RESEARCH ARTICLE

WILEY

A signature-based approach to quantify soil moisture dynamics under contrasting land-uses

Ryoko Araki¹ | Flora Branger² | Inge Wiekenkamp³ | Hilary McMillan¹

¹Department of Geography, San Diego State University, San Diego, California, USA

²INRAE, UR RiverLy, Centre Lyon-Grenoble Auvergne-Rhône-Alpes, Villeurbanne, France ³Helmholtz Centre Potsdam, GFZ German Research Centre for Geosciences, Postdam, Germany

Correspondence

Ryoko Araki, Department of Geography, San Diego State University, 5500 Campanile Dr, San Diego, CA 92182, USA. Email: raraki8159@sdsu.edu

Abstract

Soil moisture signatures provide a promising solution to overcome the difficulty of evaluating soil moisture dynamics in hydrologic models. Soil moisture signatures are metrics that quantify the dynamic aspects of soil moisture timeseries and enable process-based model evaluations. To date, soil moisture signatures have been tested only under limited land-use types. In this study, we explore soil moisture signatures' ability to discriminate different dynamics among contrasting land-uses. We applied a set of nine soil moisture signatures to datasets from six in-situ soil moisture networks worldwide. The dataset covered a range of land-use types, including forested and deforested areas, shallow groundwater areas, wetlands, urban areas, grazed areas, and cropland areas. Our set of signatures characterized soil moisture dynamics at three temporal scales: event, season, and a complete timeseries. Statistical assessment of extracted signatures showed that (1) event-based signatures can distinguish different dynamics for all the land-uses, (2) season-based signatures can distinguish different dynamics for some types of land-uses (deforested vs. forested, urban vs. greenspace, and cropped vs. grazed vs. grassland contrasts), (3) timeseries-based signatures can distinguish different dynamics for some types of land-uses (deforested vs. forested, urban vs. greenspace, shallow vs. deep groundwater, wetland vs. nonwetland, and cropped vs. grazed vs. grassland contrasts). Further, we compared signature-based process interpretations against literature knowledge; event-based and timeseries-based signatures generally matched well with previous process understandings from literature, but season-based signatures did not. This study will be a useful guideline for understanding how catchment-scale soil moisture dynamics in various land-uses can be described using a standardized set of hydrologically relevant metrics.

KEYWORDS

hydrologic signature, land-use, metrics-based approach, process-based evaluation, soil moisture, soil moisture signature

This is an open access article under the terms of the Creative Commons Attribution-NonCommercial License, which permits use, distribution and reproduction in any medium, provided the original work is properly cited and is not used for commercial purposes. © 2022 The Authors. Hydrological Processes published by John Wiley & Sons Ltd.

1 | INTRODUCTION

Soil moisture is an important control of water and energy cycles. For example, in rainfall-runoff processes, soil moisture determines the initiation and the response patterns of streamflow (McMillan & Srinivasan, 2015; Penna et al., 2011; Tromp-van Meerveld & McDonnell, 2006; Zehe et al., 2005). In land-atmosphere processes, soil moisture regulates moisture availability in land and atmosphere, and subsequently influences rainfall and evapotranspiration patterns (Eltahir, 1998; Koster & Suarez, 2001; McColl et al., 2019). The role of soil moisture as a modulator between the atmosphere and groundwater storage is explicitly incorporated in many hydrologic models (Singh & Frevert, 2010).

1.1 | Scales of soil moisture measurement

Nevertheless, the so-called 'scaling problem' often prevents hydrologists from using in-situ soil moisture data for input, calibration, or validation of hydrological models. The scaling problem refers to the mismatch of spatial scales between observations and models. In the field, soil moisture is commonly observed at a point scale by sensors measuring only around the 3-cm vicinity of the installation point (Babaeian et al., 2019). Therefore, the point-scale measurement does not necessarily represent the catchment-scale values, which is often the target scale for hydrologic modelling. Point-scale soil moisture data often contain local variability due to pedology and topography (Vereecken et al., 2016), and such spatially heterogeneous data are sensitive to scaling (Blöschl & Sivapalan, 1995). These scaling issues have discouraged hydrologists from using in-situ soil moisture data for model input or evaluation. However, when evaluated solely based on streamflow dynamics, different hydrologic models can produce similar streamflow responses while producing different soil moisture patterns (Bouaziz et al., 2021). This, in its turn, leads to misrepresentation of soil moisture processes.

This 'scaling problem' has motivated research on representative soil moisture values of a catchment. For example, researchers have intensively studied the best monitoring locations and strategies to capture the soil moisture dynamics (De Lannoy et al., 2006; Korres et al., 2015; Mälicke et al., 2020; Skøien et al., 2003; Vanderlinden et al., 2012; Vereecken et al., 2007). It is becoming common to evaluate modelled soil moisture values or bias-correct the soil moisture values for model input based on the observed mean and variabilities (Draper & Reichle, 2015). However, such statistical metrics do not directly measure the soil moisture dynamics that models aim to reproduce. There remains a need for process-based methods to evaluate soil moisture processes information observed at point scales to model scales.

1.2 | Hydrological signature concepts applied to soil moisture

Hydrological signatures have been developed to overcome the difficulty of using hydrologic data in model calibration and evaluation. Hydrological signatures are metrics representing catchment dynamics (Gupta et al., 2008; McMillan, 2020a, 2020b). Hydrological signatures offer a way to identify preferred model structure and parameterization based on the models' ability to reproduce the observed signatures, and therefore the underlying hydrologic processes and dynamics (McMillan, 2020a). Researchers have developed hydrologic signatures to represent various processes, such as streamflow (Gnann, Coxon, et al., 2021; McDonnell et al., 2007; Yarnell et al., 2015), groundwater (Heudorfer et al., 2019), and snow processes (Horner et al., 2020; Schaefli, 2016), and the impact of environmental alteration on those processes (Richter et al., 1996). When the hydrologic signature concept is applied to analyse soil moisture processes, we call these metrics 'soil moisture signatures.'

1.3 | Selecting soil moisture signatures

Soil moisture signatures are designed to quantify soil moisture dynamics at three main temporal scales (Branger & McMillan, 2020; Draper & Reichle, 2015): per storm event ('event-based signatures'), per season ('season-based signatures'), and per a complete time series ('time series-based signatures'). Recent advancements of dense in-situ networks of soil moisture sensors provide soil moisture observation at high spatio-temporal resolution and have enabled the development of various types of signatures. Examples of existing soil moisture signatures include event-based signatures that measure preferential flow occurrence (Graham & Lin, 2011) and progression of the wetting front (Blume et al., 2009), season-based signatures that measure the persistence of seasonal wet and dry states (Ghannam et al., 2016), and a timeseries-based signature that measures hysteresis in wetting and drying processes (Rosenbaum et al., 2012). Note that these signatures are often mentioned by a different name or are unnamed in literature but are summarized here as 'soil moisture signatures'. Based on individual signatures proposed by these studies, a few studies proposed sets of soil moisture signatures to capture soil moisture dynamics in a standardized manner (Branger & McMillan, 2020; Chandler et al., 2017; Graham & Lin, 2012).

When designing soil moisture signatures, one of the important criteria is discriminatory power: that is, an ability to discriminate among different soil moisture regimes influenced by relevant physical factors, such as climate, geology, and land-use (McMillan et al., 2017). Fulfilling this criterion allows us to understand and compare soil moisture regimes using signatures. Previous studies have shown that signatures can discriminate between soil moisture dynamics in contrasting climate and geology. Chandler et al. (2017) characterized seasonal wetting, drying, freezing, and melting dynamics in various soil texture types using four timeseries-based signatures for Boise catchments in the United States. Branger and McMillan (2020) explicitly tested the discriminatory power of season- and timeseries-based signatures among climate classes and among geology classes in New Zealand catchments.



FIGURE 1 Maps of the study sites. The contours are based on a field survey for WB (Graf et al., 2014), Shuttle Radar Topography Mission Elevation Dataset (National Aeronautics and Space Administration, NASA et al., 2002) for HB, RM, TX, MQ, and OZ. All maps are north upward

Although land-use is a major determinant of rainfall-runoff and soil moisture processes (Alaoui et al., 2018; Rogger et al., 2017; Viglione et al., 2016), the discriminatory power of signatures between different land-uses has been tested only under limited types of environments. At the same time, previous studies show that describing the discriminatory power of soil moisture signatures is inconclusive. Branger and McMillan (2020) found low discriminatory power of event-based signatures in non-forested and forested areas. Chandler et al. (2017) found low power of timeseries-based signatures to discriminate soil hydraulic characteristics among different tree species. Wiekenkamp et al. (2019), on the other hand, found high discriminatory power of event-based signatures between forested and deforested areas. Some studies found distinct soil moisture values across a wider variety of land-uses, including grazing, cultivation, forests, and grasslands, but their characterizations are limited to spatial mean or variability (Deng et al., 2016; Fu et al., 2003; Gao et al., 2014; Jawson & Niemann, 2007). Testing soil moisture signatures for various landuses is important for developing a standardized set of signatures that can discriminate the distinct soil moisture processes.

1.4 | Aims of this paper

This paper aims to test soil moisture signatures' ability to describe soil moisture dynamics under a range of land-uses. Our work extends the

TABLE 1 Ke the annual total _l	ey climatic and geological cl precipitation rate to the an	haracteristics of stu nual potential evap	dy sites. The data are obtained from 'Key referen' oration rate. For each station, aridity calculated at	t all sensor	. Aridity was calculated us points and averaged for t	sing GLDAS-2.1 (Rodell et the observation period	t al., 2014) as the ratio of
Study site (abbreviation)	Land-use, in the order of degree of disturbance	Annual precipitation (mm/year)	Annual mean temperature (°C)	Aridity	Vegetation	Soil type (texture and soil type)	Key reference papers
Wüstebach WB	Forested versus deforested (Logging removed 97% of tree biomass. Stumps and litter remained. Trees were transported by skid rails to minimize soil compaction)	1220	7 (<0C Dec. to Mar.)	0.97	Coniferous trees (Norway Spruce and Sitka spruce) planted in the 1940s. Average density 370 trees/ha, average height 25 m	Silty clay loam with fractions of coarse material; cambisols, planosols, and gleysols	(Bogena et al., 2015; Rosenbaum et al., 2012; Wiekenkamp et al., 2019)
Hamburg HB	Greenspace versus urban (The urban area mostly consists of housings. The degree of sealing is 50%–60%. Soil moisture sensors were installed in the backyards. Soil profile contains construction waste)	775	Avg 9; max 17; min 1	0.78	Lawn, high pasture grass, short grass, and deciduous trees	Sand, sandy loam, loamy sand, and peat; Cambisols, Technosol, Luvisol, Anthrosol, Gleysol, Histosol, and Regosol	(Wiesner et al., 2014, 2016)
R aam R M	Deep (>1 m) versus shallow groundwater (The definition follows Benninga, Carranza, Michiel-Pezij, et al., 2018). The groundwater table fluctuates 25– 160 cm below the soil surface.)	818	Avg 9.1; max 18.3; min 3.3;	0.58	Grass	Sand with 20% loam content: Podzols and Anthrosols	(Benninga, Carranza, Pezij, et al., 2018)
Texas	Ungrazed versus grazed (The definition follows field note in the metadata)	807	18.4	0.40	Oak trees, woody plants (ashe juniper and honey mesquite), and grass	Sand, sandy loam, clay loam, silty clay, clay; Calciustolls, Haplustepts, Calciustepts	(Bureau of Economic Geology, 2020; Caldwell et al., 2019; Woodruff & Woodruff &
Maqu MQ	Non-wetland versus wetland (Soil organic matter content is 17–56 g/kg and 136–229 g/kg, respectively)	593	1.3 (<0C from Nov. to Mar.)	0.42	Grass	Silt loam; N/A	(Dente et al., 2012; Su et al., 2011; Wang et al., 2019)

previous studies of soil moisture signatures (Branger & McMillan, 2020; Chandler et al., 2017; Graham & Lin, 2012) by applying their signatures to a wider range of land-uses. The six study sites around the globe are chosen to represent 12 land-use types. All study sites include an internal contrast between two to three land-uses (e.g., deforested vs. forested areas). The paper consists of three sections. The first section reports the impact of data quality on signature calculation (Section 4.1). The second section uses multivariate analysis to evaluate the ability of soil moisture signatures to identify differences in soil moisture dynamics between land-uses (Section 4.2). The third section derives process implications from the differences in signature values between land-uses, by comparing calculated signatures against literature knowledge (Section 4.3).

2 | DATA

We analysed soil moisture data from six networks worldwide under diverse land-uses (Figure 1). We selected soil moisture network sites that have (1) two contrasting land-uses within a network; (2) both soil moisture and rainfall data available at hourly interval; (3) more than 2 years of data available: (4) catchment scale in size, as larger continental or national scale networks would have large climatic and geologic variation within the network that we sought to avoid. Finally, six sites were chosen to represent 12 types of land-uses from a commonly used land-use and land-cover classification (Anderson et al., 1976: Friedl et al., 2010). For two of the sites, the contrast was in the hydrologic processes (wetland vs. non-wetland in Magu, and shallow vs. deep groundwater areas in Raam). The site descriptions and sensor configurations are given in Table 1 and Table S1, respectively. The soil moisture data were downloaded through the networks' website or obtained from the site manager on request (see Data Availability Section). The soil moisture data were collected using either water content reflectometers, capacitance sensors, or soil dielectric sensors, which respectively calculate the permittivity from the travel time of electromagnetic waves, the change in frequency of electromagnetic waves, or the ratio of reflected voltage. Each observatory used empirical equations suitable for the soil texture to convert the permittivity to the volumetric water content (m³ of water/m³ of soil). The original data, whose intervals range from 15 to 60 min, were aggregated into hourly averages for consistency. We preprocessed soil moisture data for quality control. In most cases, data were preprocessed by each observatory based on its standards. We inspected the remaining errors automatically and manually, as described in Text S1.

We used rainfall datasets either from the soil moisture network station or a nearby weather station (see Data Availability Section and Table S1). The rainfall data were given in a cumulative amount of rainfall (mm) and measured using tipping buckets or weight-based sensors. The original data, whose intervals range from 30 min to 60 min, were aggregated into hourly cumulative amounts (mm/h) for consistency. If there are multiple rainfall stations at a given site, the one closest to the soil moisture sensors was used for the analysis.

Continued
\sim
-
ш
-
Ω
4
E.

 \simeq

Study site (abbreviation)	Land-use, in the order of degree of disturbance	Annual precipitation (mm/year)	Annual mean temperature (°C)	Aridity	Vegetation	Soil type (texture and soil type)	Key reference papers
OZ OZ	Grass versus grazed versus crop (The definition follows the metadata. Grazing is sheep, beef, and dairy. Cropping includes both irrigated and non-irrigated method)	Varies (300-1900)	16	0.17	Grass, pasture, crops (rice, barley, and oats)	Silty loam; N/A	(Smith et al., 2012; Young et al., 2008)

3 | METHODS

We tested the discriminatory power of soil moisture signatures to differentiate soil moisture dynamics between land-uses. First, we extracted soil moisture signatures that represent soil moisture dynamics (Section 3.1). Second, we used a multivariate statistic called the Kruskal-Wallis test to compare signature values among land-uses (Section 3.2). Third, we interpreted the process implication of signature differences between land-uses by testing hypotheses built on literature review against the calculated signatures (Section 3.3).

3.1 | Soil moisture signatures

As illustrated in Figure 2, we tested nine soil moisture signatures covering three aspects of dynamics (shape, timing, speed) at three temporal scales (per event, per season, and per complete timeseries). The signatures tested are: rising time, normalized amplitude, no-response rate, response type, rising limb density for the event-based signatures; seasonal transition start day and duration for the season-based signatures; distribution type, estimated field capacity, and estimated wilting point for the timeseries-based signatures. All signatures require only soil moisture and rainfall data. The following sections provide detailed descriptions and the algorithm to calculate each signature. The signature definition and the algorithm were based on the original methods, but we adapted them to suit a wide range of soil moisture dynamics and data quality.

3.1.1 | Event rising time, normalized amplitude, and no-response rate

Event rising time, amplitude, and response rate characterize the runoff dynamics in response to precipitation (Liang et al., 2011; Tian et al., 2019). These signatures were calculated for each storm event. First, following McMillan et al. (2014), rainfall records were divided into events; the start of the event was defined as when the minimum intensity exceeds 2 mm/h or 10 mm/day after more than 12 h of no rainfall; the end of the rainfall was defined as the start of the next rainfall or 5 days after the last rainfall, whichever occurred first. For each event, event rising time was calculated as the timelag from the start of an event to the soil moisture peak. Event amplitude was calculated as the difference between the soil moisture values at their maximum and at the start of the event, normalized using estimated field capacity and wilting point at the station (defined in Section 3.1.6) as practiced by Sumargo et al. (2021). Soil moisture was judged as not responding if there was no soil moisture peak detected. In other words, no response of soil moisture means that soil moisture values continued increasing or decreasing during the event. The 'no-response rate' was calculated as the number of events with no response divided by the number of all events.

3.1.2 | Event response type

We can characterize the flow pathway by comparing the order of response timings along soil profile (Graham & Lin, 2011, 2012; Wiekenkamp, Huisman, Bogena, Lin, & Vereecken, 2016). We applied the methods by Graham and Lin (2011) and Wiekenkamp, Huisman, Bogena, Lin, and Vereecken (2016) for classifying response types. First, event rising times were calculated as in Section 3.1.1, except that we set the minimum size of response magnitude as 2% of volumetric water content. Then, the response type was classified as 'sequential' when the response order was sequential from the shallow to the deeper sensor. The response type was classified as 'non-sequential' when the order of response times is non-sequential for at least one sensor. 'No-response' was assigned when none of the sensors responded.

3.1.3 | Rising limb density

Rising limb density characterizes the catchment flashiness and is often used in streamflow analysis (Sawicz et al., 2011). Rising limb density can also be translated as averaged rising time. We propose rising limb density as a new soil moisture signature that captures the shape of the event rising limbs. We applied an algorithm by Gnann, Coxon, et al. (2021) for the calculation. First, the rising limb was detected when the rising duration was more than an hour, and the magnitude of change in soil moisture was more than 1% volumetric water content. A 0.01% decrease in volumetric water content during the rising period was allowed. For each rising limb, the length and duration were calculated. Then, rising limb density was calculated as the sum of the rising limb length of all events divided by the sum of the rising time of all events.

3.1.4 | Seasonal transition date and duration

Seasonal transition signatures characterize the switching of soil moisture between wet and dry seasons, where different runoff regimes dominate (Grayson et al., 2006). We calculated seasonal transition signatures by fitting a piecewise linear model to the soil moisture timeseries for each wet-to-dry and dry-to-wet transition period. We chose piecewise linear models because the inflection point and plateau can represent the soil moisture value reaching its wetting and drying limit. The seasonal transition was calculated for time series that had bimodal distribution type (defined in Section 3.1.5) because the signature is only meaningful when soil moisture data show seasonality. First, to remove event-based variability, we aggregated the timeseries from hourly to daily intervals. Then, the wet-to-dry and dry-to-wet transition periods were cropped out. A piecewise linear model was fitted to the cropped time series. Last, the start and end days of the transition were defined as the inflection points of the piecewise linear model, expressed in the day of the year. Transition duration was defined as the length of time between the start and the end day.

(a)



(b)

		Timescale							
		Event	Season	Complete timeseries					
Dynamics	Shape	Rising limb density (Sawicz <i>et al.,</i> 2011)	-	Distribution type (Branger & McMillan, 2019; Graham and Lin, 2012)					
	Timing	Response type (Graham and Lin, 2012; Wiekenkamp <i>et al.,</i> 2016)	Transition date (Branger & McMillan, 2019)	-					
	Speed	Rising time (Branger & McMillan 2019)	Transition duration (Branger & McMillan, 2019)	-					
	Magnitude	Normalized amplitude (Branger & McMillan, 2019)	-	Estimated field capacity Estimated wilting point (Branger & McMillan, 2019; Chandler <i>et al.</i> , 2017)					

FIGURE 2 A set of signatures describing the soil moisture dynamics. (a) Illustrations show the signatures calculated. (b) A table shows the aspects of soil moisture dynamics represented by the signatures

3.1.5 | Distribution type

Distribution type characterizes the soil moisture storage and seasonality (D'Odorico et al., 2000; Laio et al., 2001; Rodriguez-Iturbe, D'Odorico, et al., 1999; Rodriguez-Iturbe, Porporato, et al., 1999; Samuel et al., 2008). The distribution type was classified based on the number of peaks in the probability density function (PDF) of the soil moisture data. First, we removed trends unrelated to seasonal variability by subtracting the one-year moving mean from the time series as practiced by Basak et al. (2017). Second, the soil moisture PDF was obtained using Kernel smoothing with twice the optimal bandwidth, which is optimal to represent PDF by normal distributions. Third, PDF peaks were detected if a given data sample point was larger than the two neighbouring data samples. Peaks with a magnitude smaller than 20% of the largest peak were eliminated. We used MATLAB Signal Processing Toolbox for peak detection. Last, PDFs were classified according to the number of peaks into 'unimodal' (one peak), 'bimodal' (two peaks), or 'multimodal' (three or more peaks).

3.1.6 | Estimated field capacity and wilting point

Soil moisture timeseries often exhibit seasonal wet and dry equilibriums, which represent the water holding capacity of the soil. Since the values are known to be comparable to field capacity and wilting point estimated from soil core sample experiments (Bean et al., 2018; Chandler et al., 2017), we define them in this paper as 'estimated' field capacity and wilting point. We calculated the estimated field capacity and wilting point as the peaks of the soil moisture PDF. First, peaks of the soil moisture PDF were detected as in Section 3.1.5. The peak with the largest and smallest volumetric soil moisture content was defined as the estimated field capacity and wilting point, respectively. If the estimated field capacity and wilting point coincided (i.e., distribution type was unimodal), both values were discarded. In this way, we automated the calculation of estimated field capacity and wilting point, which is commonly done by manually labelling the wet and dry equilibrium values in the timeseries.

3.2 | Statistical assessments

After calculating the signatures described in Section 3.1, we compared signature differences between land-uses using statistical tests. The statistical significances represent the discriminatory power of signatures to distinguish differences in dynamics across land-uses; in other words, the differences in dynamics outweigh the overall data uncertainty. A comparison was made between two or three contrasting land-uses within each study site (i.e., in total, six land-use comparisons for six study sites). As climate and geology will be strong confounding factors, comparison across all study sites was not implemented. For most signatures, we used the non-parametric Kruskal-Wallis test (Kruskal & Wallis, 1952). The Kruskal-Wallis test is a non-parametric method to test whether the data originate from identical distributions based on ranks. Non-parametric tests were chosen because soil moisture signatures often show skewed distributions (Branger & McMillan, 2020). We interpreted the difference as significant when the p-value is less than 0.05. The Kruskal-Wallis test was applied to signatures in interval or ratio form (all signatures except response type and distribution type). The Kruskal-Wallis test was not applicable for categorical variables, so we took a different approach for such signatures (response type and distribution type signatures). We calculated the 'dominance' of one category: the ratio of the number of samples in one category (sequential for response type; unimodal for distribution type) to the total number of samples (which is equal to the sum of sequential and non-sequential responses for response type; the sum of unimodal, bimodal, and multimodal distribution for distribution type). We used the change in the 'dominance' ratio of one category to measure differences between the two groups.

3.3 | Process interpretation

We took a hypothesis-testing approach to understand how signature values relate to soil moisture processes (Gnann, McMillan, et al., 2021; McKnight, 2017). First, we explored the interpretation of signature values based on expert knowledge in literature. We reviewed two types of literature: articles about the study site of interest, and articles about a watershed with a similar hydrologic environment to the study site of interest that investigated the processes using a signature-based approach on their soil moisture data. To build the overarching interpretation of signature values, we focused on catchment functionality. According to Black (1997) and Wagener et al. (2007), catchment functionality consists of four basic elements: partition, transmission, storage, and release. Among them, two functionalities are closely related to the soil moisture system: partitioning that corresponds to flow pathways of rainfall in soil or at the soil surface, and storage that corresponds to the amount of water stored in the soil. After building an overarching interpretation focused on these two functionalities, we tested them against the signature values from the soil moisture networks. We refined or updated our hypotheses if the signature differences were not satisfactorily explained.

4 | RESULTS

4.1 | Data quality assessment and its impact on signature extraction

This section demonstrates the data quality and its impact on our research design. The results of the data quality assessment show that sufficient data were obtained for statistical assessments. Kruskal-Wallis test requires a sample size of five or more to determine statistical significance (Riffenburgh, 2006). In Figure 3, the number of reliable timeseries exceeds five for most of the study sites. When there were less than five reliable stations within a testing group (consisting of a combination of a depth and a land-use), we could not complete the statistical assessment, especially for signatures that can be only extracted once per time series (estimated field capacity, estimated wilting point, no-response rate, and rising limb density signatures). Other signatures were robust to the lack of reliable data as they can be extracted once per season (seasonal transition date and duration) or event (event rising time, response type, amplitude).

Overall, signature values showed clear differences among the study sites (Figure 4). This implies that the signatures were successfully extracted and can be used for further analysis. Signature differences between study sites can be attributed to the differences in their climate and geology. For example, estimated field capacity was clearly correlated with aridity index, except for Maqu (MQ), where wetland areas produced unusually organic-rich soil. However, analysis of climate and geology controls on signature values is beyond our scope and not further discussed.

4.2 | Signature differences between contrasting land-uses

This section provides an overview of how soil moisture signature values change depending on the land-use. We explain signature differences between land-uses from two perspectives: the magnitude (whether the signature magnitude for a given soil depth differs between land-uses) and the profile along soil depth (whether the increasing or decreasing trend of signature values relative to soil depth differs between land-uses). Figure 5 and Figure S1 show the signature differences in terms of the magnitude and the profile, respectively. Figures 6, 7, and 8 show the boxplots of selected signatures that showed notable differences between land-uses. Please refer to the supplemental material for boxplots of signature values for all the study sites (Figures S2, S3, and S4).

Interpretation of Figure 5 is as follows. In Figure 5, signatures that were statistically significantly different between land-uses are highlighted in darker blue. For example, many cells in the column of 'event-based signatures' are highlighted in darker blue in Figure 5, indicating that event-based signatures showed a high ability to distinguish different dynamics between the study sites (called



FIGURE 3 Number of stations that passed the final quality control. The categories that have five or more variables can be used for statistical analysis (indicated by a horizontal line)

'discriminatory power' hereafter). The arrows in the cells help understand the direction of change in signature values. For example, the up-pointing arrow for amplitude signature in Wüstebach (WB) means the event amplitudes were larger in the deforested area than the forested area.

Overall, event-based signatures showed high discriminatory power between contrasting land-uses for all sites. Season- and timeseries-based signatures showed moderate discriminatory power in deforested, urban, shallow groundwater, and croplands. Signature differences between land-uses were observed both in terms of their magnitude and profile. The following subsections describe the detailed results by signature timescale (event-, season-, and timeseries-based signatures).

4.2.1 | Event-based signatures

Event-based signatures showed differences between land-uses both in magnitude and in signature profile with soil depth. Differences in signature values were found across most land uses, with notable differences between deforested versus forested and urban versus greenspace contrasts. Figure 5 shows that event-based signatures varied in magnitude with land-use for all study sites; in Figure 5, cells are highlighted in darker blue for statistically significant signatures. Statistically significant differences were found for amplitude and rising time signatures at all sites, and for rising limb density and 'no-response rate' signatures at Wüstebach. These changes in signature magnitudes indicate a more responsive regime especially in the deforested area than the forested area at Wüstebach, and the shallow groundwater area than the deep groundwater area at Raam.

Figure 6 shows examples of how event-based signature profiles with soil depth changed between land-uses in Wüstebach (deforested vs. forested) and Hamburg (urban vs. greenspace). In Wüstebach, rising limb density increases with depth in the forested area, whereas the values were similar with soil depths in the deforested area (Figure 6a). In Hamburg, the event-based signatures were more pronounced at the shallow depth (sensors at 5 and 20 cm depths) in the urban area than in the greenspace (Figure 6b–d).

We interpret the changes in event-based signatures to represent the influences of wetness conditions on the storage processes and the influences of soil properties on the flow partitioning process (see Section 4.3.1).



FIGURE 4 Signature values for all the study sites, in the order of aridity (large to small from left to right based on the aridity values listed in Table 1). Signature values were aggregated for sensor depths and land-uses. The boxplots are drawn using Matlab package gramm (Morel, 2018). The box is drawn between the first and third quartile, with a line in between indicating the median. The whiskers extended within a distance to the box equal to 1.5 times the interquartile range. Dots indicate the outliers

4.2.2 | Season-based signatures

Season-based signatures showed differences in magnitude and in profile with soil depth for some types of land-uses, namely, deforested versus forested, urban versus greenspace, and cropland versus grazed versus grassland contrasts.

Figure 5 shows that season-based signature values varied in magnitude with land-use in Wüstebach (deforested vs. forested), Hamburg (urban vs. greenspace), and Oznet (crop vs. grazed vs. grassland); in Figure 5, cells are highlighted in darker blue for statistically significant signatures. In Wüstebach, the wet season persisted longer in the deforested area than in the forested area; the dry-to-wet transition started earlier and took a shorter time, and the wet-to-dry transition duration took a longer time. In Hamburg, wetting up was more gradual, and drying out was more rapid in the urban area than in the greenspace.

Figure 7 shows that season-based signature profiles with soil depth changed between land-uses in Wüstebach (deforested vs. forested) and Oznet (crop vs. grazed vs. grassland). In most sites, the seasonal transition propagated from shallow to deep soil layer, or occurred in tandem at all depths. On the contrary, the transition started earliest in the deeper layer in the deforested area in



FIGURE 5 Signature differences in magnitude between contrasting land-uses for a given depth. In each study site, signatures from a disturbed land-use were compared with those from an undisturbed land-use (e.g., deforested as disturbed vs. forested as undisturbed). The upward, downward, and horizontal arrows indicate if the signature values in the disturbed land-use were larger, smaller, or unchanged, respectively, compared to undisturbed land-use. The cells are highlighted with colours associated with the *p*-value of the Kruskal-Wallis test, or percent change in signature dominance. The cells are white when the sample size was not enough for the Kruskal-Wallis test (less than five). Most signatures for the Maqu sites did not reach enough sample size for the Kruska-Wallis test; thus, they were excluded from the table

FIGURE 6 Box plots of event-based signatures for the sites showing significant differences in signatures. Refer to Figure S2 for full results. The box is drawn between the first and third quartile, with a line in between indicating the median. The whiskers extend to the most extreme data value within a distance to the box equal to 1.5 times the interquartile range. Dots indicate the outliers



Wüstebach (Figure 7a) and cropland in Oznet (Figure 7b,c). We interpret the changes in season-based signatures to represent the influences of water balance and soil wetness conditions on storage processes (see Section 4.3.2).

4.2.3 | Timeseries-based signatures

Timeseries-based signatures showed differences in magnitude and in profile with soil depth for most types of land-uses, namely, deforested

(a) Wüstebach Duration of wet to dry transition



(b) Oznet Start of dry to wet transition



Grass Grazed Crop Land cover/use

Start of wet to dry transition

depth(cm)

3

4

15

45

75

(c) Oznet

008 ear

ਦੂ 200

(b) Oznet

(a) Maqu Estimated field capacity



FIGURE 7 Box plots of season-based signatures for the sites showing significant differences in signatures. Refer to Figure S3 for full results. The box is drawn between the first and third quartile, with a line in between indicating the median. The whiskers extend to the most extreme data value within a distance to the box equal to 1.5 times the interquartile range. Dots indicate the outliers

FIGURE 8 Box plots of timeseries-based signatures for the sites showing significant differences in signatures. Refer to Figure S4 for full results. The box is drawn between the first and third quartile, with a line in between indicating the median. The whiskers extend to the most extreme data value within a distance to the box equal to 1.5 times the interquartile range. Dots indicate the outliers

versus forested, wetland versus non-wetland, shallow versus deep groundwater, and cropped versus grazed versus grassland contrasts.

Figure 5 shows that timeseries-based signature values varied in magnitude with land-use; changes in estimated field capacity and wilting point were statistically significant in Wüstebach (deforested vs. forested), and changes in the dominance of unimodal distribution type were more than 15% in most of the study sites except Texas (grazed vs. ungrazed). Not statistically significant due to small sample sizes, but visual differences in the signature magnitude were seen in Maqu (wetland vs. non-wetland) for estimated field capacity (Figure 8a) and Oznet (crop vs. grazed vs. grassland) for estimated wilting point (Figure 8b). These changes in signature magnitude imply

wetter conditions in the deforested area in Wüstebach, wetlands in Maqu, and grasslands in Oznet.

Figure 8 shows the timeseries-based signature profiles with soil depth changed between land-uses in Hamburg (urban vs. greenspace) and Raam (shallow vs. deep groundwater). In Hamburg, variability of estimated field capacity and wilting point decreased with depth in the greenspace, whereas they increased in the urban area (Figure 8c). In the shallow groundwater area of Raam, the bimodal distribution is dominant at the deepest and shallowest soil, contrasting to mixed modality along all depths in the deep groundwater area (Figure 8d). We interpret that the changes in timeseries-based signatures represent the influences of

soil properties, vegetation, and groundwater on the storage processes (see Section 4.3.3).

4.3 | Interpretation of signature differences between land-uses

This section provides interpretations of the signature difference among contrasting land-uses derived in Section 4.2. Figure 9 shows whether the observed signature differences between land-uses agreed with literature interpretations. Overall, event-based and timeseries-based signatures mostly agreed (cells are highlighted blue in Figure 9), whereas season-based signatures poorly agreed with literature (highlighted red in Figure 9). The following sections describe the detailed results by signature timescale (event-, season-, and timeseries-based signatures).

4.3.1 | Event-based signatures represent partitioning processes

In general, event-based signatures matched with expert knowledge in literature (highlighted blue in Figure 9). Event-based signature differences in magnitude represented changes in storage flashness, and those in the signature profile represent changes in flow partitioning processes depending on the land-uses.

We interpreted the event-based signature magnitudes between land-uses to represent the storage flashiness depending on the soil wetness conditions. Larger response amplitude, shorter rising time, larger rising limb density, and lower 'no-response rate' imply flashier storage response in high soil wetness conditions. Our signatures showed greater storage flashiness in deforested areas (Wüstebach) and cropped areas (Oznet). These land disturbances are known to increase soil wetness (and therefore flashiness) through reduced transpiration and interception (Wiekenkamp, Huisman, Bogena, Graf, et al., 2016) and irrigation (Smith et al., 2012), respectively. Response amplitude gets smaller when the soil wetness is close to saturation (Soylu & Bras, 2021). We observed this change in Raam (shallow vs. deep groundwater) and Maqu (wetland vs. non-wetland).

We interpreted that the changes in the event-based signature profiles imply changes in flow partitioning processes. According to Graham and Lin (2011), sequential responses ordering from shallow to deep soil layer represent vertical infiltration and overland flow regime, and non-sequential response patterns (random response order along soil depth) represent preferential or lateral flow regime. Additionally, more pronounced responses in shallow soils within sequentialresponse patterns represent the overland flow regime (Ziegler et al., 2001). Our signature values agreed with this interpretation; we saw sequential and more pronounced responses in shallow soil in urban areas in Hamburg and cropped areas in Oznet, where surface sealing (Scalenghe & Ajmone-Marsan, 2009) and compaction (Alaoui et al., 2018) are expected to increase overland flow, respectively. A decrease in non-sequential response was found in Wüstebach, where preferential flow is known to decrease after deforestation (Wiekenkamp et al., 2019). On the other hand, event-based signatures did not show significant changes in grazed versus ungrazed areas in Texas (Alaoui et al., 2018), contrary to the expectation that compaction increases overland flow at this site. This might be due to scale, as plot-scale compaction does not always influence catchment-scale response (Alaoui et al., 2018; Rogger et al., 2017).

4.3.2 | Season-based signatures represent storage processes

Season-based signatures only partially matched with expert knowledge in literature (highlighted blue for a match, red for no match in Figure 9). We interpret that a combination of the following factors related to storage processes affects season-based signatures' magnitude and profile: changes in water balance depending on the active root depth and rainfall rate (Laio, 2002), the closeness of soil wetness conditions to soil moisture threshold (Detty & McGuire, 2010), and other land-use influences such as groundwater (Miguez-Macho & Fan, 2012), construction waste (Wiesner et al., 2016), and irrigation (Smith et al., 2012). For example, reduced rainfall rate and root depth explained earlier transition start date, and higher wetness conditions explained shorter transition duration in the shallow soil laver in deforested versus forested contrast in Wüstebach; still, literature did not fully explain the changes of the signature profile along soil depth. The mismatch was more obvious in land-uses that complicate the boundary conditions of soil water storage, such as construction waste presence in the soil in Hamburg or strong groundwater influence in Raam (highlighted red in Figure 9). The mismatch can also be attributed to a lack of studies on season-based signatures. Many studies on soil moisture seasonality mainly concentrate on detecting anomalies for drought analysis or general trends for land-surface process understandings (Koster & Suarez, 2001; Kumar et al., 2019; Potter et al., 2005; Teuling et al., 2005). In contrast, few studies exist on the influence of land-use on soil moisture seasonal transition timings and durations.

4.3.3 | Timeseries-based signatures represent storage characteristics

In general, the timeseries-based signature matched with expert knowledge in literature (highlighted blue in Figure 9). Changes in timeseries signatures represented the interaction between soil water storage and soil properties, vegetation, and groundwater depending on the land-uses.

We interpreted the timeseries-based signature magnitudes to represent the amount of soil water storage. Larger estimated field capacity, wilting point, and dominance of unimodality imply more soil water stored. Signature values matched literature expectations in Wüstebach (deforested vs. forested), Maqu (wetland vs. non-wetland), and Oznet (crop vs. grazed vs. grassland), where deforested, wetland,

		Signatures											
			E	vent-based				Seaso	n-based		Ti	meseries-	based
		Response type (% of	Amplitude	Rising	Rising limb	No- response	Dry-to-we	t transition	Wet-to-dr	y transition	Field	Wilting	Distribution type (% of
	Expected	sequential) chine density rate			Earlier trar rate↑ &	nsition due t	to <u>intercepti</u> (<u>Wiekenk</u>	$\underline{on} \downarrow \& rain$ amp et al.,	<u>Storage</u> ↑	due to tr	unimodal) anspiration↓		
Wüstebach Deforested vs. Forested	process	storag	<u>se个 (Wieker</u>	<u>nkamp et al.</u>	., 2016a & 20	019)	2016b; threshold o	Laio, 2002)_ due to <u>stora</u> 20	; closer to tr <u>ge个 (</u> Detty)10)	ansition & McGuire,	<u>& interce</u>	eption \downarrow () et al., 20:	<u>Wiekenkamp</u> 16a)
	Expected signature	Ţ	\uparrow	\downarrow	\uparrow	\downarrow	\downarrow	\downarrow	\downarrow	\downarrow	Ţ	Ţ	Ţ
	Observed signature	^	\uparrow	\downarrow	shallow↑ deep↓	\downarrow	4	¥	<i>→</i>	shallow ↑ deep ↓	↑	Ŷ	Ŷ
Hamburg Housing vs. Urban	Expected process	Vertical infil (Scalenghe st	tration -> ov & Ajmone-N orage flashii	rerland flow 1arsan, 2009 ness↓ due 1	due to surfa 9; Ziegler et to storage↓	ace sealing al., 2001);	Delayed t rain rate <u>rapid dra</u> (Wiesner e threshold e	transition du \downarrow (Laio, 200 <u>ainage due t</u> <u>et al., 2016)</u> due to stora <u>20</u>	ue to surface D2); <u>stagnan</u> <u>co construct</u> ; less close t ge↓ (Detty D10)	e sealing & <u>it water &</u> i <u>on waste</u> o transition & McGuire,	Storage∖ infiltra Ajmone-I	↓ & <u>GW ta</u> ation ↓ (So Marsan, 2 <u>et al., 20</u>	<u>ble↓</u> due to alenghe & 009; <u>Wiesner</u> <u>16)</u>
	Expected signature	^	shallow↑ deep↓	shallow↓ deep↑	shallow↑ deep↓	shallow↓ deep↑	Ŷ	Ŷ	Ţ	<u>↓</u> or ↑	variabil deep so	ity↑ in pil layer	deep ↓
	Observed signature	↑	shallow↑ deep↑	shallow↓ deep↑	shallow↑ deep↓	shallow↓ deep↑	↓	\rightarrow	\rightarrow	\downarrow	↓ variabil deep so	↓ ity↑ in pil layer	shallow↑ deep↓
Raam Shallow vs.	Expected process	Vertical infiltration -> lateral flow; less variable soil moisture due to near-saturated soil (Soylu & Bras, 2021)				Earlier tran Macho & F threshold o	nsition due t Fan, 2012); r due to stora 20	to shallow G more close t ge个 (Detty 010)	W (Miguez- o transition & McGuire,	<u>Storage</u> (Benning	<u>↑</u> due to <u>a et al., 20</u> Bras, 20	capillary rise) <u>18b</u> ; Soylu & 20)	
Deep groundwater	Expected signature	\downarrow	\downarrow	\downarrow	\rightarrow	\rightarrow	\downarrow	\downarrow	\downarrow	\downarrow	Ţ	Ţ	\uparrow
(GW)	Observed signature	\downarrow	\downarrow	^	\rightarrow	\rightarrow	\rightarrow	\rightarrow	\checkmark	\rightarrow	\rightarrow	\rightarrow	shallow↓ deep↑
Texas Grazed	Expected process	(Woodruff	Wilding, 2	008; Alaoui al., 2001)	w due to cor et al., 2018;	npaction Ziegler et	Less clo stora	se to transit ge↓ (Detty	ion thresho & McGuire,	ld due to 2010)	Storage (Borma Selase	↓ due to Inn & Klaa sie & Ayar	compaction ssen, 2008; ma, 2013)
VS.	Expected signature	1	shallow↑ deep↓	shallow↓ deep↑	shallow↑ deep↓	shallow↓ deep↑	\rightarrow	^	\rightarrow	^	\downarrow	\downarrow	\downarrow
Ungrazed	Observed signature	1	shallow↑ deep↓	↑	\rightarrow	\rightarrow	\rightarrow	\downarrow	\rightarrow	\rightarrow	\rightarrow	\rightarrow	\rightarrow
Maqu Wetland vs. Non-wetland	Expected processes	Less variable soil moisture due to near-saturated soil (Soylu & Bras, 2021); less responses while frozen				Seasonal transition timing of vegetation growth do not change (Dente et al., 2012); Storage↑ due to soil organistic Freeze/thaw process takes longer and delayed due to heat capacity↑ Matter (Dente et al., 2014)				<u>soil organic</u> <u>t al., 2012;</u> ., 2014)			
	Expected signature	\downarrow	\downarrow	\downarrow	\downarrow	1	<u>→</u> or ↑	<u>→</u> or ↑	\rightarrow or \uparrow	<u>→</u> or ↑		Ϋ́	\uparrow
	Observed signature	Not enough data	\rightarrow	\rightarrow	\downarrow	\uparrow	<i>→</i>	\rightarrow	\rightarrow	\rightarrow	<u>↑</u>	↑	1
Oznet Crop vs. Grazed vs.	Expected process	Vertical infiltration -> overland-flow due to compaction (Alaoui et al., 2018; Ziegler et al., 2001); storage flashiness ↑ due to storage↑					More close to transition threshold due to Storage↓ due to com More close to transition threshold due to (Bormann & Klaassen storage↑(Detty & McGuire, 2010); extended Selassie & Ayanna, 2 wet period due to irrigation (Smith et al., Storage↑ due to irrig 2012) (Smith et al., 2012; Law al., 2017) al., 2017)			compaction ssen, 2008; na, 2013); o <u>irrigation</u> l; Lawston et 7)			
Grass	Expected signature	1	shallow↑ deep↓	shallow↓ deep↑	shallow↑ deep↓	shallow↓ deep↑	\downarrow	\downarrow	\uparrow	\downarrow	\downarrow or \uparrow	\downarrow or \uparrow	↓ or ↑
	Observed signature	\downarrow	shallow↓ deep↑	\uparrow	\downarrow	\uparrow	\downarrow	\uparrow	mixed ↑ & ↓	shallow ↑ deep ↓	\uparrow	1	shallow↓ deep↑

Observed signature matches with literature interpretation

Observed signature does not match with literature interpretation



and cropped conditions are respectively known to increase soil wetness through changes in transpiration (Wiekenkamp, Huisman, Bogena, Graf, et al., 2016), soil organic content (Dente et al., 2012; Hudson, 1994), and irrigation (Smith et al., 2012). We interpreted that the changes in the timeseries-based signature profile with soil depth imply the external influence on soil water storage. Generally, the estimated field capacity and wilting point either consistently decrease or increase with soil depth, and the



FIGURE 10 An example flow chart that classifies soil moisture dynamics using event-based soil moisture signatures

dominance of unimodal distribution increases with soil depth, because of less influence of climate and compaction of pore spaces in the deeper soil (Trimble, 2007). Different behaviour seen in the shallow groundwater area at Raam can be explained as follows; at the groundwater interface, the saturation is controlled by whether the groundwater meets the soil sensors or not, and bimodal distribution becomes dominant again. High variability of estimated field capacity and wilting point in deeper soil in urban areas in Hamburg can be explained by the urban structures or construction waste that creates different sizes of pores (Wiesner et al., 2016).

5 | DISCUSSION

5.1 | Limitations

We recognize several limitations in our study. First, future work should test differences in signature values attributed to land-use against confounding factors. For example, we explicitly examined groundwater influence for Raam, but groundwater could also influence soil moisture dynamics in Wüstebach, Hamburg, and Maqu. Such confounding factors include topography, slope aspects, position in slope, snow influence, distances between sensors, and sensor types. However, investigation on confounding factors requires detailed datasets on elevation, groundwater depth, snow depth, or temperature at each sensor location, which are not consistently available for all the study sites. We treated the contrasting land-use as the major controls on soil moisture processes and took variability of other factors within a catchment as residual uncertainty in this study (Beven, 2000). Our selection of sites, where sensors are within watershed-scale, helps reduce the impact of the confounding factors. For confounding factors regarding soil moisture network design (e.g., size of the network and distance between sensors), it would be beneficial to implement geospatial analysis. Previous studies suggest that investigating the influence of spatial scale on soil moisture values advances our understanding of the soil moisture processes (Brocca et al., 2007; Gómez-Plaza et al., 2001; Western et al., 2004).

Second, the signature approach needs attention when adapted to different hydrologic environments. We encountered several difficulties in extracting and interpreting signatures under different climate and soil conditions (e.g., defining seasonal transition for sites with an unstable wet season, multiple process interpretations for bimodal distribution signatures, and the impact of data quality practice on signature calculation). We summarized our experiences and recommendations in Text S2. Also, our datasets did not cover some

16 of 21 WILEY-

combinations of land-use and climates. For example, grazed land-use was tested only in Texas and Oznet under an arid climate, not in humid and temperate climates. Therefore, the users should be careful using signatures on other climates, soil types, or soil developments. Future work should fill the gaps using larger datasets, such as the International Soil Moisture Network dataset (Dorigo et al., 2011) or SMAP satellite observation (Entekhabi et al., 2014).

5.2 | Novelty, usefulness, and future direction of soil moisture signature approach

There are two novelties of this study. First, this study showed clear differences in soil moisture signatures depending on land-uses. Previous studies compared signatures under limited land-uses (e.g., forest vs. non-forest in Branger & McMillan, 2020; forests with various tree species in Chandler et al., 2017). Previous studies also compared signatures from the large-scale observation networks, where climate and geology are the strong confounding factors. This study covered a wide range of land-uses and conducted internal comparisons within small to mesoscale observation networks. The research design allowed analyses with a strong focus on land-use impacts on signature values, and interpretation of the signature values based on catchment-scale processes. Second, this study differentiated soil moisture processes between land-uses only using soil moisture and rainfall datasets. Usually, watershed processes are understood using a variety of hydrological and soil observations. However, rich process knowledge from previous studies allowed us to interpret processes from signature values calculated only from soil moisture and rainfall data. Using standardized metrics, the process interpretation across study sites also helped integrate individual knowledge of existing soil moisture studies.

Our results suggest potential uses of soil moisture signatures in hydrologic analysis to represent the different dynamics with landuses. In the future, hydrologists could use soil moisture signatures to calibrate, constrain, or evaluate models against observation data, as practiced in streamflow signatures (Shafii & Tolson, 2015; Westerberg et al., 2011). Models could be evaluated whether the model represented significant differences or similarities in soil moisture signature values expected between different land-uses. Signatures could also be used to compare satellite data against in-situ data in terms of soil moisture dynamics. Our results imply that significant differences in signature values between land-uses appear even at 5 cm soil depth, which is a typical penetration depth of remote sensing observation. Furthermore, signatures could be used for process investigation or model structure identification between contrasting land-uses especially for the event- and the timeseries-based signatures, whose process implications were successfully derived in this study. Signatures would be especially useful to represent different dynamics for the land-use contrasts that showed significant signature differences (deforested vs. forested, urban vs. greenspace, crop vs. grazed vs. grassland).

ARAKI ET AL.

Ultimately, we would like to develop a systematic classification of catchment processes between land-uses based on signatures (Wagener et al., 2007). As an example, we designed a flow chart to show how partitioning processes might be classified using eventbased signatures (Figure 10). First, the flow pathways could be categorized into sequential and non-sequential types based on response type signatures, and then further refined based on other event-based signatures. Several signatures are lacking (in grey letters in Figure 10), but this flow chart demonstrates the potential of a signature-based process classification system. For example, the flow chart represents the signature difference in urban versus greenspace area between vertical versus overland flow processes, which we observed in Hamburg. Previous studies have suggested promising classification frameworks for soil moisture processes. For example, Boorman et al. (1995) propose 11 basic modes for partitioning processes depending on the soil profile and groundwater position, and Grayson et al. (1997) propose four basic modes for storage seasonality depending on the soil wetness conditions. We could potentially classify catchment processes using soil moisture signatures at all temporal scales based on these studies.

6 | CONCLUSIONS

Soil moisture signatures are metrics that represent soil moisture dynamics. This study aimed to test soil moisture signatures' ability to discriminate different dynamics under contrasting land-uses (called 'discriminatory power'). We integrated nine soil moisture signatures from previous studies (Branger & McMillan, 2020; Chandler et al., 2017; Graham & Lin, 2012; Sawicz et al., 2011). The set of signatures quantified the dynamics at three temporal scales: event, season, and complete timeseries. We applied the signatures to six soil moisture network data with diverse land-uses, including deforested, shallow groundwater, wetlands, urban, grazed, and cropland areas. Using statistical, visual, and literature analysis, we tested the discriminatory power of soil moisture signatures.

Event-based signatures had the highest discriminatory power; they showed clear statistical and visual differences across all land-uses. Literature supported the link between partitioning and storage processes, and event-based signatures. Season-based signatures had moderate discriminatory power; they showed statistical and visual differences in a range of land-uses (e.g., deforested vs. forested, urban vs. greenspace, crop vs. grazed vs. grassland). However, literature could not fully explain the differences in season-based signatures depending on the land-uses due to the lack of observational studies using the season-based signature approach. Timeseries-based signatures had moderate discriminatory power in all land-uses except in grazed versus ungrazed. The differences of timeseries-based signatures between land-uses were linked to differences in storage characteristics.

Our results demonstrated that soil moisture signatures, calculated only from soil moisture and rainfall timeseries, can capture the landuse impacts on catchment-scale soil moisture dynamics. We also explored and documented the limitation in extracting signatures from datasets covering a wide range of climate conditions. This study will be a useful guideline for hydrologists to apply soil moisture signatures for evaluating land-use impacts on hydrologic processes and developing a standardized classification system of soil moisture processes.

ACKNOWLEDGEMENTS

We thank Dr. Heye Bogena, Dr. Sarah Wiesner and Dr. Ingo Lange, Dr. Harm Jan Frederik Benninga, Dr. Bongiovanni Tara, Dr. Bob Su, Dr. Laura Dente, Dr. Jeffrey Walker, and Dr. Mei Sun Yee for providing data and site information. We thank Dr. Trent Biggs, Dr. Alicia Kinoshita, Dr. Takahiro Sayama, and Dr. Sebastian Gnann for helpful discussions. Last but not least, we are grateful to the editor and two anonymous reviewers for their thoughtful comments on this manuscript.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available in online repository or on request from the corresponding author. The datasets used in this study are available from the following. Please visit the observatory's website or inquire the site manager for the availability of data.

Study sites	Soil moisture data source	Rainfall data source
Wüstebach (WB)	Requested to Dr. Heye Bogena (h.bogena@fz- juelich.de) Note that data through 2009 to 2015 are available online (Bogena, 2021)	Online. Used Monschau- Kalterherberg station data (The Deutscher Wetterdienst, DWD, 2021)
Hamburg (HB)	Requested to Dr. Sarah Wiesner (sarah. wiesner@uni-hamburg. de) Network description is available online (University of Hamburg, 2021)	Online. Used Hamburg- Fuhlsbüttel station data (The Deutscher Wetterdienst, DWD, 2021)
Raam (RM)	Online. 2016–2017 data (Benninga et al., 2017) 2017–2018 data (Benninga, Carranza, Michiel-Pezij, et al., 2018) 2018–2019 data (Benninga et al., 2020)	Online. Used Volkel weather station data (The Royal Netherlands Meteorological Institute, KNMI, 2021)
Texas (TX)	Online (Bongiovanni & Caldwell, 2019)	Online (Bongiovanni & Caldwell, 2019)
Maqu (MQ)	Requested to Dr. Bob Su (z.su@utwente.nl) 5 cm sensor data is available online (Dorigo et al., 2011)	Requested to Dr. Bob Su (z.su@utwente.nl)
Oznet (OZ)	Online (Smith et al., 2012)	Online (Smith et al., 2012)

ORCID

Ryoko Araki b https://orcid.org/0000-0002-3647-9768 Flora Branger b https://orcid.org/0000-0003-4273-8938 Inge Wiekenkamp b https://orcid.org/0000-0003-4800-1160 Hilary McMillan b https://orcid.org/0000-0002-9330-9730

REFERENCES

- Alaoui, A., Rogger, M., Peth, S., & Blöschl, G. (2018). Does soil compaction increase floods? A review. *Journal of Hydrology*, 557, 631-642. https://doi.org/10.1016/j.jhydrol.2017.12.052
- Anderson, J. R., Hardy, E. E., Roach, J. T., & Witmer, R. E. (1976). A Land Use and Land Cover Classification System for Use with Remote Sensor Data. U.S. Geological Survey Professional Paper 964 (p. 28).
- Babaeian, E., Sadeghi, M., Jones, S. B., Montzka, C., Vereecken, H., & Tuller, M. (2019). Ground, proximal, and satellite remote sensing of soil moisture. *Reviews of Geophysics*, 57(2), 530–616. https://doi.org/10. 1029/2018RG000618
- Basak, A., Mengshoel, O. J., Kulkarni, C., Schmidt, K., Shastry, P., & Rapeta, R. (2017). Optimizing the decomposition of time series using evolutionary algorithms: Soil moisture analytics. In *Proceedings of the Genetic and Evolutionary Computation Conference* (pp. 1073–1080). Association for Computing Machinery. https://doi.org/10.1145/ 3071178.3071191
- Bean, E. Z., Huffaker, R. G., & Migliaccio, K. W. (2018). Estimating field capacity from volumetric soil water content time series using automated processing algorithms. *Vadose Zone Journal*, 17(1), 180073– 180073. https://doi.org/10.2136/vzj2018.04.0073
- Benninga, H. F., Carranza, C. D., Michiel-Pezij, M. J., van der Ploeg, D. C. M., & Augustijn, R., & van der Velde, R. (2017). Regional soil moisture monitoring network in the Raam catchment in the Netherlands– 2016-04/2017-04 [version 1]. University of Twente. https://doi.org/10. 4121/UUID:DC364E97-D44A-403F-82A7-121902DEEB56
- Benninga, H. F., Carranza, C. D., Michiel-Pezij, M. J., van der Ploeg, D. C. M., Augustijn, R., & van der Velde, R. (2018). Regional soil moisture monitoring network in the Raam catchment in the Netherlands– 2017-04/2018-04. University of Twente. https://doi.org/10.4121/ UUID:AFB36AC8-E266-4968-8F76-0D1F6988E23D
- Benninga, H. F., Carranza, C. D., Michiel-Pezij, M. J., van der Ploeg, D. C. M., Augustijn, R., & van der Velde, R. (2020). Regional soil moisture monitoring network in the Raam catchment in the Netherlands– 2018-04/2019-04. University of Twente. https://doi.org/10.4121/ UUID:B68E3971-C73E-4D7F-B52F-9EF7D7FE1ED2
- Benninga, H. J. F., Carranza, C. D. U., Pezij, M., Van Santen, P., Van Der Ploeg, M. J., Augustijn, D. C. M., & Van Der Velde, R. (2018). The Raam regional soil moisture monitoring network in The Netherlands. *Earth System Science Data*, 10(1), 61–79. https://doi.org/10.5194/essd-10-61-2018
- Beven, K. J. (2000). Uniqueness of place and process representations in hydrological modelling. Hydrology and Earth System Sciences, 4(2), 203–213. https://doi.org/10.5194/hess-4-203-2000
- Black, P. E. (1997). Watershed functions. Journal of the American Water Resources Association, 33(1), 1–11. https://doi.org/10.1111/j.1752-1688.1997.tb04077.x
- Blöschl, G., & Sivapalan, M. (1995). Scale issues in hydrological modelling: A review. Hydrological Processes, 9(3–4), 251–290. https://doi.org/10. 1002/hyp.3360090305
- Blume, T., Krause, S., Meinikmann, K., Lewandowski, J., Zehe, E., & Bronstert, A. (2009). Use of soil moisture dynamics and patterns at different spatio-temporal scales for the investigation of subsurface flow processes. *Hydrology and Earth System Sciences*, 13(7), 1215–1233. https://doi.org/10.5194/hess-13-1215-2009
- Bogena, H. (2021). TERENO (Eifel-Rur). SoilNet Wuestebach. https://ddp. tereno.net/ddp/dispatch?searchparams=freetext-soilnet&metadata.

18 of 21 WILEY-

 $\label{eq:constraint} detail.view.id=d4b917ca-4e8b-3b0f-8f24-5475f7390d99\&metadata.\\ detail.view.origin=EIFEL.RUR\&metadata.detail.view.type=org.fzj.ibg.\\ catalog.shared.ISO19115Bean$

- Bogena, H. R., Bol, R., Borchard, N., Brüggemann, N., Diekkrüger, B., Drüe, C., Groh, J., Gottselig, N., Huisman, J. A., Lücke, A., Missong, A., Neuwirth, B., Pütz, T., Schmidt, M., Stockinger, M., Tappe, W., Weihermüller, L., Wiekenkamp, I., & Vereecken, H. (2015). A terrestrial observatory approach to the integrated investigation of the effects of deforestation on water, energy, and matter fluxes. *Science China Earth Sciences*, 58(1), 61–75. https://doi.org/10.1007/s11430-014-4911-7
- Bongiovanni, T., & Caldwell, T. G. (2019). Texas soil observation network (TxSON). Texas Data Repository. https://doi.org/10.18738/T8/JJ16CF
- Boorman, D. B., Hollis, J. M., & Lilly, A. (1995). Hydrology of soil types: A hydrologically-based classification of the soils of United Kingdom. Institute of Hydrology. http://nora.nerc.ac.uk/id/eprint/7369/1/IH_ 126.pdf
- Bormann, H., & Klaassen, K. (2008). Seasonal and land use dependent variability of soil hydraulic and soil hydrological properties of two Northern German soils. *Geoderma*, 145(3), 295–302. https://doi.org/10. 1016/j.geoderma.2008.03.017
- Bouaziz, L. J. E., Fenicia, F., Thirel, G., de Boer-Euser, T., Buitink, J., Brauer, C. C., De Niel, J., Dewals, B. J., Drogue, G., Grelier, B., Melsen, L. A., Moustakas, S., Nossent, J., Pereira, F., Sprokkereef, E., Stam, J., Weerts, A. H., Willems, P., Savenije, H. H. G., & Hrachowitz, M. (2021). Behind the scenes of streamflow model performance. *Hydrology and Earth System Sciences*, 25(2), 1069–1095. https://doi.org/10.5194/hess-25-1069-2021
- Branger, F., & McMillan, H. K. (2020). Deriving hydrological signatures from soil moisture data. *Hydrological Processes*, 34(6), 1410–1427. https://doi.org/10.1002/hyp.13645
- Brocca, L., Morbidelli, R., Melone, F., & Moramarco, T. (2007). Soil moisture spatial variability in experimental areas of Central Italy. *Journal of Hydrology*, 333(2), 356–373. https://doi.org/10.1016/j.jhydrol.2006. 09.004
- Bureau of Economic Geology. (2020). *Texas soil observation network* (*TxSON*). The University of Texas at Austin. https://www.beg.utexas. edu/research/programs/txson
- Caldwell, T. G., Bongiovanni, T., Cosh, M. H., Jackson, T. J., Colliander, A., Abolt, C. J., Casteel, R., Larson, T., Scanlon, B. R., & Young, M. H. (2019). The Texas soil observation network: A comprehensive soil moisture dataset for remote sensing and land surface model validation. *Vadose Zone Journal*, *18*(1), 1–20. https://doi.org/10.2136/vzj2019. 04.0034
- Chandler, D. G., Seyfried, M. S., McNamara, J. P., & Hwang, K. (2017). Inference of soil hydrologic parameters from electronic soil moisture records. Frontiers of Earth Science in China, 5(April), 1–17. https://doi. org/10.3389/feart.2017.00025
- De Lannoy, G. J. M., Verhoest, N. E. C., Houser, P. R., Gish, T. J., & Van Meirvenne, M. (2006). Spatial and temporal characteristics of soil moisture in an intensively monitored agricultural field (OPE3). *Journal* of Hydrology, 331(3–4), 719–730. https://doi.org/10.1016/j.jhydrol. 2006.06.016
- Deng, L., Yan, W., Zhang, Y., & Shangguan, Z. (2016). Severe depletion of soil moisture following land-use changes for ecological restoration: Evidence from northern China. Forest Ecology and Management, 366, 1–10. https://doi.org/10.1016/j.foreco.2016.01.026
- Dente, L., Vekerdy, Z., Wen, J., & Su, Z. (2012). Maqu network for validation of satellite-derived soil moisture products. *International Journal of Applied Earth Observation and Geoinformation*, 17(1), 55–65. https:// doi.org/10.1016/j.jag.2011.11.004
- Detty, J. M., & McGuire, K. J. (2010). Threshold changes in storm runoff generation at a till-mantled headwater catchment. *Water Resources Research*, 46(7). https://doi.org/10.1029/2009wr008102
- D'Odorico, P., Ridolfi, L., Porporato, A., & Rodriguez-Iturbe, I. (2000). Preferential states of seasonal soil moisture: The impact of climate

fluctuations. Water Resources Research, 36(8), 2209–2219. https://doi. org/10.1029/2000WR900103

- Dorigo, W. A., Wagner, W., Hohensinn, R., Hahn, S., Paulik, C., Xaver, A., Gruber, A., Drusch, M., Mecklenburg, S., van Oevelen, P., Robock, A., & Jackson, T. (2011). The international soil moisture network: A data hosting facility for global in situ soil moisture measurements. *Hydrology and Earth System Sciences*, 15(5), 1675–1698. https://doi.org/10.5194/hess-15-1675-2011
- Dorigo, W. A., Xaver, A., Vreugdenhil, M., Gruber, A., Hegyiová, A., Sanchis-Dufau, A. D., Zamojski, D., Cordes, C., Wagner, W., & Drusch, M. (2013). Global automated quality control of in situ soil moisture data from the international soil moisture network. *Vadose Zone Journal*, 12(3), 1–21. https://doi.org/10.2136/vzj2012.0097
- Draper, C., & Reichle, R. (2015). The impact of near-surface soil moisture assimilation at subseasonal, seasonal, and inter-annual timescales. *Hydrology and Earth System Sciences*, 19(12), 4831–4844. https://doi. org/10.5194/hess-19-4831-2015
- Eltahir, E. A. B. (1998). A soil moisture-rainfall feedback mechanism: 1. Theory and observations. *Water Resources Research*, 34(4), 765–776. https://doi.org/10.1029/97WR03499
- Entekhabi, D., Das, N., Njoku, E., Yueh, S., Johnson, J., & Shi, J. (2014). Soil moisture active passive (SMAP) algorithm theoretical basis document level 2 & 3 soil moisture (passive) data products. Revision A. https://nsidc. org/sites/nsidc.org/files/technical-references/L2_SM_P_ATBD_ revision C Dec2016 v2.pdf
- Friedl, M. A., Sulla-Menashe, D., Tan, B., Schneider, A., Ramankutty, N., Sibley, A., & Huang, X. (2010). MODIS collection 5 global land cover: Algorithm refinements and characterization of new datasets. *Remote Sensing of Environment*, 114(1), 168–182. https://doi.org/10.1016/j. rse.2009.08.016
- Fu, B., Wang, J., Chen, L., & Qiu, Y. (2003). The effects of land-use on soil moisture variation in the Danangou catchment of the loess plateau, China. *Catena*, 54(1), 197–213. https://doi.org/10.1016/S0341-8162 (03)00065-1
- Gao, X., Wu, P., Zhao, X., Wang, J., & Shi, Y. (2014). Effects of land-use on soil moisture variations in a semi-arid catchment: Implications for land and agricultural water management. *Land Degradation & Development*, 25(2), 163–172. https://doi.org/10.1002/ldr.1156
- Ghannam, K., Nakai, T., Paschalis, A., Oishi, C. A., Kotani, A., Igarashi, Y., Kumagai, T., & Katul, G. G. (2016). Persistence and memory timescales in root-zone soil moisture dynamics. *Water Resources Research*, 52(2), 1427–1445. https://doi.org/10.1002/2015WR017983
- Gnann, S. J., Coxon, G., Woods, R. A., Howden, N. J. K., & McMillan, H. K. (2021). TOSSH: A toolbox for streamflow signatures in hydrology. *Environmental Modelling and Software*[*R*], 138, 104983. https://doi. org/10.1016/j.envsoft.2021.104983
- Gnann, S. J., McMillan, H. K., Woods, R. A., & Howden, N. J. K. (2021). Including regional knowledge improves baseflow signature predictions in large sample hydrology. *Water Resources Research*, 57(2). https:// doi.org/10.1029/2020wr028354
- Gómez-Plaza, A., Martínez-Mena, M., Albaladejo, J., & Castillo, V. M. (2001). Factors regulating spatial distribution of soil water content in small semiarid catchments. *Journal of Hydrology*, 253(1), 211–226. https://doi.org/10.1016/S0022-1694(01)00483-8
- Graham, C. B., & Lin, H. S. (2011). Controls and frequency of preferential flow occurrence: A 175-event analysis. Vadose Zone Journal, 10(3), 816–831. https://doi.org/10.2136/vzj2010.0119
- Graf, A., Bogena, H. R., Drüe, C., Hardelauf, H., Pütz, T., Heinemann, G., & Vereecken, H. (2014). Spatiotemporal relations between water budget components and soil water content in a forested tributary catchment. *Water Resources Research*, 50(6), 4837–4857. https://doi.org/10. 1002/2013WR014516
- Graham, C. B., & Lin, H. S. (2012). The Hydropedograph toolbox and its application. Hydrology and Earth System Sciences Discussions, 9(12), 14231–14271. https://doi.org/10.5194/hessd-9-14231-2012

- Grayson, R. B., Western, A. W., & Chiew, F. H. S. (1997). Preferred states in spatial soil moisture patterns. *Water Resources Research*, 33(12), 2897–2908. https://doi.org/10.1029/97WR02174
- Grayson, R. B., Western, A. W., Walker, J. P., Kandel, D. G. D., Costelloe, J. F., & Wilson, D. J. (2006). In P. D'Odorico & A. Porporato (Eds.), *Controls on patterns of soil moisture in arid and semi-arid systems* (pp. 109–127). Kluwer Academic Publishers.
- Gupta, H. V., Wagener, T., & Liu, Y. (2008). Reconciling theory with observations: Elements of a diagnostic approach to model evaluation. *Hydrological Processes*, 22(18), 3802–3813. https://doi.org/10.1002/ hyp.6989
- Heudorfer, B., Haaf, E., Stahl, K., & Barthel, R. (2019). Index-based characterization and quantification of groundwater dynamics. Water Resources Research, 55(7), 5575–5592. https://doi.org/10.1029/ 2018WR024418
- Horner, I., Branger, F., McMillan, H., Vannier, O., & Braud, I. (2020). Information content of snow hydrological signatures based on streamflow, precipitation and air temperature. *Hydrological Processes*, 34(12), 2763–2779. https://doi.org/10.1002/hyp.13762
- Hudson, B. D. (1994). Soil organic matter and available water capacity. *Journal of Soil and Water Conservation*, 49(2), 189.
- Jawson, S. D., & Niemann, J. D. (2007). Spatial patterns from EOF analysis of soil moisture at a large scale and their dependence on soil, land-use, and topographic properties. Advances in Water Resources, 30(3), 366– 381. https://doi.org/10.1016/j.advwatres.2006.05.006
- Korres, W., Reichenau, T. G. G., Fiener, P., Koyama, C. N. N., Bogena, H. R. R., Cornelissen, T., Baatz, R., Herbst, M., Diekkrüger, B., Vereecken, H., & Schneider, K. (2015). Spatio-temporal soil moisture patterns—A meta-analysis using plot to catchment scale data. *Journal* of Hydrology, 520, 326–341. https://doi.org/10.1016/j.jhydrol.2014. 11.042
- Koster, R. D., & Suarez, M. J. (2001). Soil moisture memory in climate models. *Journal of Hydrometeorology*, 2(6), 558–570. https://doi.org/ 10.1175/1525-7541(2001)002<0558:SMMICM>2.0.CO;2
- Kruskal, W. H., & Wallis, W. A. (1952). Use of ranks in one-criterion variance analysis. Journal of the American Statistical Association, 47(260), 583–621. https://doi.org/10.1080/01621459.1952.10483441
- Kumar, S., Newman, M., Wang, Y., & Livneh, B. (2019). Potential reemergence of seasonal soil moisture anomalies in North America. *Journal of Climate*, 32(10), 2707–2734. https://doi.org/10.1175/JCLI-D-18-0540.1
- Laio, F. (2002). On the seasonal dynamics of mean soil moisture. Journal of Geophysical Research, 107(D15), ACL 8-1–ACL 8-9. https://doi.org/10. 1029/2001jd001252
- Laio, F., Porporato, A., Fernandez-Illescas, C. P., & Rodriguez-Iturbe, I. (2001). Plants in water-controlled ecosystems: Active role in hydrologic processes and response to water stress IV. Discussion of real cases. Advances in Water Resources, 24(7), 745–762. https://doi.org/ 10.1016/S0309-1708(01)00007-0
- Lawston, P. M., Santanello, J. A., Jr., & Kumar, S. V. (2017). Irrigation signals detected from SMAP soil moisture retrievals. *Geophysical Research Letters*, 44(23), 11,860–11,867. https://doi.org/10.1002/ 2017GL075733
- Liang, W.-L., Kosugi, K., & Mizuyama, T. (2011). Soil water dynamics around a tree on a hillslope with or without rainwater supplied by stemflow: Soil water dynamics with or without stemflow. Water Resources Research, 47(2). https://doi.org/10.1029/2010wr009856
- Mälicke, M., Hassler, S. K., Blume, T., Weiler, M., & Zehe, E. (2020). Soil moisture: Variable in space but redundant in time. *Hydrology and Earth System Sciences*, 24(5), 2633–2653. https://doi.org/10.5194/hess-24-2633-2020
- Martini, E., Wollschläger, U., Kögler, S., Behrens, T., Dietrich, P., Reinstorf, F., Schmidt, K., Weiler, M., Werban, U., & Zacharias, S. (2015). Spatial and temporal dynamics of hillslope-scale soil moisture patterns: Characteristic states and transition mechanisms. *Vadose Zone*

Journal, 14(4), vzj2014.10.0150. https://doi.org/10.2136/vzj2014.10. 0150

- McColl, K. A., He, Q., Lu, H., & Entekhabi, D. (2019). Short-term and longterm surface soil moisture memory time scales are spatially anticorrelated at global scales. *Journal of Hydrometeorology*, 20(6), 1165– 1182. https://doi.org/10.1175/jhm-d-18-0141.1
- McDonnell, J. J., Sivapalan, M., Vaché, K., Dunn, S., Grant, G., Haggerty, R., Hinz, C., Hooper, R., Kirchner, J., Roderick, M. L., Selker, J., & Weiler, M. (2007). Moving beyond heterogeneity and process complexity: A new vision for watershed hydrology. *Water Resources Research*, 43(7), 1–6. https://doi.org/10.1029/2006WR005467
- McKnight, D. M. (2017). Debates-hypothesis testing in hydrology: A view from the field: The value of hydrologic hypotheses in designing field studies and interpreting the results to advance hydrology: Hypotheses of one kind or another. *Water Resources Research*, *53*(3), 1779–1783. https://doi.org/10.1002/2016WR020050
- McMillan, H. (2020a). Linking hydrologic signatures to hydrologic processes: A review. *Hydrological Processes*, 34(6), 1393–1409. https:// doi.org/10.1002/hyp.13632
- McMillan, H. (2020b). A review of hydrologic signatures and their applications. WIREs Water, 8(1), e1499. https://doi.org/10.1002/wat2.1499
- McMillan, H., Gueguen, M., Grimon, E., Woods, R., Clark, M., & Rupp, D. E. (2014). Spatial variability of hydrological processes and model structure diagnostics in a 50 km 2 catchment. *Hydrological Processes*, 28(18), 4896–4913. https://doi.org/10.1002/hyp.9988
- McMillan, H., & Srinivasan, M. S. (2015). Characteristics and controls of variability in soil moisture and groundwater in a headwater catchment. *Hydrology and Earth System Sciences*, 19(4), 1767–1786. https://doi. org/10.5194/hess-19-1767-2015
- McMillan, H., Westerberg, I., & Branger, F. (2017). Five guidelines for selecting hydrological signatures. *Hydrological Processes*, 31(26), 4757– 4761. https://doi.org/10.1002/hyp.11300
- Miguez-Macho, G., & Fan, Y. (2012). The role of groundwater in the Amazon water cycle: 2. Influence on seasonal soil moisture and evapotranspiration. *Journal of Geophysical Research*, 117(D15). https://doi. org/10.1029/2012jd017540
- Morel, P. (2018). Gramm: Grammar of graphics plotting in Matlab. Journal of Open Source Software, 3(23), 568. https://doi.org/10.21105/joss. 00568
- National Aeronautics and Space Administration (NASA), National Imagery and Mapping Agency (NIMA), German Aerospace Center (DLR), Italian Space Agency (ASI). (2002). *Shuttle Radar Topography Mission* (SRTM) Elevation Dataset. U.S. Geological Survey. http://seamless. usgs.gov.
- Penna, D., Tromp-Van Meerveld, H. J., Gobbi, A., Borga, M., & Dalla, F. G. (2011). The influence of soil moisture on threshold runoff generation processes in an alpine headwater catchment. *Hydrology and Earth System Sciences*, 15(3), 689–702. https://doi.org/10.5194/hess-15-689-2011
- Potter, N. J., Zhang, L., Milly, P. C. D., McMahon, T. A., & Jakeman, A. J. (2005). Effects of rainfall seasonality and soil moisture capacity on mean annual water balance for Australian catchments: WATER BAL-ANCE OF AUSTRALIAN CATCHMENTS. Water Resources Research, 41(6). https://doi.org/10.1029/2004wr003697
- Richter, B. D., Baumgartner, J. V., Powell, J., & Braun, D. P. (1996). A method for assessing hydrologic alteration within ecosystems. *Conservation Biology: The Journal of the Society for Conservation Biology*, 10 (Aug), 1163–1174. https://doi.org/10.1007/s13361-012-0389-8
- Riffenburgh, R. H. (2006). Chapter summaries. In R. H. Riffenburgh (Ed.), Statistics in medicine (pp. 533–580). Elsevier. https://doi.org/10.1016/ b978-012088770-5/50067-8
- Rodriguez-Iturbe, I., D'Odorico, P., Porporato, A., & Ridolfi, L. (1999). On the spatial and temporal links between vegetation, climate, and soil moisture. Water Resources Research, 35(12), 3709–3722. https://doi. org/10.1029/1999wr900255

20 of 21 WILEY-

- Rodell, M., Houser, P. R., Jambor, U., Gottschalck, J., Mitchell. K., Meng, C-J., Arsenault, K., Cosgrove, B., Radakovich, J., Bosilovich, M., Entin, J. K., Walker, J. P., Lohmann, D., & Toll, D. (2004). The global land data assimilation system. *Bulletin of the American Meteorological Society*, 85(3), 381–394. https://doi.org/10.1175/bams-85-3-381
- Rodriguez-Iturbe, I., Porporato, A., Ridolfi, L., Isham, V., & Coxi, D. R. (1999). Probabilistic modelling of water balance at a point: The role of climate, soil and vegetation. *Proceedings of the Royal Society of London*. *Series A: Mathematical, Physical and Engineering Sciences*, 455(1990), 3789–3805. https://doi.org/10.1098/rspa.1999.0477
- Rogger, M., Agnoletti, M., Alaoui, A., Bathurst, J. C., Bodner, G., Borga, M., Chaplot, V., Gallart, F., Glatzel, G., Hall, J., Holden, J., Holko, L., Horn, R., Kiss, A., Kohnová, S., Leitinger, G., Lennartz, B., Parajka, J., Perdigão, R., ... Blöschl, G. (2017). Land-use change impacts on floods at the catchment scale: Challenges and opportunities for future research. *Water Resources Research*, *53*(7), 5209–5219. https://doi. org/10.1002/2017WR020723
- Rosenbaum, U., Bogena, H. R., Herbst, M., Huisman, J. A., Peterson, T. J., Weuthen, A., Western, A. W., & Vereecken, H. (2012). Seasonal and event dynamics of spatial soil moisture patterns at the small catchment scale. *Water Resources Research*, 48(10), 1–22. https://doi.org/ 10.1029/2011WR011518
- Samuel, J. M., Sivapalan, M., & Struthers, I. (2008). Diagnostic analysis of water balance variability: A comparative modeling study of catchments in Perth, Newcastle, and Darwin, Australia. *Water Resources Research*, 44(6), 1–13. https://doi.org/10.1029/2007WR006694
- Sawicz, K., Wagener, T., Sivapalan, M., Troch, P. A., & Carrillo, G. (2011). Catchment classification: Empirical analysis of hydrologic similarity based on catchment function in the eastern USA. *Hydrology and Earth System Sciences Discussions*, 8(3), 4495–4534. https://doi.org/10. 5194/hessd-8-4495-2011
- Scalenghe, R., & Ajmone-Marsan, F. (2009). The anthropogenic sealing of soils in urban areas. *Landscape and Urban Planning*, 90(1–2), 1–10. https://doi.org/10.1016/j.landurbplan.2008.10.011
- Schaefli, B. (2016). Snow hydrology signatures for model identification within a limits-of-acceptability approach. *Hydrological Processes*, 30(22), 4019–4035. https://doi.org/10.1002/hyp.10972
- Selassie, Y. G., & Ayanna, G. (2013). Effects of different land use systems on selected physico-chemical properties of soils in Northwestern Ethiopia. *Journal of Agricultural Science*, 5(4), 112. https://doi.org/10. 5539/jas.v5n4p112
- Shafii, M., & Tolson, B. A. (2015). Optimizing hydrological consistency by incorporating hydrological signatures into model calibration objectives. *Water Resources Research*, 51(5), 3796–3814. https://doi.org/10. 1002/2014wr016520
- Singh, V. P., & Frevert, D. K. (2010). Watershed models. CRC Press.
- Skøien, J. O., Blöschl, G., & Western, A. W. (2003). Characteristic space scales and timescales in hydrology: Characteristic scales in hydrology. *Water Resources Research*, 39(10). https://doi.org/10.1029/ 2002wr001736
- Smith, A. B., Walker, J. P., Western, A. W., Young, R. I., Ellett, K. M., Pipunic, R. C., Grayson, R. B., Siriwardena, L., Chiew, F. H. S., & Richter, H. (2012). The Murrumbidgee soil moisture monitoring network data set. *Water Resources Research*, 48(7). https://doi.org/10. 1029/2012WR011976
- Soylu, M. E., & Bras, R. L. (2021). Detecting shallow groundwater from spaceborne soil moisture observations. Water Resources Research, 57(2). https://doi.org/10.1029/2020wr029102
- Su, Z., Wen, J., Dente, L., van der Velde, R., Wang, L., Ma, Y., Yang, K., & Hu, Z. (2011). The Tibetan plateau observatory of plateau scale soil moisture and soil temperature (Tibet-Obs) for quantifying uncertainties in coarse resolution satellite and model products. *Hydrology* and Earth System Sciences, 15(7), 2303–2316. https://doi.org/10. 5194/hess-15-2303-2011

- Sumargo, E., McMillan, H., Weihs, R., Ellis, C. J., Wilson, A. M., & Ralph, F. M. (2021). A soil moisture monitoring network to assess controls on runoff generation during atmospheric river events. *Hydrological Processes*, 35(1). https://doi.org/10.1002/hyp. 13998
- Teuling, A. J., Uijlenhoet, R., & Troch, P. A. (2005). On bimodality in warm season soil moisture observations. *Geophysical Research Letters*, 32 (June), 10–13. https://doi.org/10.1029/2005GL023223
- The Deutscher Wetterdienst (DWD). (2021). Open Data Server, climate data provided by DWD's Climate Data Center. https://opendata.dwd. de/climate_environment/CDC/
- The Royal Netherlands Meteorological Institute (KNMI) (2021). Dagwaarden neerslagstations (Daily values of precipitation stations). https://www.knmi.nl/nederland-nu/klimatologie/monv/reeksen
- Tian, J., Zhang, B., He, C., Han, Z., Bogena, H. R., & Huisman, J. A. (2019). Dynamic response patterns of profile soil moisture wetting events under different land covers in the mountainous area of the Heihe River watershed, Northwest China. Agricultural and Forest Meteorology, 271, 225–239. https://doi.org/10.1016/j.agrformet.2019.03.006
- Trimble, S. W. (2007). Encyclopedia of water science. CRC Press.
- Tromp-van Meerveld, H. J., & McDonnell, J. J. (2006). On the interrelations between topography, soil depth, soil moisture, transpiration rates and species distribution at the hillslope scale. Advances in Water Resources, 29(2), 293–310. https://doi.org/10.1016/j.advwatres.2005.02.016
- University of Hamburg. (2021). HUSCO-Hamburg urban soil climate observatory (2010-2016, project completed). CliSAP. https://www.clisap.de/ research/b:-climate-manifestations-and-impacts/b5:-urban-systemstest-bed-hamburg/husco-hamburg-urban-soil-climate-observatory/
- Vanderlinden, K., Vereecken, H., Hardelauf, H., Herbst, M., Martínez, G., Cosh, M. H., & Pachepsky, Y. A. (2012). Temporal stability of soil water contents: A review of data and analyses. *Vadose Zone Journal*, 11(4), vzj2011.0178. https://doi.org/10.2136/vzj2011.0178
- Vereecken, H., Kamai, T., Harter, T., Kasteel, R., Hopmans, J., & Vanderborght, J. (2007). Explaining soil moisture variability as a function of mean soil moisture: A stochastic unsaturated flow perspective. *Geophysical Research Letters*, 34(22). https://doi.org/10.1029/ 2007gl031813
- Vereecken, H., Schnepf, A., Hopmans, J. W. W., Javaux, M., Or, D., Roose, T., Vanderborght, J., Young, M. H. H., Amelung, W., Aitkenhead, M., Allison, S. D., Assouline, S., Baveye, P., Berli, M., Brüggemann, N., Finke, P., Flury, M., Gaiser, T., Govers, G., ... Young, I. M. (2016). Modeling soil processes: Review, key challenges, and new perspectives. *Vadose Zone Journal*, *15*(5), vzj2015.09.0131. https://doi.org/10.2136/vzj2015.09.0131
- Viglione, A., Merz, B., Viet Dung, N., Parajka, J., Nester, T., & Blöschl, G. (2016). Attribution of regional flood changes based on scaling fingerprints. Water Resources Research, 52(7), 5322–5340. https://doi.org/ 10.1002/2016WR019036
- Wagener, T., Sivapalan, M., Troch, P., & Woods, R. (2007). Catchment classification and hydrologic similarity. *Geography Compass*, 1(4), 901–931. https://doi.org/10.1111/j.1749-8198.2007.00039.x
- Wang, J., Luo, S., Li, Z., Wang, S., & Li, Z. (2019). The freeze/thaw process and the surface energy budget of the seasonally frozen ground in the source region of the Yellow River. *Theoretical and Applied Climatology*, 138(3-4), 1631–1646. https://doi.org/10.1007/s00704-019-02917-6
- Westerberg, I. K., Guerrero, J.-L., Younger, P. M., Beven, K. J., Seibert, J., Halldin, S., Freer, J. E., & Xu, C.-Y. (2011). Calibration of hydrological models using flow-duration curves. *Hydrology and Earth System Sciences*, 15(7), 2205–2227. https://doi.org/10.5194/hess-15-2205-2011
- Western, A. W., Zhou, S.-L. L., Grayson, R. B., Wilson, D. J., Mcmahon, T. A., Blöschl, G., & Wilson, D. J. (2004). Spatial correlation of soil moisture in small catchments and its relationship to dominant spatial hydrological processes. *Journal of Hydrology*, 286(1–4), 113– 134. https://doi.org/10.1016/j.jhydrol.2003.09.014

- Wiekenkamp, I., Huisman, J. A., Bogena, H. R., Graf, A., Lin, H. S., Drüe, C., & Vereecken, H. (2016). Changes in measured spatiotemporal patterns of hydrological response after partial deforestation in a headwater catchment. *Journal of Hydrology*, 542, 648–661. https://doi.org/ 10.1016/J.JHYDROL.2016.09.037
- Wiekenkamp, I., Huisman, J. A., Bogena, 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
- Wiekenkamp, I., Huisman, J. A., Bogena, H. R., & Vereecken, H. (2019). Effects of deforestation on water flow in the Vadose zone. Water, 12(1), 35–35. https://doi.org/10.3390/w12010035
- Wiesner, S., Eschenbach, A., & Ament, F. (2014). Urban air temperature anomalies and their relation to soil moisture observed in the city of Hamburg. *Meteorologische Zeitschrift*, 23(2), 143–157. https://doi.org/ 10.1127/0941-2948/2014/0571
- Wiesner, S., Gröngröft, A., Ament, F., & Eschenbach, A. (2016). Spatial and temporal variability of urban soil water dynamics observed by a soil monitoring network. *Journal of Soils and Sediments*, 16(11), 2523– 2537. https://doi.org/10.1007/s11368-016-1385-6
- Woodruff, C. M., & Wilding, L. P. (2008). Bedrock, soils, and hillslope hydrology in the Central Texas Hill country, USA: Implications on environmental management in a carbonate-rock terrain. *Environmental Geology*, 55(3), 605–618. https://doi.org/10.1007/s00254-007-1011-4
- Yarnell, S. M., Petts, G. E., Schmidt, J. C., Whipple, A. A., Beller, E. E., Dahm, C. N., Goodwin, P., & Viers, J. H. (2015). Functional flows in modified riverscapes: Hydrographs, habitats and opportunities. *Biosci*ence, 65(10), 963–972. https://doi.org/10.1093/biosci/biv102

- Young, R., Walker, J. P., Yeoh, N., Smith, A., Ellett, K., Merlin, O., & Western, A. W. (2008). *Soil moisture and meteorological observations from the Murrumbidgee catchment*. Department of Civil and Environmental Engineering, The University of Melbourne. Retrieved from https://www.oznet.org.au/
- Zehe, E., Becker, R., Bárdossy, A., & Plate, E. (2005). Uncertainty of simulated catchment runoff response in the presence of threshold processes: Role of initial soil moisture and precipitation. *Journal of Hydrology*, 315(1–4), 183–202. https://doi.org/10.1016/j.jhydrol.2005.03.038
- Ziegler, A. D., Giambelluca, T. W., Sutherland, R. A., Vana, T. T., & Nullet, M. A. (2001). Horton overland flow contribution to runoff on unpaved mountain roads: A case study in northern Thailand. *Hydrological Processes*, 15(16), 3203–3208. https://doi.org/10.1002/hyp.480

SUPPORTING INFORMATION

Additional supporting information may be found in the online version of the article at the publisher's website.

How to cite this article: Araki, R., Branger, F., Wiekenkamp, I., & McMillan, H. (2022). A signature-based approach to quantify soil moisture dynamics under contrasting land-uses. *Hydrological Processes*, *36*(4), e14553. <u>https://doi.org/10.</u>1002/hyp.14553