. Hu. This code was based on the Matlab-code developed by A. Grinsted that is available under <http://www.glaciology.net/wavelet-coherence>.

2.4 | Crop development in field and lysimeter

The development of plant height was observed at the field plot from autumn 2016 to spring 2018 (Figure 3). The winter rye (*Secale cereale* L.) crop was planted in autumn 2016 and 2017 and used only as a cover crop before cultivation for the summer crops maize (*Zea mays* L., 2017) and oat (*Avena sativa* L., 2018). Crop yield was measured as dry mass of biomass for maize and as grain yield for oat (Table 3). It was larger for the lysimeter than for the field plot in both years. Depth of

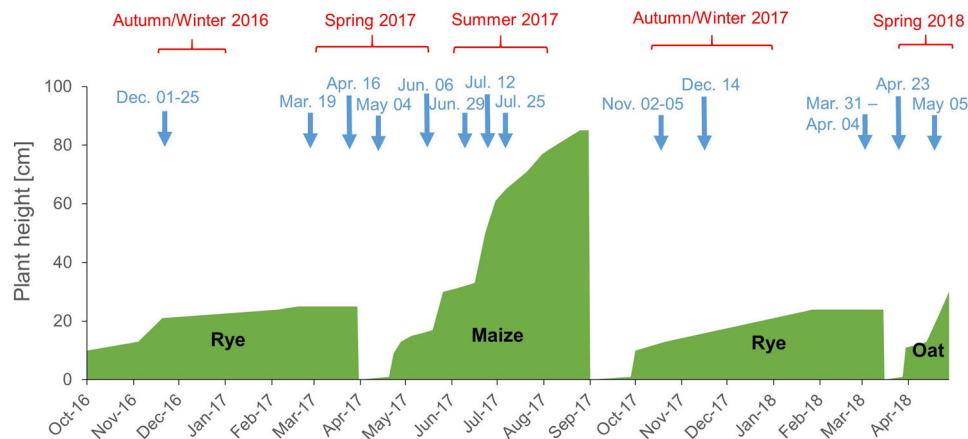


FIGURE 3 Crops and height of vegetation during the investigation period. Blue arrows indicate the occurrence of the analyzed precipitation events. Planting dates are found in Table 3. Periods of investigation with wavelet coherence analysis are marked with red braces

the rooting system was not recorded since this would lead to distortions in the lysimeter measurements. A previous study of Herbrich et al. (2018) suggested a maximal rooting depths for wheat (*Triticum aestivum* L.) of 150 cm at this site. Average maximal rooting depth for grains like rye and oat of 150–180 cm and 120–150 cm for maize can be assumed (Kutschera et al., 2009).

3 | RESULTS

This chapter is structured to first explain results of the WCA and then compare lysimeter and field data for relatively wet (2017) and relatively dry periods (autumn 2016, spring 2018). These periods were without any frost or snow cover in winter, such that any delay in infiltration response to precipitation due to melting of ice snow was unlikely.

3.1 | Wavelet coherence analyses of the SWC in the wet year (2017)

The water content increased after major precipitation events on the 19 Mar. 2017 and the 16 Apr. 2017 in a soil depth

of 15 cm of the lysimeter and field (A1 in Figure 4). Note the different SWC levels for field and lysimeter are not artifacts but related to the differently compacted topsoil regions in which sensors in the field were installed; the lysimeter soil was less compacted due to manual cultivation. All replicate sensors measured similar ranges of SWC values (Figure 4); in the following figures, we therefore focus on mean values from replicate sensors.

The response of the water content on the precipitation events are reflected in the wavelet spectra as significant deviations (i.e., marked as thick contour lines, significance level: 5%) from the background spectrum (red noise) in lysimeter and field (A2 in Figure 4); the x axis is the time in number of hours from the beginning of the year, and the y axis depicts the periodicity. The periodicity is in the unit of hours and characterizes temporal significance patterns (e.g., a significant deviation on a daily basis is observed if the thick contour line appears at a periodicity of 24 h). The shaded area outside the COI marks the part of the plot with larger edge effects (see Section 2). The color scale indicates the magnitude of the wavelet power. A high wavelet power (yellow color) denotes a high similarity between the wavelet function and the time series at this point in time and this scale. This means that at scales where the wavelet power is high, this periodicity is also found in the signal.

The interpretation of the wavelet spectra is explained for the example in Figure 4. The wavelet spectrum of the SWC (A2 in Figure 4) during precipitation event on 19 Mar. 2017 deviates significantly from the background spectrum at periodicities ranging for the lysimeter from 4 to 256 h (~11 d) and periodicities of 4–32 h for the field. A similar pattern but without deviations from the background spectrum at periodicities from 72 to 200 h is found for the lysimeter for the precipitation event on 16 Apr. 2017. The cross wavelet spectrum (A3 in Figure 4) contains additional information about the time shift and the covariance between two time series; it here indicates a high covariance during the two precipitation

TABLE 3 Cropping dates and dry mass of biomass for maize (2017) and grain yield of oat (2018) for the lysimeter (Lys) and the field plot (Michael Sommer & Gernot Verch, ZALF, personal communication, July 2020)

Crop	Plot	Planting date	Harvest date	Dry mass
				kg m ⁻²
Maize	Lys	24 Apr. 2017	25 Sept. 2017	3.81
	Field	24 Apr. 2017	25 Sept. 2017	1.98
Oat	Lys	9 Apr. 2018	30 July 2018	0.37
	Field	9 Apr. 2018	30 July 2018	0.30

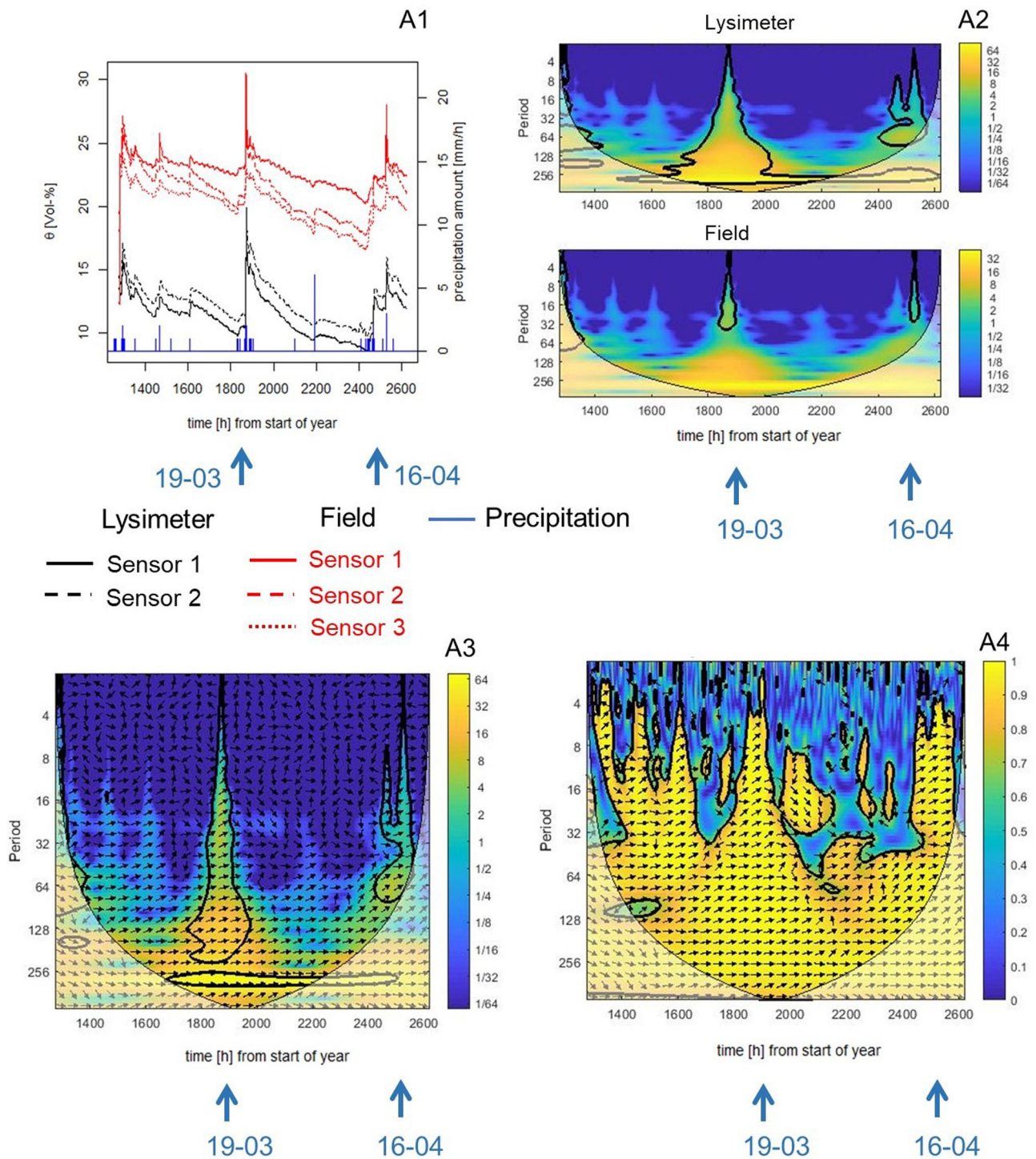


FIGURE 4 (A1) Response of soil water content (SWC, θ) at 15-cm depth (spring 2017) in the lysimeter (black lines) and field (red lines) profile on precipitation events vs. time in hours from the beginning of the year, and plots of (A2) wavelet spectra of SWC (15 cm) in the lysimeter (top) and field (bottom), (A3) cross wavelet spectrum, and (A4) wavelet coherence spectrum (WTC). Major precipitation events that were further analyzed are marked with a blue arrow and a date (day-month) below the plot

events mentioned before. Arrows pointing upwards indicate a faster reaction to precipitation (i.e., a faster increase in SWC) in the field soil as compared with the lysimeter soil, whereas arrows turned downwards show a faster reaction in the lysimeter. A faster reaction to precipitation in one plot in comparison

with another plot refers to a faster increase in SWC or pressure heads in response to precipitation. Since the cross wavelet transform is the product of the two wavelet spectra of the field and lysimeter soil, the color scale of the cross wavelet spectrum (A3 in Figure 4) indicates the strength of the covariance

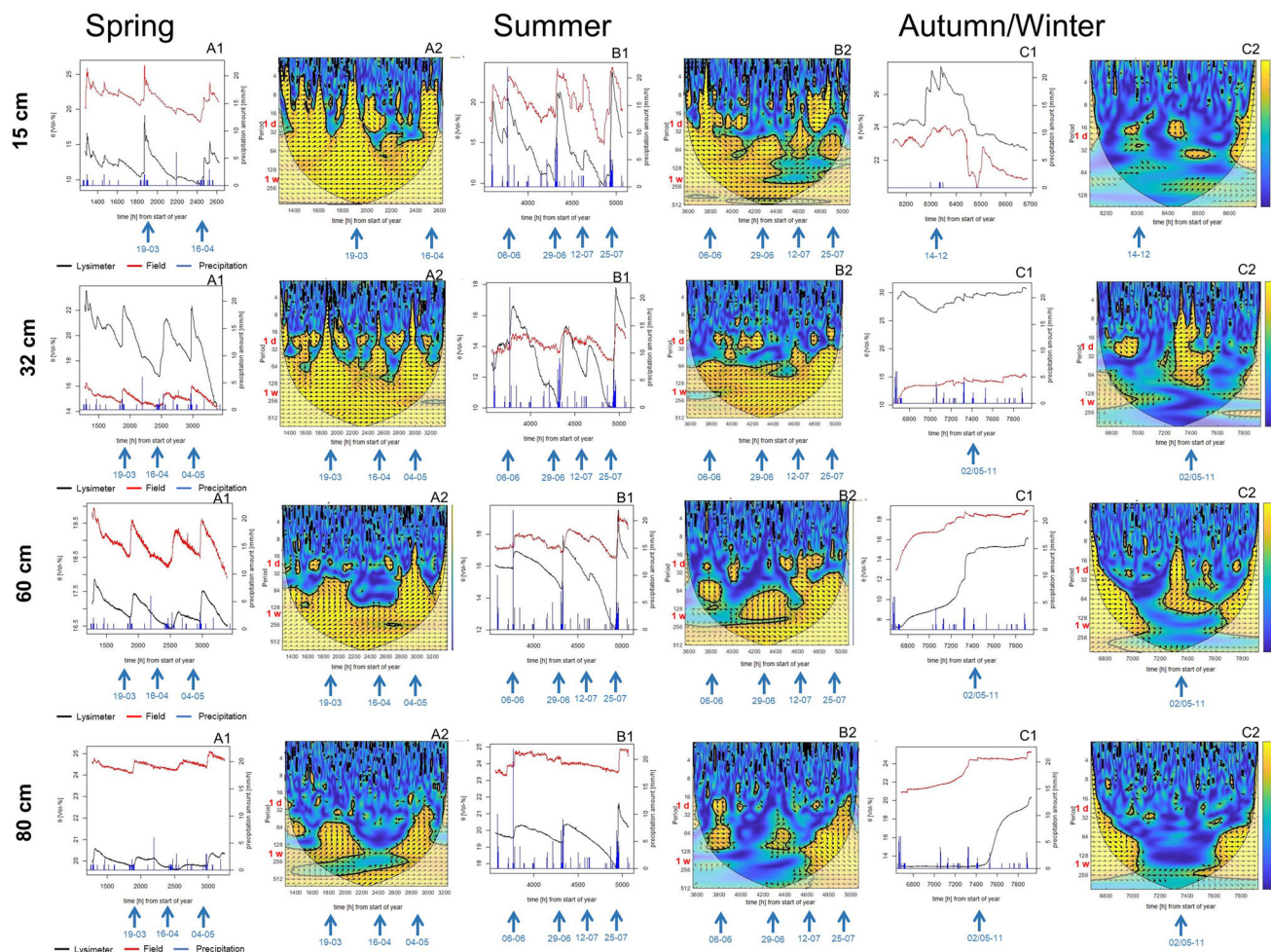


FIGURE 5 Time series of the soil water content (SWC, θ) in lysimeter and field (A1, B1, and C1) and wavelet coherence spectra (WTC plots) of SWC in lysimeter and field (A2, B2, and C2) at 15-cm, 32-cm, 60-cm, and 80-cm depth in spring, summer, and autumn of the wet year 2017. Major precipitation events that were further analyzed are marked with a blue arrow and a date (day-month) below the plot. The x axis of the plots denotes the time in number of hours from the start of the year; the period of the WTC plots is given in hours (more explanations of the WTC plots can be found in the text)

between the spectra at a certain point in time and at a certain scale. The plot of the WTC provides information about the time shift in the correlation between two time series (A4 in Figure 4). For the abovementioned precipitation events, high correlations are indicated across all scales from 6 h to 2 wk. The strength of the correlation (color scale) is here indicated by a relative scale, with 0 indicating no correlation and 1 indicating a perfect correlation. The information on phase shift are similarly provided by the arrows as in the cross wavelet spectrum; arrows pointing upwards indicate a faster reaction to precipitation of SWC in the field soil as compared with the lysimeter. Note that the wavelet spectra and the cross wavelet spectrum of data from lysimeter and field of other depths and seasons are presented in the Appendix (Figures A4–A6).

Selected seasonal time series in 2017 and WTC plots of SWC dynamics in 15-, 32-, 60-, and 80-cm depths in spring, summer, and autumn 2017 (Figure 5) differ between lysimeter and field soil with respect to the levels and temporal pat-

terns of the SWC. The response to precipitation is generally decreasing with soil depth (A1, B1, and C1 in Figure 5). For the spring period (15-cm depth: 23 Feb. until 20 Apr. 2017; 32-to-80-cm depth: 23 Feb. until 22 May 2017; unfortunately not for all the depths time series with the same length were available due to sensor and logger failures), the WTC plots (A2 in Figure 5) reflect these patterns and indicate that the response of the SWC in the field profile on precipitation is generally faster than that of the SWC in the lysimeter soil. The periodicity of significant relations is between 6 h to 2 wk at the precipitation events in 15-cm depth; this periodicity increases with soil depth to 1 d to 2 wk (32-cm depth) and 2 d to 2 wk (60-cm depth). In 80-cm depth almost no significant correlations between rain and SWC increase in lysimeter and field are found.

During the summer period (1 June until 31 July 2017), the moisture dynamics (drying–wetting) increased in comparison with spring (B1 in Figure 5). However, the WTC plots (B2 in

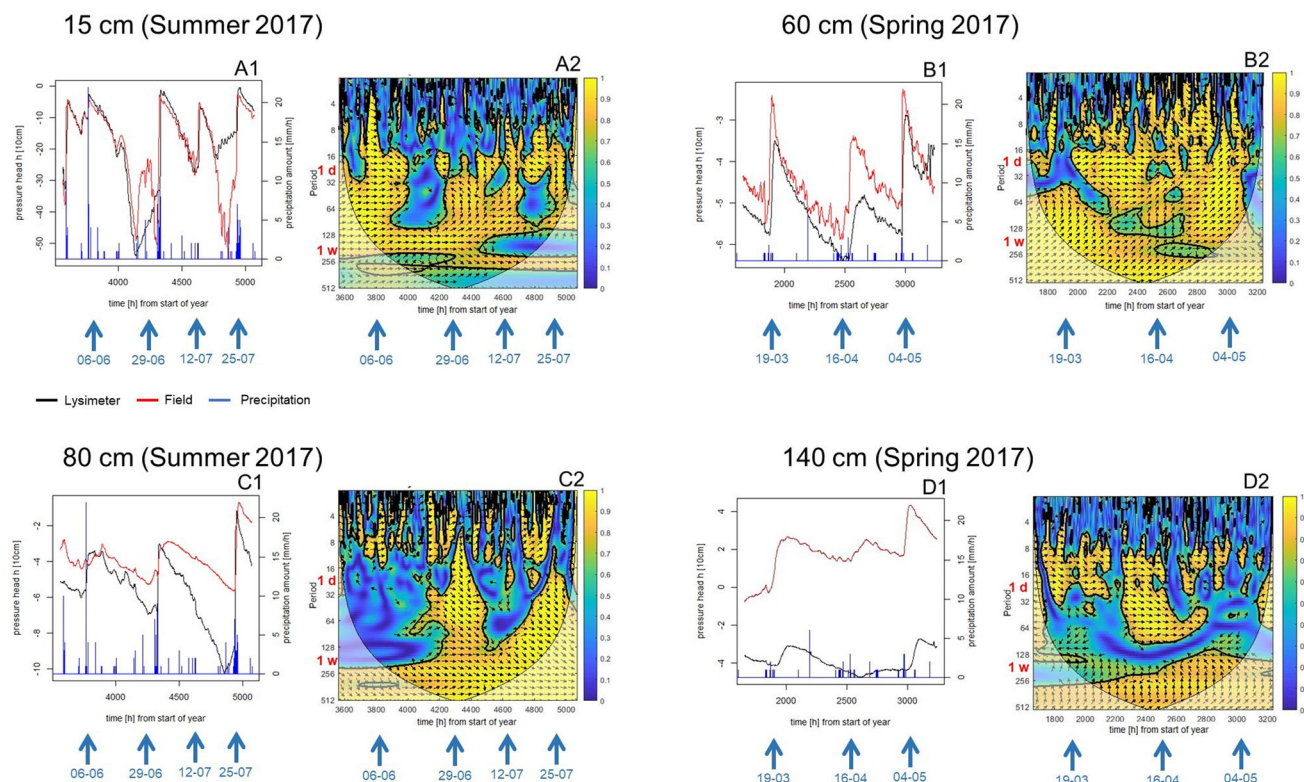


FIGURE 6 Time series of the pressure head values in lysimeter and field (A1, B1, C1, and D1) and wavelet coherence spectra (WTC plots) of pressure head values in lysimeter and field (A2, B2, C2, and D2) at 15-cm (summer 2017), 60-cm (spring 2017), 80-cm (summer 2017), and 140-cm depth (spring 2017). Major precipitation events are marked with a blue arrow and a date (day-month) below the plots; the time is given in hours since the beginning of the year; the period of the WTC plots is given in hours (more explanations of the WTC plots can be found in the text)

Figure 5) indicate fewer significant periods at higher periodicities (2 d to 2 wk) as compared with the spring. High correlations at smaller periodicities (6 h to 1 d) are only found in 15 cm at times of precipitation. More significant correlations at precipitation events at 80-cm depth are found in summer than in spring. The field plot moisture sensor at 32-cm depth showed almost no response to precipitation resulting in only a few short correlations at the periodicity of 1 d in the WTC plot (B2 in Figure 5). For the summer season, arrows indicating the phase shift throughout the precipitation events are in phase or point upwards in the shallower depths (15- and 32-cm depth). This marks a simultaneous water content increase in lysimeter and field or a faster water content increase in the field as compared with the lysimeter soil, respectively, similar to the patterns found in spring. In contrast, in the deeper horizons (60- and 80-cm depth) arrows indicating the phase shift point downwards (B2 in Figure 5), denoting a faster response in the lysimeter soil than in the field soil at the corresponding precipitation events.

During the autumn and winter period (32-to-80-cm depth: 10 Oct. until 30 Nov. 2017; 15-cm depth: 1 Dec. until 31 Dec. 2017), the lysimeter and field plot moisture dynamics was mostly uncorrelated and without response to precipitation (C1 and C2 in Figure 5) except perhaps for 32-cm and 60-cm

depth, where the WTC plot is significant at periodicities from 6 h to 3 d from 2 until 5 Nov. 2017. Phase shift arrows indicate a faster response of SWC to precipitation in the field soil as compared with the lysimeter soil, similar to the patterns found in spring.

Note that the relatively small SWC values in the lysimeter soil (Figure 5) of about 10 Vol-% (unit of the volumetric soil water content in volume percentage) during summer (all depths) and spring (topsoil) are well above a residual SWC determined earlier of about 3.5 Vol-% at 15-cm depth and 4 Vol-% at 80-cm depth (Rieckh et al., 2012).

3.2 | Pressure head values in wet year 2017

Pressure head values increased in the wet year 2017 after precipitation events (A1 to D1 in Figure 6), which is reflected by significant correlations between lysimeter and field soil across all scales from 6 h to 2 wk in the WTC plots (A2 to D2 in Figure 6).

At 15-cm depth, lysimeter and field reacted simultaneously to precipitation on 6 June 2017, whereas for the later events, pressure head values increased faster in the field than in the lysimeter (A2 in Figure 6), similar to the patterns found for

TABLE 4 Characterization of major precipitation events in autumn 2016, 2017, and spring 2018 and sequence of soil water content (SWC) response to precipitation

Season	Start	Dur	Ra	Ri_av	Ri_max	First reaction				
						15	32	60	80	140
	date (h:min)	h	mm	—mm h ⁻¹ —		cm				
Autumn/winter	1 Dec. 2016 07:00	6	6	1	1	L	L	F	/	n.d.
	11 Dec. 2016 04:00	8	9	1.1	2	L	F	F	F	F
	25 Dec. 2016 01:00	1	3	3	3	F	F	F	S	F
Spring	19 Mar. 2017 15:00	9	11	1.2	2	F	S	F	L	n.d.
	16 Apr. 2017 06:00	3	5	1.7	3	F	F	F	F	n.d.
	4 May 17 08:00	12	21	1.8	3	n.d.	S	F	F	n.d.
Summer	6 June 2017 17:00	4	31	7.8	22	S	L	L	L	n.d.
	29 June 2017 09:00	6	11	1.8	7	S	L	L	L	n.d.
	12 July 2017 13:00	9	12	1.3	2	F	F	L	S	n.d.
	22 July 2017 17:00	3	8	2.7	4	F	L	L	L	n.d.
Autumn/winter	2 Nov. 2017 00:00	8	20	2.5	4	n.d.	F	F	F	n.d.
	5 Nov. 2017 18:00	6	8	1.3	2	n.d.	F	F	F	n.d.
	14 Dec. 2017 04:00	4	4	1	1	L	n.d.	n.d.	n.d.	n.d.
Spring	29 Mar. 2018 01:00	5	3	0.6	1	F	F	F	F	F
	31 Mar. 2018 14:00	3	2	0.7	1	F	F	F	F	F
	31 Mar. 2018 20:00	2	2	1	1	F	F	F	F	F
	1 Apr. 2018 02:00	7	5	0.7	1	F	F	F	F	F

Note. L, lysimeter reacts first; F, field reacts first; S, simultaneous reaction; /, no reaction observed; n.d., no data; numbers and letters in italic indicate precipitation events in Figures 8 and 9; other events are depicted in Appendix Figure A7. Dur, duration; Ra, precipitation amount; Ri_av, average intensity; Ri_max, maximum precipitation intensity.

the water content in the corresponding depth and season (B2 in Figure 5). At 60-cm depth, the pressure heads increased faster in the field than in the lysimeter soil for all major precipitation events in spring (B2 in Figure 6). Increase in pressure heads in the lysimeter as compared with the field was faster at 80-cm depth in summer (C2 in Figure 6). At 140-cm depth, the lysimeter showed a faster reaction to precipitation than the field in spring 2017 (D2 in Figure 6).

3.3 | SWC values in relatively dry years 2016 and 2018

Selected time series of SWC in lysimeter and field of the dry years 2016 and 2018 show a general increase of water content in autumn and winter 2016 and a decrease in spring 2018 (A1 and B1 in Figure 7). Note that there were no data available during the summer periods. Impacts on SWC increase due to precipitation diminish with depth. The corresponding WTC plots also show a decrease of correlations between SWC changes in lysimeter and field with depth (A2 and B2 in Figure 7). Significant correlations are generally found in connection with precipitation events. The smallest periodicities with significant correlations increase from 6 h at 15-cm depth to 1 d at 60-to-140-cm depth. Arrows representing the phase shift indicate a

faster increase in water content in the field soil as compared with the lysimeter soil at almost all precipitation events. Only on 1 Dec. 2016, the lysimeter soil shows a faster increase in water content than the field at 15- and 32-cm depth at periodicities from 2 d to 1 wk (A2 in Figure 7). Note that at 15-cm depth (A2 in Figure 7), the phase shifts on 1 Dec. 2016 are contradictory because they are indicating a faster reaction in the field soil than in the lysimeter at periodicities of 2 d and a slower response at periodicities of 1 wk.

3.4 | Response time for SWC to precipitation

The distribution of the precipitation at the site is typically characterized by lower intensity rain and a few higher intensity summer events (Herbrich et al., 2017), as for the selected period, in which precipitation events with higher amount and rate occurred during summer and those with less intensity and lower amounts in spring, autumn, and winter (Table 4). The response time between the start of the rain and the first SWC reaction seasonally differed when plotted with respect to the maximal rain intensity (Figure 8). Below 32-cm soil depth, the field SWC reacted earlier to precipitation in spring and in autumn, whereas during summer, the SWC in the lysimeter reacted faster than that in the field soil (Figure 8)

Autumn/Winter - 2016

Spring - 2018

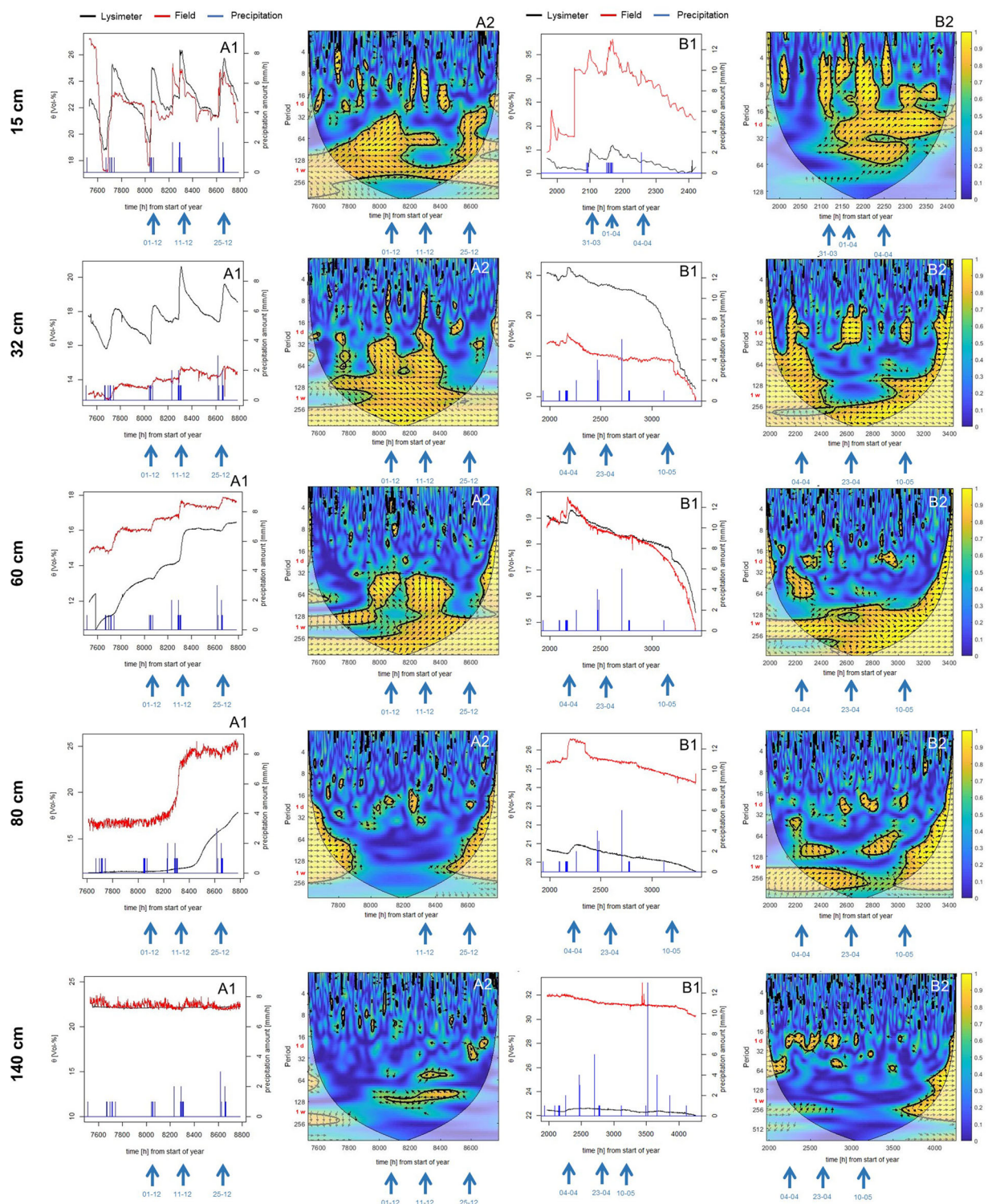


FIGURE 7 Time series of the soil water content (SWC) in lysimeter and field (A1 and B1) and wavelet coherence spectra (WTC plots) of SWC in lysimeter and field (A2 and B2) at 15-, 32-, 60-, 80-, and 140-cm depth in autumn 2016 (dry year) and spring 2018 (dry year). Major precipitation events are marked with a blue arrow and a date (day-month) below the plot. The x axis of the plots is time in number of hours from the beginning of the year; the period of the WTC plots is given in hours (more explanations of the WTC plots can be found in the text)

FIGURE 8 Response time difference (i.e., difference in reaction time in hours between lysimeter and field) of soil water content (SWC) increase in lysimeter and field related to maximal precipitation intensity for the four soil depths and the season. If the reaction time is positive, the field soil reacted faster than the lysimeter soil in that same depth. If the reaction time is negative, the field SWC increased later than the lysimeter SWC in response to the rain event

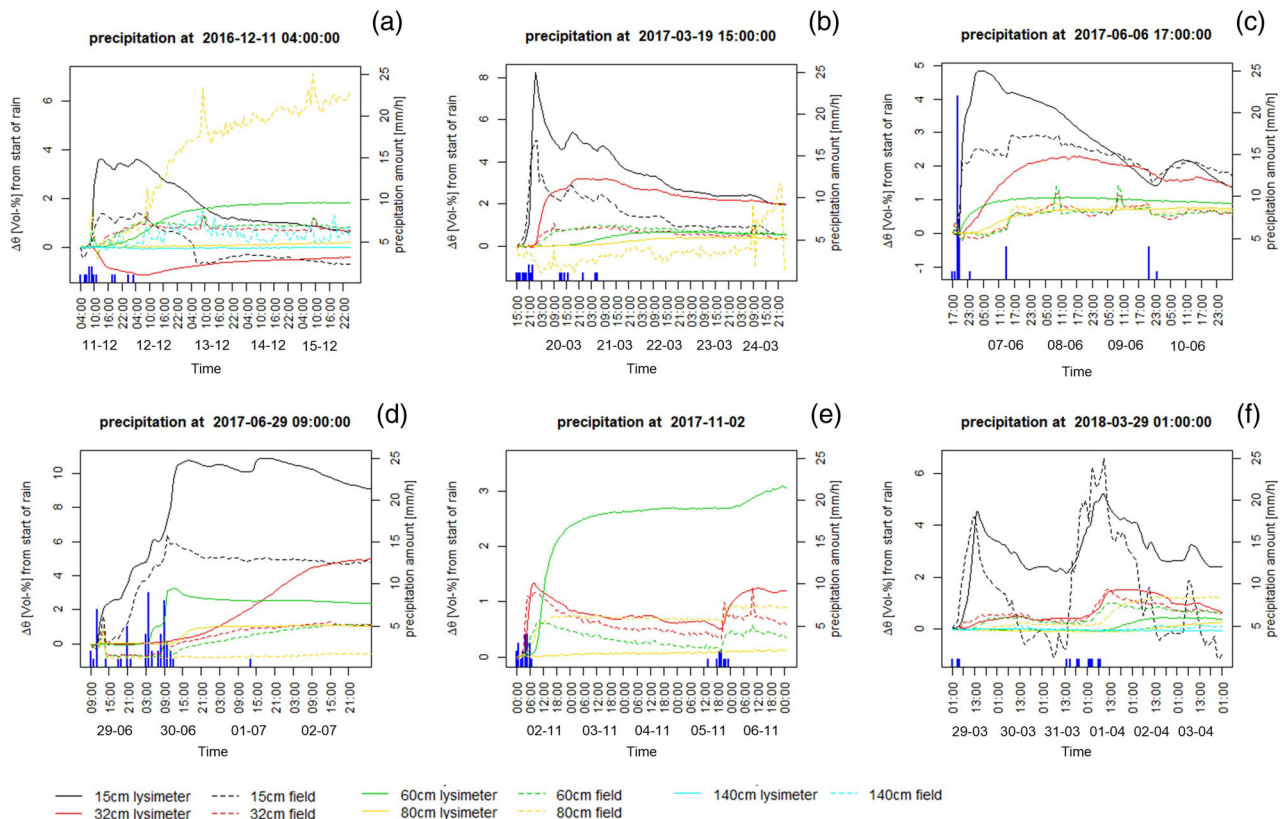
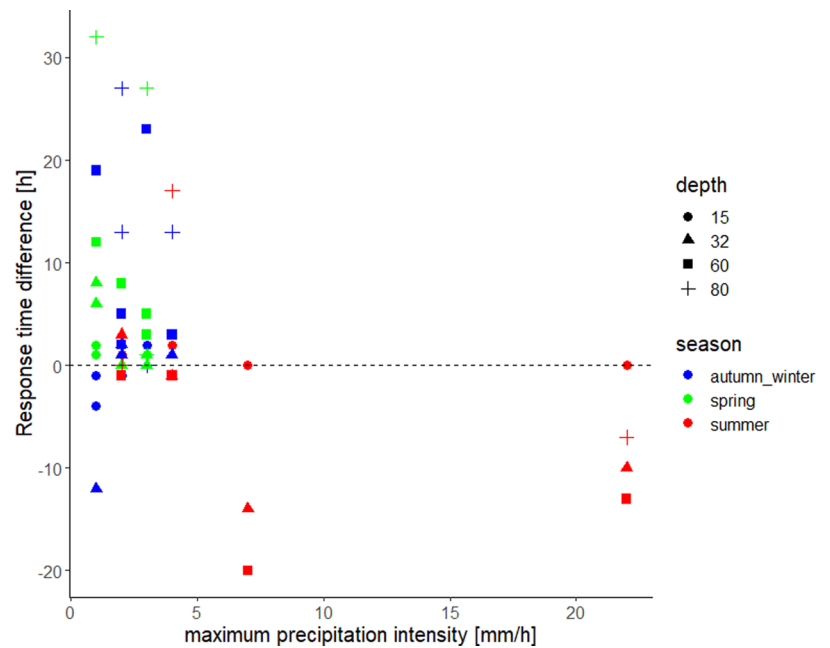


FIGURE 9 Soil water content (SWC, θ) change (increase) in response to selected precipitation events in lysimeter and field at the 15-, 32-, 60-, 80-, and 140-cm depths in 2016, 2017, and 2018

regardless of the antecedent moisture condition (i.e., for wet and dry years).

The sequence of the SWC response to precipitation in field and lysimeter that was found in the WTC plots is also visible in the plots of the single precipitation events (Figure 9 and

Appendix Figure A7). From the top to the bottom of the profile, the sensors responded sequentially to precipitation events (i.e., the upper horizons increase in water content before the lower horizons). However, in the field (Figure 9, A–C), a simultaneous reaction to precipitation is found in 32-cm and

60-cm depth. In addition, for at least two events, vertical preferential flow occurred in the soil profile of the lysimeter, as the response of the SWC on the precipitation event at 60-cm depth was faster than the SWC response at 32-cm depth (Figure 9, C and D). On 2 Nov. 2017 (Figure 9, E), we can see a sequential vertical response in the lysimeter, but the increase of SWC in 60 cm was larger and continued longer than the SWC at 32-cm soil depth.

4 | DISCUSSION

For identification of LSF based on discrepancies in water dynamics between lysimeter and field, one has to consider that the position of the soil profile in the field is at the toe slope close to the kettlehole depression (Figures 1 and 2). A faster and more intensive water content increase in the field in comparison with the lysimeter could indicate lateral flow from the upper slope, if at the same time the SWC of the soil profile in the lysimeter responds sequentially in a vertical direction on infiltration. If the field reacts slower and less intensively to precipitation than the lysimeter, this could be attributed to lateral drainage downslope, whereas in the lysimeter soil, the infiltrating water moves vertically and leads to sequential SWC increase. Under these standard multidimensional flow presumptions (Filipović et al., 2018) and considering combinations with spatial heterogeneity (Guo & Lin, 2018; Lin & Zhou, 2008) and vertical preferential flow effects due to macropore-centred saturation (Newman et al., 2004), we will discuss the WCA results for time series of lysimeter and field state variables to identify periods of deviations that might be interpreted as vertical preferential flow or LSF.

4.1 | Verification of WCA-derived deviations in time series

Correlations in water dynamics between field and lysimeter were observed across all scales in response to precipitation events (Figures 4–7). These correlations occurred regardless of the season or the antecedent SWC conditions. The time lag between SWC increase in the field and in the lysimeter after precipitation indicated by phase shift arrows could be verified when analyzing the water content increase for each single precipitation event (Figure 9). In spring and autumn, the WTC plots (Figures 5 and 7) indicated an earlier response in the field as compared with the lysimeter as observed in the time series directly (Figure 9). In summer 2017, the WTC plots showed a faster reaction in SWC increase in response to precipitation in the lysimeter than in the field (Figure 5). Again, this response pattern was found in the plots (Figure 9).

Similar to results reported by Bravo et al. (2020), correlations between water dynamics inside and outside the lysime-

ter occurred especially in response to heavy precipitation events. This was explained by the decrease in variability of soil hydraulic properties at higher SWC during rain events due to more water connecting pores between the soil inside and outside the lysimeter as compared with times of less precipitation. Unlike our findings, correlations in the study of Bravo et al. (2020) were mostly in phase, indicating a simultaneous increase in water content or pressure heads in response to precipitation. However, the soil profiles in the study of Bravo et al. (2020) were not extracted at a hillslope and had no compacted soil horizons. In our study, LSF was expected because of contrasting hydraulic properties (Laine-Kaulio et al., 2014; Liu & Lin, 2015) with more over less permeable horizons (Table 2). The soil of the Ahb horizon was characterized by hydraulic anisotropy with a higher horizontal (23.7 cm d^{-1}) than vertical hydraulic conductivity (14.4 cm d^{-1}) at the 70-to-88-cm depth. The more compact (bulk density of 1.82 g cm^{-3}) subsoil horizon below at the 135-to-147-cm depth had more than 20 times lower hydraulic conductivity values (Table 2) at the same pressure head of -1 hPa for the vertical (0.7 cm d^{-1}) and horizontal direction (1.0 cm d^{-1}). This supports the presumption that LSF could occur in the field while pressure buildup would occur in the lysimeter, which could lead to differences in soil water dynamics between lysimeter and field.

Bravo et al. (2020) related short-term temporal correlations to rather extreme conditions like heavy precipitation, whereas long-term patterns of periodicities between 1 and 2 mo were ascribed to slower hydraulic processes during continuous drying or wetting periods. In our study, such continuous wetting and drying periods were observed in autumn 2016 and in the spring seasons, which was reflected in the WTC plots by positive correlations between lysimeter and field at higher scales of 2–3 wk (Figures 4–7). Thus, similar overall trends in the different seasons in drying and wetting of the soil can be identified by WCA. The coherence at high-frequency periodicities between precipitation and soil moisture also decreases with depth (Liu et al., 2017), which was here more pronounced for the lysimeter than the field soil because of the SWC increase caused by restricted LSF (Figures 5 and 7).

4.2 | Causes for deviations between lysimeter and field data

Although lysimeter and field soil profile were equipped with the same sensors in the diagnostic horizons with similar soil physical properties, the sensors monitor the soil water dynamics of only a small region of the soil. Thus, observed deviations in the SWC and soil water pressure head response between field and lysimeter soil (Figure 4) may be caused by small-scale spatial heterogeneity (Guo & Lin, 2018; Lin & Zhou, 2008) or differences induced during horizontal

insertion of sensors. Bravo et al. (2020) attributed periods without correlation between lysimeter and field to effects of small-scale spatial heterogeneity. Here, correlations could be interpreted similarly by heterogeneity effects except that correlations between field and lysimeter were shifted in time (Figures 4–7).

The observed time lags between the increase in water content in the lysimeter and field (for example, in Figures 5–9) might be explained by differences in the plant development. The lysimeter soil produced almost twice the biomass yield than that of the field in 2017 (Table 3). This larger yield may be attributed to LSF when assuming that more water can be stored in the lysimeter that could laterally move downwards in the field soil (Newman et al., 2004). However, the SWC in the lysimeter soil was lower than in the field, which is consistent with a larger crop water use by a more intense plant growth at the lysimeter. Also, especially in winter and early spring (Figures 4–7), the field soil could have received additional water by LSF from uphill positions, such that crop and root growth was limited during periods of higher pore water saturation (Herbrich et al., 2018).

The onset of the SWC increase after precipitation could also differ between field and lysimeter soil because of different initial SWC at the beginning of an event (e.g., Figure 4, A1, spring 2017, 15-cm depth). Thus, the hydraulic conductivity of the field soil is initially higher than that of the lysimeter soil, possibly inducing a faster vertical movement as response to precipitation as compared with the lysimeter soil. In fact, the conditions for the onset of LSF, although requiring relatively high water saturation of the soil pore system, are mainly depending on the hydraulic potential gradients as the driving force for water movement in soils. Furthermore and also considering measurement uncertainty of the sensors, the absolute values of the SWC do not inform about pore water saturation (compare 15 and 80 cm in Figure 5, B1, and Figure 6, A1 and C1). Nevertheless, by applying WCA, it is possible to identify the timing of changes in the SWC (Liu et al., 2017), and differences in the flow dynamics between lysimeter and field. A more detailed quantitative analysis (Guo et al., 2018) requires soil water balance calculations considering the nonlinear soil hydraulic properties. The present analysis could help selecting out of long-term time series, the most appropriate periods for the follow-up detailed analysis (Lin & Zhou, 2008).

Despite limitations, the observed differences in soil water dynamics between lysimeter and field soil profile (Figure 5) in the Ahb horizon (sensor in 80-cm depth) and in the colluvic soil horizon above (sensor in 60-cm depth) might be interpreted as LSF in the following way: a faster increase in SWC in the field than in the lysimeter soil in spring and autumn could be caused by water flowing from uphill positions when SWC in the profile increased sequentially. For example, during the event on 2 Nov. 2017, the SWC in 32- and 60-cm depth increased faster in the field as compared with the lysimeter

(Figure 5, C2, Table 4, and Figure 8). For the values at the 60-cm depth, however, the response time between lysimeter and field was greater than at the 32-cm depth (Figure 5, C2), indicated by the stronger deviation from the eastward direction (perfect correlation) of the time gap arrows at 60-cm depth as compared with the 32-cm depth. Since the FDR sensors at the 32- and 60-cm depth in the field responded sequentially, no vertical preferential flow did occur but the water must have entered the subsoil laterally (Lee & Kim, 2019; Xie et al., 2019). Also, the SWC increase at the 60-cm depth was more intense in the lysimeter than in the field (Figure 5 C1, Figure 9, E). Because of the lysimeter construction, infiltrating water could only move vertically downwards to the 60-cm depth, whereas in the field, the smaller increase in SWC could be explained by lateral water movement away from the sensor.

The assumption of LSF occurrence is also supported by analyzing the occurrence of response sequences (Graham & Lin, 2011; Wiekenkamp et al., 2016) in different depths for single precipitation events (Table 4, Figure 8). On 1 Dec. 2016, the lysimeter increases faster in water content at the 15- and 32-cm depth than in the field, whereas in the deeper horizons, the SWC of field reacts earlier than SWC in the lysimeter (Figure 7, A2). On 12 July 2017 and on 22 July 2017, the field soil reacted earlier than the lysimeter in the upper soil horizons in contrast with the lower horizons, where the SWC and soil water pressure head in the lysimeter increased faster than in the field (Figures 5, 6 and 8; Table 4). This indicates that in each horizon, different processes influence soil water dynamics such as swelling and shrinking in the upper two soil horizons (15- and 32-cm soil depth). Also, effects of different plant and root developments between the lysimeter and field are more pronounced in the upper soil horizons. A higher root density might favor the development of macropores for vertical preferential flow (Mitchell et al., 1995). The response sequences during the precipitation events (Table 4, Figures 8 and 9), in deeper soil horizons were different from those of the upper ones, which could also be attributed to either LSF or vertical preferential flow.

In summer 2017, vertical preferential flow was also observed in the lysimeter and field soil profile throughout heavy precipitation events (Figure 9, c and d) as in Filipović et al. (2018). It may be assumed that due to shrinkage during summer, the infiltrating water could move vertically through cracks (Greve et al., 2010) or along the cylinder walls (Corwin, 2000), leading to a faster increase in SWC and soil water pressure head in the lysimeter than in the field. The SWC in the field soil increased simultaneously at the 32- and 60-cm depth (Figure 9, c and d). In the lysimeter, the FDR sensor at the 60-cm depth responded earlier than the FDR sensor at the 32-cm depth, indicating nonsequential preferential flow (Graham & Lin, 2011; Wiekenkamp et al., 2016). Since the SWC increase in the lysimeter at both depths was more intense (despite the generally lower total amount of SWC) than in the

field, LSF may be assumed in combination with vertical preferential flow (Dasgupta et al., 2006; Xie et al., 2019). In their study on vertical preferential flow in the Wüstebach catchment (Eifel, Germany), Wickenkamp et al. (2016) observed an increase in the nonsequential SWC responses with the amount of precipitation. Lin and Zhou (2008) could also relate vertical preferential flow to rain intensities in the Shale Hills catchment (Pennsylvania, USA).

The position of the observed soil profile at the hillslope was proposed as yet another factor contributing to the occurrence of lateral flow. Lee and Kim (2019) observed in a hillslope in Korea that vertical preferential flow was dominant in soils at uphill positions, whereas LSF occurred in soils at the lower slope positions. These authors identified LSF by the wavelet coherency of the SWC between uphill and downhill positions; their coherence spectra revealed stronger relationships between greater than smaller distances and depths to be indicative for either bypass flow or boundary flows along bedrock. Liu and Lin (2015) also identified hilltops and valley floors as topographic controls enhancing preferential flow; here, the SWC time series at slope foot position could be affected by an increased water table (Figure 7, A1, 80- and 140-cm depth).

One major disadvantage of the proposed method to identify LSF is that it is an indirect approach that does not show the soil water flow as for instance when using water tracers (Gerke et al., 2015; Laine-Kaulio et al., 2014; Wienhöfer & Zehe, 2014). Additionally, the analysis was impeded by a rather short time of a few months, where data were available due to sensor and logger failures. A longer uninterrupted time series could have given more insight in the occurrence of LSF on higher scales. Also, deviations in vegetation dynamics in lysimeter and field and differing absolute SWC values restricted the interpretation of the results. The SWC values alone may not be sufficient to conclude whether the conditions of SLF occurrence are met. Nevertheless, the WCA could be for hillslope hydrology (Lee & Kim, 2019) also a tool for soil hydrology applications to identify the timing of SWC changes providing qualitative information about changes in flux dynamics. The advantage is that the approach is nondestructive and applicable to already available larger data series that capture changes in water content and pressure heads, which is not possible if destructive techniques including tracer applications are used for the detection of LSF.

5 | CONCLUSIONS

The aim of this study was to test whether the WCA is able to capture temporal shifts in the correlation between lysimeter and field data in the reaction of soil water state variables to precipitation and to analyze whether these deviations can be attributed to LSF.

The results based on correlation patterns between soil water dynamics in the lysimeter and field after precipitation events indicate that lysimeter and field soil did not react synchronously to precipitation. Thus, it seems possible to identify distinct periods of deviations from a long time series of water content or pressure heads to identify differences in the soil water dynamics with this setup.

In addition to possible LSF events vertical preferential flow could be observed as indicated by an earlier response in the lysimeter as compared with the field on rare events in summer. The phase shifts and periodicities indicated by the wavelet coherency spectra reflected the response times to rain events in the same depth of lysimeter and field soil. In the 3 yr (2016–2018), only a few periods could be identified, in which LSF was likely to occur because of dry weather conditions and limited data. The condensed information in wavelet coherency spectra are providing an overview of the temporal patterns of time shifts and correlations for data time series, and identifying potentially relevant periods for more detailed analyses.

ACKNOWLEDGMENTS

This study was financially supported by the Deutsche Forschungsgemeinschaft (DFG), Bonn, Germany, under Grant GE 990/13-1 “Vadose Zone Modelling of water flow in hillslope soil (VAMOS).” The authors thank Dr. B. Si (Canada) and Dr. W. Hu (China) for providing the Matlab-Code for the implementation of the wavelet transform and wavelet coherency analysis. We thank Dr. Ralf Gründling (UFZ, Halle, Germany) for preparation and flagging of the SWC and pressure head time series and Prof. Dr. Wilfried Hierold (ZALF, Müncheberg) for the soil profile description. We thank Prof. Dr. Sommer (ZALF, Müncheberg) for providing soil physical and chemical data, Ute Moritz (ZALF, Müncheberg) for support in the processing of the precipitation data, and Martin Schmidt (ZALF, Müncheberg) for measuring the soil hydraulic conductivities and bulk densities. We are grateful for the setup and maintenance of the lysimeter and field profile by Prof. Dr. Hans-Jörg Vogel, Dr. Max Köhne, and Robert Lüdtke from the UFZ, Halle, Germany and Nico Zindler (ZALF, Müncheberg). We thank Nico Zindler and Marten Schmidt (ZALF, Müncheberg) for providing information on the precipitation gauges.

AUTHOR CONTRIBUTIONS

Annelie Ehrhardt: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Resources; Software; Validation; Visualization; Writing-original draft; Writing-review & editing. Jannis Groh: Data curation; Methodology; Validation; Writing-review & editing. Horst H. Gerke: Conceptualization; Funding acquisition; Methodology; Project administration; Resources; Supervision; Validation; Writing-review & editing.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

ORCID

Annelie Ehrhardt  <https://orcid.org/0000-0003-0512-4814>

Jannis Groh  <https://orcid.org/0000-0002-1681-2850>

Horst H. Gerke  <https://orcid.org/0000-0002-6232-7688>

REFERENCES

- Ad-hoc-Arbeitsgruppe Boden. (2006). *Bodenkundliche Kartieranleitung. KA5*. Schweizerbart Science Publishers.
- Alaoui, A., Caduff, U., Gerke, H. H., & Weingartner, R. (2011). A preferential flow effects on infiltration and runoff in grassland and forest soils. *Vadose Zone Journal*, 10. <https://doi.org/10.2136/vzj2010.0076>
- Biswas, A., & Si, B. C. (2011). Identifying scale specific controls of soil water storage in a hummocky landscape using wavelet coherency. *Geoderma*, 165, 50–59. <https://doi.org/10.1016/j.geoderma.2011.07.002>
- Bravo, S., González-Chang, M., Dec, D., Valle, S., Wendroth, O., Zúñiga, F., & Dörner, J. (2020). Using wavelet analyses to identify temporal coherence in soil physical properties in a volcanic ash-derived soil. *Agricultural and Forest Meteorology*, 285–286, 1–10. <https://doi.org/10.1016/j.agrformet.2020.107909>
- Corwin, D. L., (2000). Evaluation of a simple lysimeter-design modification to minimize sidewall flow. *Journal of Contaminant Hydrology*, 42, 35–49. [https://doi.org/10.1016/S0169-7722\(99\)00088-1](https://doi.org/10.1016/S0169-7722(99)00088-1)
- Dasgupta, S., Mohanty, B. P., & Köhne, J. M. (2006). Impacts of juniper vegetation and karst geology on subsurface flow processes in the Edwards Plateau, Texas. *Vadose Zone Journal*, 5, 1076–1085. <https://doi.org/10.2136/vzj2005.0073>
- Falge, E., Baldocchi, D., Olson, R., Anthoni, P., Aubinet, M., Bernhofer, C., Burba, G., Ceulemans, R., Clement, R., Dolman, H., Granier, A., Gross, P., Grünwald, T., Hollinger, D., Jensen, N.-O., Katul, G., Keronen, P., Kowalski, A., Lai, C. T., ... Wofsy, S. (2001). Gap filling strategies for defensible annual sums of net ecosystem exchange. *Agricultural and Forest Meteorology*, 107, 43–69. [https://doi.org/10.1016/S0168-1923\(00\)00225-2](https://doi.org/10.1016/S0168-1923(00)00225-2)
- Farge, M. (1992). Wavelet transforms and their applications to turbulence. *Annual Review of Fluid Mechanics*, 24, 395–458. <https://doi.org/10.1146/annurev.fl.24.010192.002143>
- Filipović, V., Gerke, H. H., Filipović, L., & Sommer, M. (2018). Quantifying subsurface lateral flow along sloping horizon boundaries in soil profiles of a hummocky ground moraine. *Vadose Zone Journal*, 17, 1–12. <https://doi.org/10.2136/vzj2017.05.0106>
- Filipović, V., Coquet, Y., & Gerke, H. H. (2019). Representation of plot scale soil heterogeneity in dual-domain effective flow and transport models with mass exchange. *Vadose Zone Journal*, 18, 1–14. <https://doi.org/10.2136/vzj2018.09.0174>
- Gerke, H. H. (2006). Preferential flow descriptions for structured soils. *Journal of Plant Nutrition and Soil Science*, 169, 382–400. <https://doi.org/10.1002/jpln.200521955>
- Gerke, H. H., Koszinski, S., Kalettka, T., & Sommer, M. (2010). Structures and hydrologic function of soil landscapes with kettle holes using an integrated hydrogeological approach. *Journal of Hydrology*, 393, 123–132. <https://doi.org/10.1016/j.jhydrol.2009.12.047>
- Gerke, K. M., Sidle, R. C., & Mallants, D. (2015). Preferential flow mechanisms identified from staining experiments in forested hillslopes: Preferential flow mechanisms identified from staining experiments. *Hydrological Processes*, 29, 4562–4578. <https://doi.org/10.1002/hyp.10468>
- Graham, C. B., & Lin, H. S. (2011). Controls and frequency of preferential flow occurrence: A 175-event analysis. *Vadose Zone Journal*, 10, 816–831. <https://doi.org/10.2136/vzj2010.0119>
- Greve, A., Andersen, M. S., & Acworth, R. I. (2010). Investigations of soil cracking and preferential flow in a weighing lysimeter filled with cracking clay soil. *Journal of Hydrology*, 393, 105–113. <https://doi.org/10.1016/j.jhydrol.2010.03.007>
- Grinsted, A., Moore, J. C., & Jevrejeva, S. (2004). Application of the cross wavelet transform and wavelet coherence to geophysical time series. *Nonlinear Processes in Geophysics*, 11, 561–566. <https://doi.org/10.5194/npg-11-561-2004>
- Groh, J., Diamantopoulos, E., Duan, X., Ewert, F., Herbst, M., Holbak, M., Kamali, B., Kersebaum, K. - C., Kuhnert, M., Lischeid, G., Nendel, C., Priesack, E., Steidl, J., Sommer, M., Pütz, T., Vereecken, H., Wallor, E., Weber, T. K. D., Wegehenkel, M., ... Gerke, H. H. (2020). Crop growth and soil water fluxes at erosion-affected arable sites: Using weighing lysimeter data for model intercomparison. *Vadose Zone Journal*, 19(1). <https://doi.org/10.1002/vzj2.20058>
- Groh, J., Vanderborght, J., Pütz, T., & Vereecken, H. (2016). How to control the lysimeter bottom boundary to investigate the effect of climate change on soil processes? *Vadose Zone Journal*, 15(7). <https://doi.org/10.2136/vzj2015.08.0113>
- Guo, L., Fan, B., Zhang, J., & Lin, H. (2018). Occurrence of subsurface lateral flow in the Shale Hills Catchment indicated by a soil water mass balance method. *European Journal of Soil Science*, 69, 771–786. <https://doi.org/10.1111/ejss.12701>
- Guo, L., & Lin, H. (2018). Addressing two bottlenecks to advance the understanding of preferential flow in soils. *Advances in Agronomy*, 147, 61–117. <https://doi.org/10.1016/bs.agron.2017.10.002>
- Guo, L., Mount, G. J., Hudson, S., Lin, H., & Levia, D. (2020). Pairing geophysical techniques improves understanding of the near-surface critical zone: Visualization of preferential routing of stem-flow along coarse roots. *Geoderma*, 357. <https://doi.org/10.1016/j.geoderma.2019.113953>
- Hannes, M., Wollschläger, U., Wöhling, T., & Vogel, H. - J. (2016). Revisiting hydraulic hysteresis based on long-term monitoring of hydraulic states in lysimeters. *Water Resources Research*, 52, 3847–3865. <https://doi.org/10.1002/2015WR018319>
- Hendrickx, J., & Flury, M. (2001). Uniform and preferential flow mechanisms in the vadose zone. In N. R. Council (Ed.), *Conceptual models of flow and transport in the fractured vadose zone* (pp. 149–187). The National Academies Press.
- Herbrich, M., & Gerke, H. H. (2017). Scales of water retention dynamics observed in eroded Luvisols from an arable postglacial soil landscape. *Vadose Zone Journal*, 16(10). <https://doi.org/10.2136/vzj2017.01.0003>
- Herbrich, M., Gerke, H. H., Bens, O., & Sommer, M. (2017). Water balance and leaching of dissolved organic and inorganic carbon of eroded Luvisols using high precision weighing lysimeters. *Soil & Tillage Research*, 165, 144–160.
- Herbrich, M., Gerke, H. H., & Sommer, M. (2018). Root development of winter wheat in erosion-affected soils depending on the position in a hummocky ground moraine soil landscape. *Journal of Plant Nutrition and Soil Science*, 181, 147–157. <https://doi.org/10.1002/jpln.201600536>
- Hopp, L., McDonnell, J. J., & Condon, P. (2011). Lateral subsurface flow in a soil cover over waste rock in a humid temperate environment.

- Vadose Zone Journal*, 10, 332–344. <https://doi.org/10.2136/vzj2010.0094>
- Hu, W., & Si, B. C. (2013). Soil water prediction based on its scale-specific control using multivariate empirical mode decomposition. *Geoderma*, 193–194, 180–188. <https://doi.org/10.1016/j.geoderma.2012.10.021>
- IUSS. (2006). World reference base for soil resources 2006 (*World Soil Resources Rep. 103*). FAO
- Julich, D., Julich, S., & Feger, K. - H. (2017). Phosphorus fractions in preferential flow pathways and soil matrix in hillslope soils in the Thuringian Forest (Central Germany). *Journal of Plant Nutrition and Soil Science*, 180, 407–417. <https://doi.org/10.1002/jpln.2016.00305>
- Kahl, G., Ingwersen, J., Nutniyom, P., Totrakool, S., Pansombat, K., Thavornnyutikarn, P., & Streck, T. (2008). Loss of pesticides from a litchi orchard to an adjacent stream in northern Thailand. *European Journal of Soil Science*, 59, 71–81. <https://doi.org/10.1111/j.1365-2389.2007.00984.x>
- Kutschera, L., Lichtenegger, E., & Sobotik, M. (2009). *Wurzelatlas der Kulturpflanzen gemäßigter Gebiete mit Arten des Feldgemüsebaues*. DLG-Verlag.
- Lamb, K. J., Macquarrie, K. T. B., Butler, K. E., Danielelescu, S., Mott, E., Grimmet, M., & Zebarth, B. J. (2019). Hydrogeophysical monitoring reveals primarily vertical movement of an applied tracer across a shallow, sloping low-permeability till interface: Implications for agricultural nitrate transport. *Journal of Hydrology*, 573, 616–630. <https://doi.org/10.1016/j.jhydrol.2019.03.075>
- Laine-Kaulio, H., Backnäs, S., Karvonen, T., Koivusalo, H., & McDonnell, J. J. (2014). Lateral subsurface stormflow and solute transport in a forested hillslope: A combined measurement and modeling approach. *Water Resources Research*, 50, 8159–8178. <https://doi.org/10.1002/2014WR015381>
- Lee, E., & Kim, S. (2019). Wavelet analysis of soil moisture measurements for hillslope hydrological processes. *Journal of Hydrology*, 575, 82–93. <https://doi.org/10.1016/j.jhydrol.2019.05.023>
- Lin, H., & Zhou, X. (2008). Evidence of subsurface preferential flow using soil hydrologic monitoring in the Shale Hills catchment. *European Journal of Soil Science*, 59, 34–49. <https://doi.org/10.1111/j.1365-2389.2007.00988.x>
- Liu, H., & Lin, H. (2015). Frequency and control of subsurface preferential flow: From pedon to catchment scales. *Soil Science Society of America Journal*, 79, 362–377. <https://doi.org/10.2136/sssaj2014.08.0330>
- Liu, Q., Hao, Y., Stebler, E., Tanaka, N., & Zou, C. B. (2017). Impact of plant functional types on coherence between precipitation and soil moisture: A wavelet analysis. *Geophysical Research Letters*, 44, 12. <https://doi.org/10.1002/2017GL075542>
- Lu, N., Kaya, B. S., & Godt, J. W. (2011). Direction of unsaturated flow in a homogeneous and isotropic hillslope. *Water Resources Research*, 47(2). <https://doi.org/10.1029/2010WR010003>
- Luo, Z., Niu, J., Xie, B., Zhang, L., Chen, X., Berndtsson, R., Du, J., Ao, J., Yang, L., & Zhu, S. (2019). Influence of root distribution on preferential flow in deciduous and coniferous forest soils. *Forests*, 10(11). <https://doi.org/10.3390/f10110986>
- Lv, M., Hao, Z., Liu, Z., & Yu, Z. (2013). Conditions for lateral downslope unsaturated flow and effects of slope angle on soil moisture movement. *Journal of Hydrology*, 486, 321–333. <https://doi.org/10.1016/j.jhydrol.2013.02.013>
- MATLAB. (2018). *MATLAB (Version 2019b)*. The MathWorks.
- Mitchell, A. R., Ellsworth, T. R., & Meek, B. D. (1995). Effect of root systems on preferential flow in swelling soil. *Communications in Soil Science and Plant Analysis*, 26, 2655–2666. <https://doi.org/10.1080/00103629509369475>
- Newman, B. D., Wilcox, B. P., & Graham, R. C. (2004). Snowmelt-driven macropore flow and soil saturation in a semiarid forest. *Hydrological Processes*, 18, 1035–1042. <https://doi.org/10.1002/hyp.5521>
- Nyquist, J. E., Toran, L., Pitman, L., Guo, L.i., & Lin, H. (2018). Testing the fill-and-spill model of subsurface flow using GPR and dye tracing. *Vadose Zone Journal*, 17, 1–13. <https://doi.org/10.2136/vzj2017.07.0142>
- Pütz, T.h., Kiese, R., Wollschläger, U., Groh, J., Rupp, H., Zacharias, S., Priesack, E., Gerke, H. H., Gasche, R., Bens, O., Borg, E., Baessler, C., Kaiser, K., Herbrich, M., Munch, J. - C., Sommer, M., Vogel, H. - J., Vanderborght, J., & Vereecken, H. (2016). TERENO-SOILCan: A lysimeter-network in Germany observing soil processes and plant diversity influenced by climate change. *Environmental Earth Sciences*, 75, 1–14. <https://doi.org/10.1007/s12665-016-6031-5>
- R Core Team. (2019). *R: A language and environment for statistical computing (Version R-3.6.2)*. R Foundation for Statistical Computing. <https://www.R-project.org>
- Rahmati, M., Groh, J., Graf, A., Pütz, T., Vanderborght, J., & Vereecken, H. (2020). On the impact of increasing drought on the relationship between soil water content and evapotranspiration of a grassland. *Vadose Zone Journal*, 19(1). <https://doi.org/10.1002/vzj2.20029>
- Rieckh, H., Gerke, H. H., Siemens, J., & Sommer, M. (2014). Water and dissolved carbon fluxes in an eroding soil landscape depending on terrain position. *Vadose Zone Journal*, 13(7). <https://doi.org/10.2136/vzj2013.10.0173>
- Rieckh, H., Gerke, H. H., & Sommer, M. (2012). Hydraulic properties of characteristic horizons depending on relief position and structure in a hummocky glacial soil landscape. *Soil and Tillage Research*, 125, 123–131. <https://doi.org/10.1016/j.still.2012.07.004>
- Ritter, A., Regalado, C. M., & Muñoz-Carpena, R. (2009). Temporal common trends of topsoil water dynamics in a humid subtropical forest watershed. *Vadose Zone Journal*, 8, 437–449. <https://doi.org/10.2136/vzj2008.0054>
- Si, B. C. (2008). Spatial scaling analyses of soil physical properties: A review of spectral and wavelet methods. *Vadose Zone Journal*, 7, 547–562. <https://doi.org/10.2136/vzj2007.0040>
- Si, B. C., & Zeleke, T. B. (2005). Wavelet coherency analysis to relate saturated hydraulic properties to soil physical properties. *Water Resources Research*, 41(11). <https://doi.org/10.1029/2005WR004118>
- Sidle, R. C., Noguchi, S., Tsuboyama, Y., & Laursen, K. (2001). A conceptual model of preferential flow systems in forested hillslopes: Evidence of self-organization. *Hydrological Processes*, 15, 1675–1692. <https://doi.org/10.1002/hyp.233>
- Sommer, M., Augustin, J., & Kleber, M. (2016). Feedbacks of soil erosion on SOC patterns and carbon dynamics in agricultural landscapes: The CarboZALF experiment. *Soil and Tillage Research*, 156, 182–184. <https://doi.org/10.1016/j.still.2015.09.015>
- Torrence, C., & Compo, G. P. (1998). A practical guide to wavelet analysis. *Bulletin of the American Meteorological Society*, 79, 61–78. [https://doi.org/10.1175/1520-0477\(1998\)079<0061:APGTWA>2.0.CO;2](https://doi.org/10.1175/1520-0477(1998)079<0061:APGTWA>2.0.CO;2)
- Torrence, C., & Webster, P. J. (1999). Interdecadal changes in the ENSO–monsoon system. *Journal of Climate*, 12, 2679–2690. [https://doi.org/10.1175/1520-0442\(1999\)012<2679:ICITEM>2.0.CO;2](https://doi.org/10.1175/1520-0442(1999)012<2679:ICITEM>2.0.CO;2)
- Umwelt-Geräte-Technik. (2013). *UGT: Novel lysimeter-techniques*. Umwelt-Geräte-Technik. www.ugt-online.de

- Villazón, M. F., & Willems, P. (2010). Filling gaps and daily disaccumulation of precipitation data for rainfall-runoff model. In M. Morell, C. Popovsk, O. Morell, & V. Stojov (Eds.), *BALWOIS 2010*. MagnaSken.
- Wickenkamp, I., Huisman, J. A., Bogen, H. R., Lin, H. S., & Vereecken, H. (2016). Spatial and temporal occurrence of preferential flow in a forested headwater catchment. *Journal of Hydrology*, 534, 139–149. <https://doi.org/10.1016/j.jhydrol.2015.12.050>
- Wienhöfer, J., Lindenmaier, F., & Zehe, E. (2011). Challenges in understanding the hydrologic controls on the mobility of slow-moving landslides. *Vadose Zone Journal*, 10, 496–511. <https://doi.org/10.2136/vzj2009.0182>
- Wienhöfer, J., & Zehe, E. (2014). Predicting subsurface stormflow response of a forested hillslope: The role of connected flow paths. *Hydrology and Earth System Sciences*, 18, 121–138. <https://doi.org/10.5194/hess-18-121-2014>
- Wilcox, B. P., Newman, B. D., Brandes, D., Davenport, D. W., & Reid, K. (1997). Runoff from a semiarid Ponderosa pine hillslope in New Mexico. *Water Resources Research*, 10, 2301–2314. <https://doi.org/10.1029/97WR01691>
- Wittenberg, H., Aksoy, H., & Miegel, K. (2019). Fast response of groundwater to heavy rainfall. *Journal of Hydrology*, 571, 837–842. <https://doi.org/10.1016/j.jhydrol.2019.02.037>
- Wittenberg, H.; Aksoy, H.; & Miegel, K. (2020). The rapid rise of groundwater after heavy rainfalls. (German title: Der schnelle Anstieg des Grundwassers nach Starkregen). *Hydrologie Und Wasserbewirtschaftung*, 2020, 64, 66–74.
- Wu, W., Geller, M. A., & Dickinson, R. E. (2002). The response of soil moisture to long-term variability of precipitation. *Journal of Hydrometeorology*, 3, 604–613. [https://doi.org/10.1175/1525-7541\(2002\)003<0604:TROSMT>2.0.CO;2](https://doi.org/10.1175/1525-7541(2002)003<0604:TROSMT>2.0.CO;2)
- Xie, M., Šimůnek, J., Zhang, Z., Zhang, P., Xu, J., & Lin, Q. (2019). Nitrate subsurface transport and losses in response to its initial distributions in sloped soils: An experimental and modelling study. *Hydrological Processes*, 33, 3282–3296. <https://doi.org/10.1002/hyp.13556>
- Yang, Y., Jia, X., Wendroth, O., & Liu, B. (2018). Estimating saturated hydraulic conductivity along a south-north transect in the Loess Plateau of China. *Soil Science Society of America Journal*, 82, 1033–1045. <https://doi.org/10.2136/sssaj2018.03.0126>
- Yang, Y., Wendroth, O., & Walton, R. J. (2016). Temporal dynamics and stability of spatial soil matric potential in two land use systems. *Vadose Zone Journal*, 15(8). <https://doi.org/10.2136/vzj2015.12.0157>

APPENDIX

A3 Gap-filling procedure

The data time series of the pressure head and volumetric SWC were quality controlled by an automatic and by a manual “flagging” procedure to remove sensor errors (Hans-Jörg Vogel and Ralf Gründling, UFZ, Halle, personal communication, 2019). In this procedure, all values outside measurement ranges (i.e., +200 to –850 hPa for pressure heads, 5 to 60 Vol-% for volumetric SWC) and errors indicated by “999” or negative SWC readings were automatically removed. Isolated spikes or noise was identified and removed by calculating the moving median of 13 values and defining a tolerance interval of ± 20 hPa for pressure heads. For the SWC the moving medians of 5, 7, and 25 values were computed and tolerance intervals of ± 1 , ± 3 , and ± 5 Vol-% were chosen to remove sharp, medium, and coarse spikes (sudden, implausible changes in SWC), respectively. Residual data steps such as short-term offsets in the level of measured SWC values due to automatic signal interpretation were identified by calculating the absolute change between two consecutive values and limiting this difference to +15 and –5 Vol-%. For the pressure heads also, shorter measurement periods were removed, if there were data gaps of 1 d and the number of values was smaller than 342 in 3 d. These short measurement periods occurred sometimes in summer between intermittent sensor failures.

Gaps in the time series of the two soil moisture state variables, pressure head and SWC, were filled according to Groh et al. (2020) by calculating linear models of the time series of parallel measurements (Villazón & Willems, 2010), if only one sensor failed. If the gaps could not be filled by using data from similar lysimeter or field measurements that were operating in parallel and the missing period was shorter than 1 d, a linear interpolation procedure between the last and the first correct data points was applied (Falge et al., 2001).

How to cite this article: Ehrhardt A, Groh, J, Gerke H H.. Wavelet analysis of soil water state variables for identification of lateral subsurface flow: Lysimeter vs. field data. *Vadose Zone J.* (2021);20:1–24. <https://doi.org/10.1002/vzj2.20129>

TABLE A1 Dates of cultivation and cropping from autumn 2016 to spring 2018 (Gernot Verch, ZALF, personal communication, November 2019)

Date	Measurement
19 Sept. 2016	Seed furrow for winter rye (breed: SU Performer)
7 Oct. 2016	Sowing winter rye
14 Mar. 2017	Herbicide application (4.5 L ha ⁻¹ Round up)
20 Apr. 2017	Fertilization (110 kg ha ⁻¹ P ₂ O ₅ , 300 kg ha ⁻¹ K ₂ O)
21 Apr. 2017	Heavy grubber (Incorporation of liquid manure)
24 Apr. 2017	Heavy grubber (treatment dead winter rye), seedbed preparation with circular grubber, sowing maize (breed: Zoey)
2 May 2017	Fertilization (160 kg N ha ⁻¹)
22 May 2017	Herbicide application (1.2 L ha ⁻¹ Calaris + 1.25 L ha ⁻¹ Dual Gold + 16 g ha ⁻¹ Peak)
25 Sept. 2017	Manual harvest lysimeters
26 Sept. 2017	Harvest field
27 Sept. 2017	Incorporation of maize stubbles with mulcher
28 Sept. 2017	Seed furrow for winter rye (breed: SU Cossanni)
13 Oct. 2017	Sowing winter rye
19 Mar. 2018	Herbicide application (3.0 L ha ⁻¹ Round up)
27 Mar. 2018	Fertilization (50 kg ha ⁻¹ P ₂ O ₅)
09 Apr. 2018	Soil cultivation with heavy grubber and circular grubber, sowing oat (breed: Apollon)
19–20 Apr. 2018	Fertilization (1 dt ha ⁻¹ Kieserit, 100 kg N ha ⁻¹)
4 May 2018	Herbicide application (70 g ha ⁻¹ Biathlon + 1.0 L ha ⁻¹ Dash)
30 Aug. 2018	Harvest

TABLE A2 Precipitation measurement equipment at the experimental field site “Holzendorf” CarboZalf-D; see Figure 2 for the location of sensors of numbers 1–5

No.	RS	Type	Product	Manufacturer	Start date
	min				
1	1	Usc	WXT520	Vaisala (Finland)	11 June 2009
		TP_h	52202	Young (USA)	
2	30	TP_nh	RG50	Seba (Germany)	18 Sept. 2009
3	10	Usc	WXT520	Vaisala	25 Sept. 2014
4	30	TP_h	SBS500H	Campbell (USA)	07 Nov. 2014 to Sept. 2015
5	30	TP_h	SBS500H	Campbell	3 Nov. 2011

Note. RS, recording sequence. Types: Usc (ultrasonic), TP (tipping bucket), TP_h (tipping bucket heatable), TP_nh (tipping bucket not heatable).

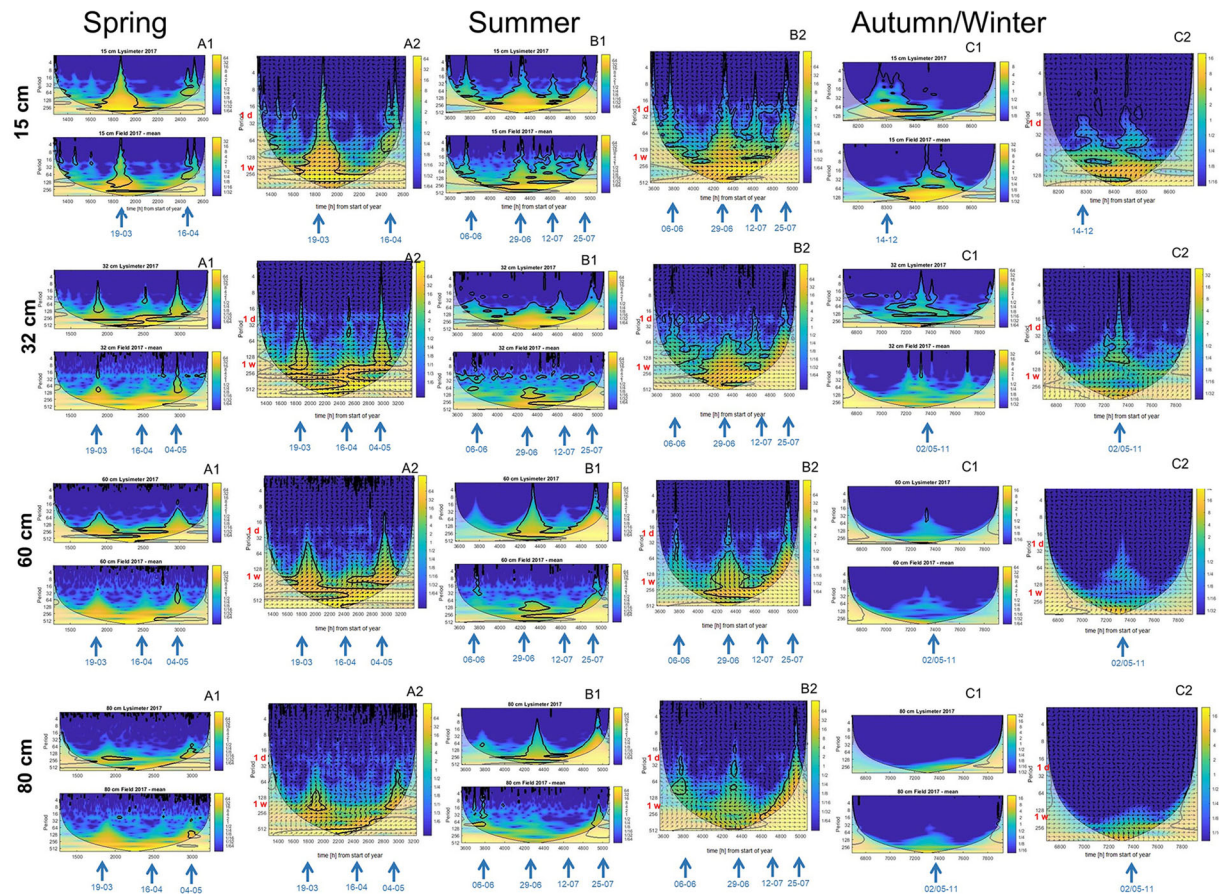


FIGURE A4 Wavelet spectra in lysimeter and field (A1, B1, C1) and cross-wavelet spectra of soil water content (SWC) in lysimeter and field (A2, B2, and C2) at 15-, 32-, 60-, and 80-cm depth in spring, summer, and autumn of the wet year 2017. Major precipitation events that were further analyzed are marked with a blue arrow and a date below the plot. Time is given at the x axis in the number of hours from the start of the year. The period of the spectra is given in hours. The area outside the cone of influence (COI) is shaded and mark the part of the plot where edge effects influence the data. Areas in the wavelet and cross wavelet spectra that differ significantly (significance level = 5%) from a background power spectrum are shown as thick contour lines. Arrows in the cross wavelet spectrum illustrate the time shifts of the water content in response to precipitation between lysimeter and field. Arrows that are turned right (east) indicate a perfect correlation. If they are turned left (west), the time series show anti-correlation. Arrows pointing upwards indicate a faster reaction to precipitation in the field soil as compared with the lysimeter soil, whereas arrows turned downwards show a faster reaction in the lysimeter

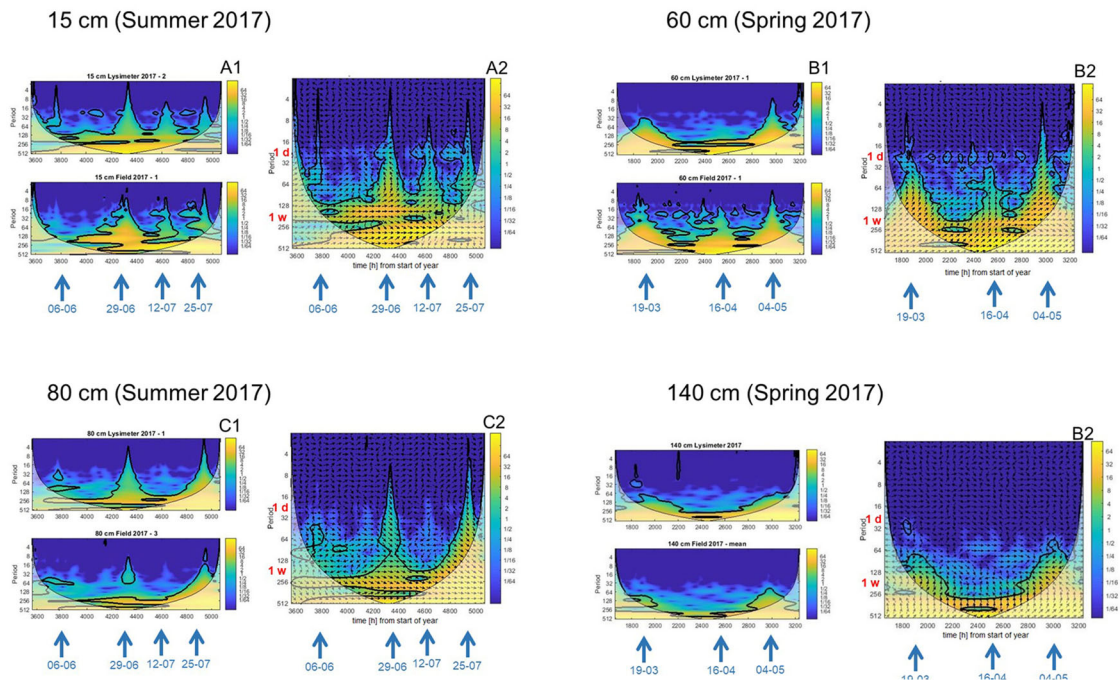


FIGURE A5 Wavelet spectra of lysimeter and field (A1, B1, C1, and D1) and cross wavelet spectra of pressure head values in lysimeter and field (A2, B2, C2, and D2) at 15-cm (summer 2017), 60-cm (spring 2017), 80-cm (summer 2017) and 140-cm depth (spring 2017). Major precipitation events that were further analyzed are marked with a blue arrow and a date below the plot. Time is given at the x axis in the number of hours from the start of the year. The period of the spectra is given in hours. The area outside the cone of influence (COI) is shaded and mark the part of the plot where edge effects influence the data. Areas in the wavelet and cross wavelet spectra that differ significantly (significance level = 5%) from a background power spectrum are shown as thick contour lines. Arrows in the cross wavelet spectrum illustrate the time shifts of the water content in response to precipitation between lysimeter and field. Arrows that are turned right (east) indicate a perfect correlation. If they are turned left (west), the time series show anti-correlation. Arrows pointing upwards indicate a faster reaction to precipitation in the field soil as compared with the lysimeter soil, whereas arrows turned downwards show a faster reaction in the lysimeter

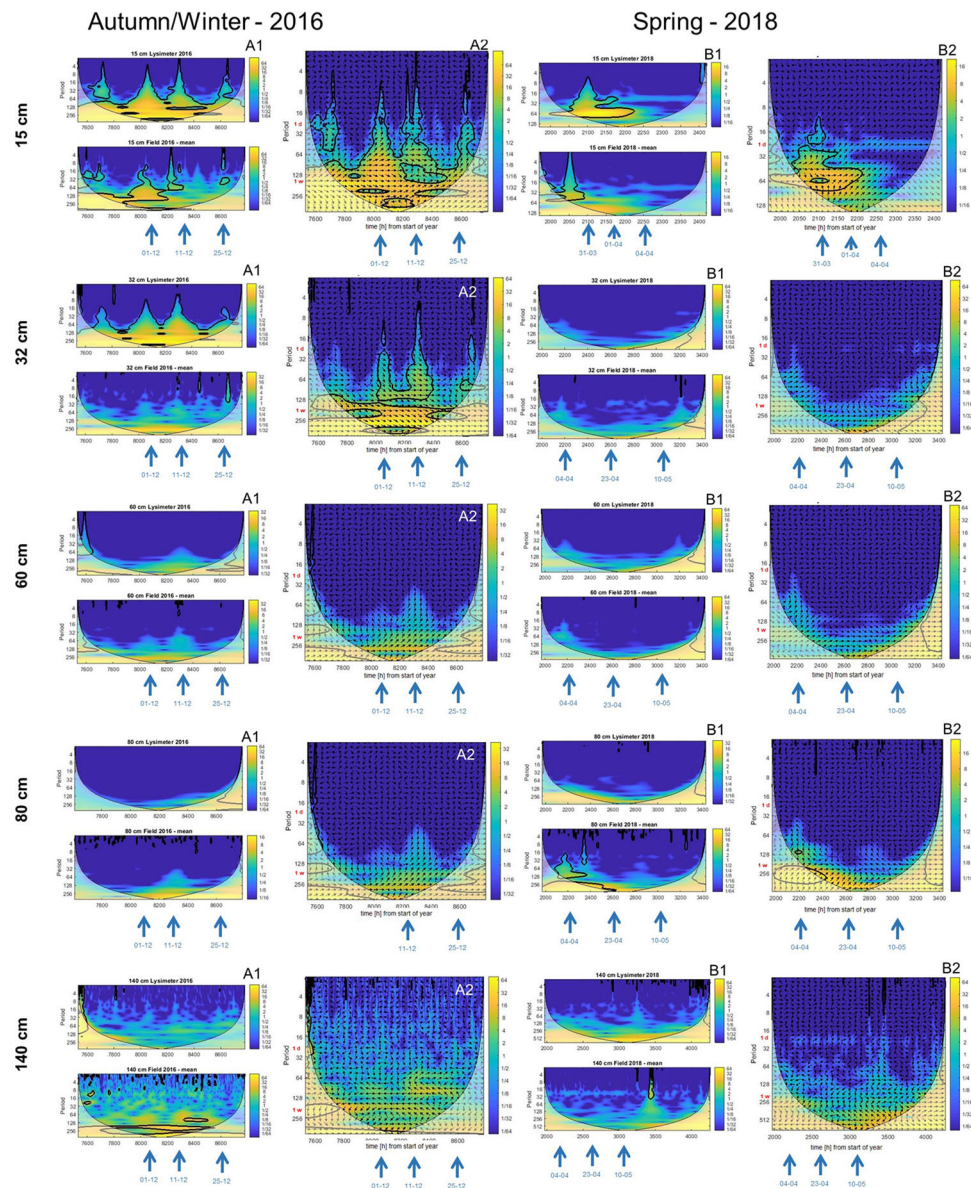


FIGURE A6 Wavelet spectra of lysimeter and field (A1, B1) and cross wavelet spectra of soil water content (SWC) in lysimeter and field (A2, B2) in 15-cm, 32-cm, 60-cm, 80-cm, and 140-cm depth in autumn 2016 (dry year) and spring 2018 (dry year). Major precipitation events that were further analyzed are marked with a blue arrow and a date below the plot. Time is given at the x axis in the number of hours from the start of the year. The period of the spectra is given in hours. The area outside the cone of influence (COI) is shaded and mark the part of the plot where edge effects influence the data. Areas in the wavelet and cross wavelet spectra that differ significantly (significance level = 5%) from a background power spectrum are shown as thick contour lines. Arrows in the cross wavelet spectrum illustrate the time shifts of the water content in response to precipitation between lysimeter and field. Arrows that are turned right (east) indicate a perfect correlation. If they are turned left (west) the time series show anti-correlation. Arrows pointing upwards indicate a faster reaction to precipitation in the field soil as compared with the lysimeter soil, whereas arrows turned downwards show a faster reaction in the lysimeter

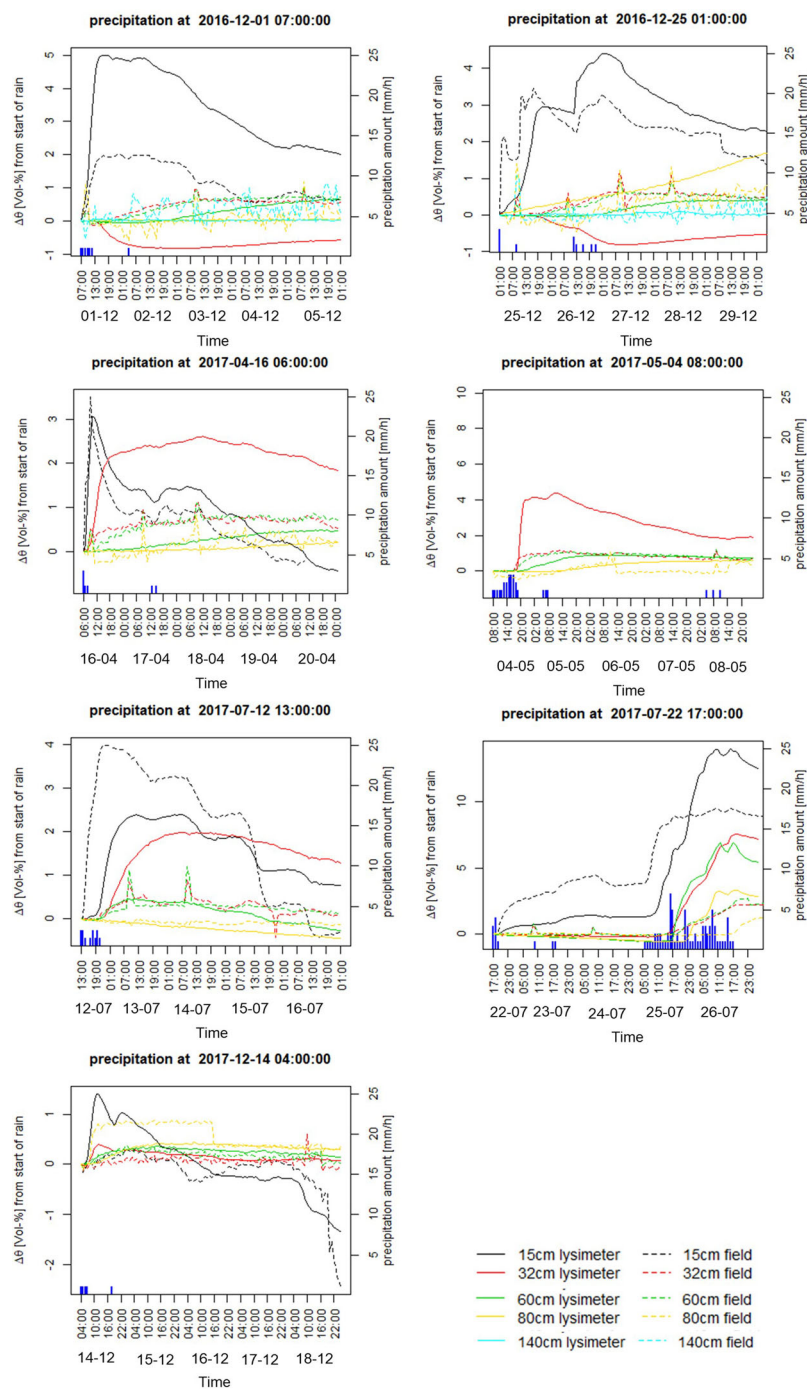


FIGURE A7 Soil water content (SWC) increase in response to additional precipitation events from Table 4 in lysimeter and field at 15-cm, 32-cm, 60-cm, 80-cm, and 140-cm depth in 2016, 2017, and 2018