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

Ryoko Araki[1], Flora Branger[2], Inge Wiekenkamp[3], and Hilary McMillan[1]

[1]San Diego State University
[2]Irstea Centre de Lyon-Villeurbanne
[3]Helmholtz Centre Potsdam German Research Centre for Geosciences

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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 represent catchment dynamics extracted from time series of data 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 covers a range of land-use types, including forested and deforested areas, shallow groundwater areas, wetlands, housing areas, grazed areas, and cropland areas. These signatures characterize soil moisture dynamics at three temporal scales: event, seasonal, and time-series scales. Statistical and visual assessment of extracted signatures showed that (1) storm event-based signatures can distinguish different dynamics for most land-uses, (2) season-based signatures are useful to distinguish different dynamics for some types of land-uses (forested vs. deforested area, greenspace vs. housing area, and deep vs. shallow groundwater area), (3) timeseries-based signatures can distinguish different dynamics for some types of land-uses (forested vs. deforested area, deep vs. shallow groundwater area, non-wetland vs. wetland area, and ungrazed vs. grazed area). We compared signature-based process interpretations against literature knowledge: event-based and time series-based signatures were generally matched well with previous process understandings from literature, but season-based signatures did not. This study demonstrates the best practices of extracting soil moisture signatures under various land-use and climate environments and applying signatures for model evaluations.

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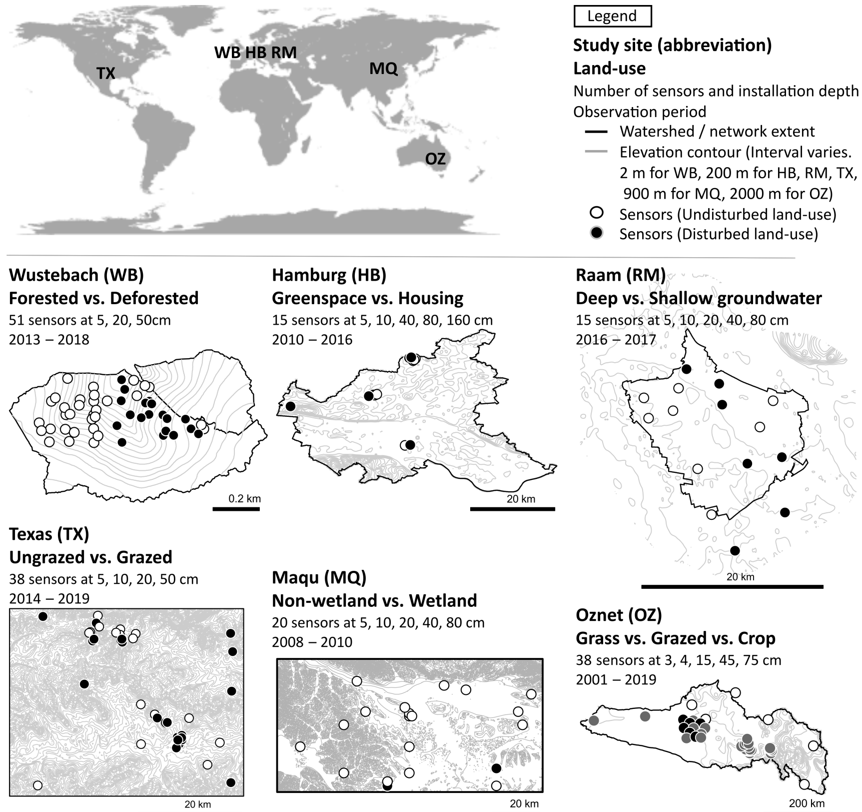
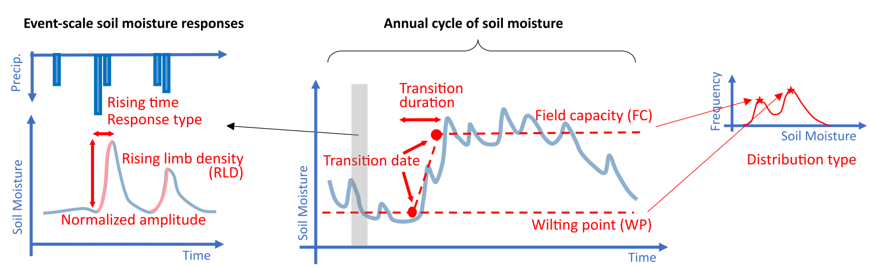
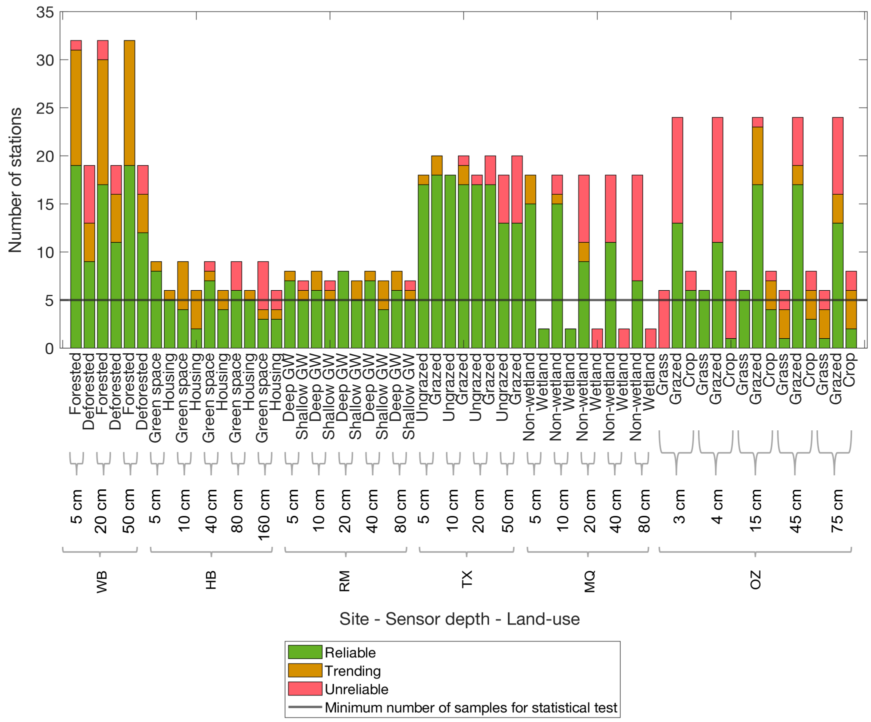


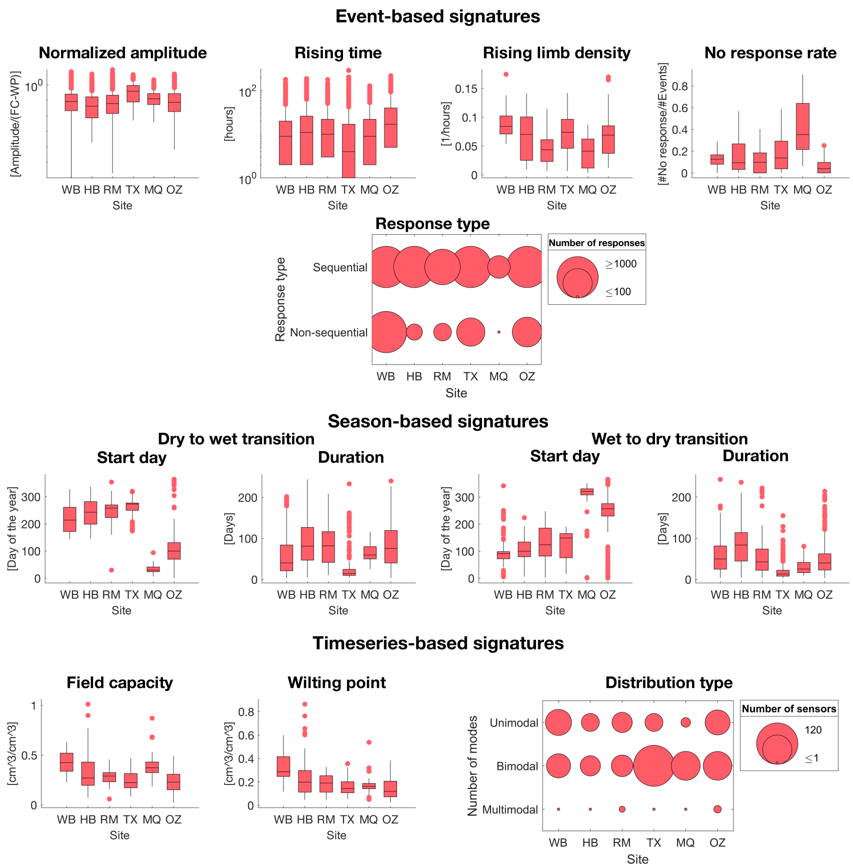
(a)



(b)

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


Number of stations
0
5
10
15
20
25
30
35
Forested
Deforested
Green space
Housing
Deep GW
Shallow GW
Ungrazed
Grazed
Non-wetland
Wetland
Grass
Crop
5 cm
20 cm
50 cm
10 cm
40 cm
80 cm
160 cm
3 cm
4 cm
15 cm
45 cm
75 cm
WB
HB
RM
TX
MQ
OZ
Site - Sensor depth - Land-use
Reliable
Trending
Unreliable
Minimum number of samples for statistical test



Study site	Land-use (undisturbed disturbed)	Event-based: Amplitude	Event-based: Rising time	Event-based: Rising limb density	Event-based: No response rate	Season-based: Dry-to-wet transition Start Day	Season-based: Dry-to-wet transition Duration	Season-based: Wet-to-dry transition Start Day	Season-based: Wet-to-dry transition Duration	Timeseries-based: Field capacity	Timeseries-based: Wilting point	Timeseries-based: Distribution type (Unimodal)
WB	Forested	→	→	↗	↗	→	↘	→	↗	↘	→	↗
	Deforested	→	→	→	↗	↘	↘	↘	↘	↘	→	→
HB	Greenspace	↘	↗	↘	↗	↗	↘	↗	↗	→	→	↘
	Housing	↘	↗	↘	↗	↗	↘	↗	↗	↘	↘	↘
RM	Deep GW	↘	↗	↘	↗	↗	→	↗	→	↗	→	→
	Shallow GW	↘	↗	↘	↗	↗	→	↗	↗	↗	→	↗
TX	Ungrazed	↘	↗	↘	↗	↗	↘	→	↗	↗	↗	↘
	Grazed	↘	↗	↘	↗	↗	→	→	↗	↗	↗	↘
MQ	Non-wetland	↘	↗	↘	↗	↗	↘	↗	↗	↘	↗	↗
	Wetland	↘	↗	↘	↗	↘	↗	↗	↘	↘	↗	↗
OZ	Grass	↘	↗	↘	↗	↗	↘	↗	↗	↗	↗	-
	Grazed	↘	↗	↘	↗	↗	↘	↗	↗	↗	↗	↘
	Crop	↘	↗	↘	↗	→	↗	→	↗	↗	↗	↗

0 0.05 0.1 ≥ 0.15

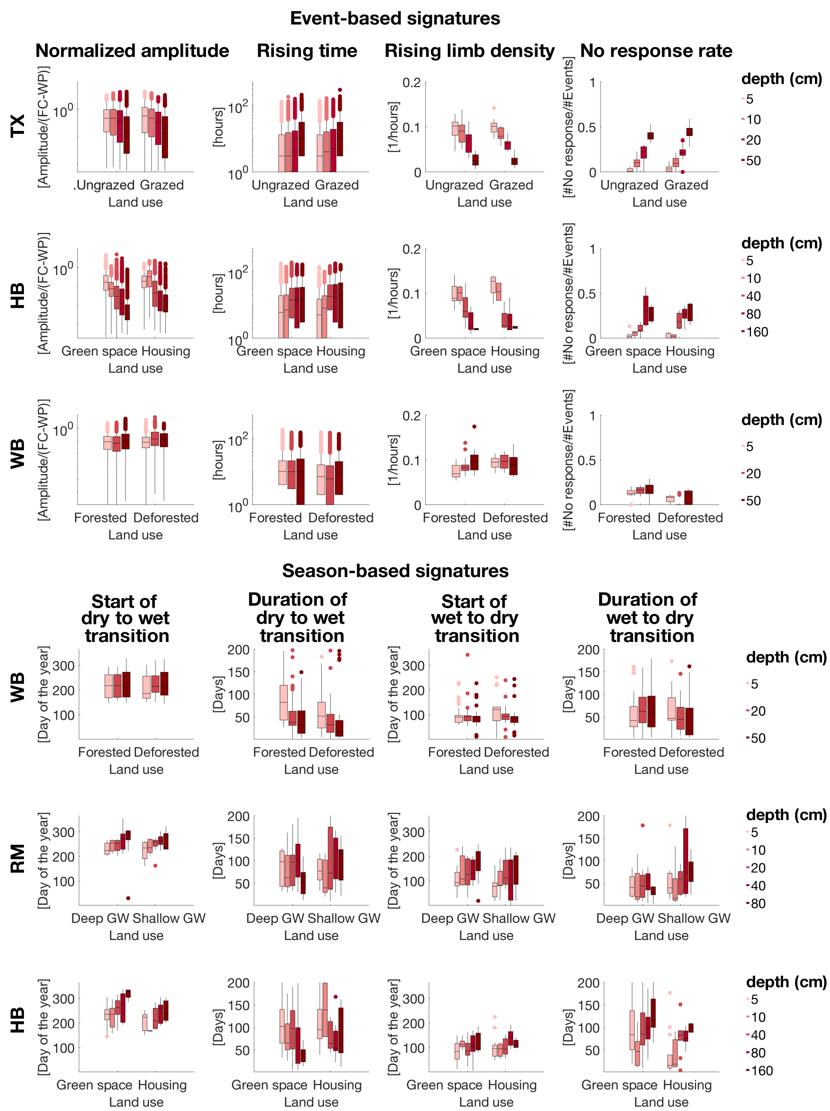
P-value color scale

Study site Land-use (disturbed vs. undisturbed)	Depth (cm)	Event-based: Response type (sequential)	Event-based: Amplitude	Event-based: Rising time	Event-based: Rising limb density	Event-based: No response rate	Season-based, Dry-to-wet transition: Start Day	Season-based, Dry-to-wet transition: Duration	Season-based, Wet-to-dry transition: Start Day	Season-based, Wet-to-dry transition: Duration	Timeseries-based: Field capacity	Timeseries-based: Witling point	Timeseries-based: Distribution type (unimodal)
WB Deforested vs. Forested	5	↑	↓	↓	↑	↓	↓	↓	↑	↑	↑	↑	↑
	20		↑	↓	↑	↓	↓	↓	→	↑	↑	↑	↑
	50		↑	↓	↓	↓	↓	↓	↓	↓	↑	↑	↑
HB Housing v. Greenspace	5	↑	↑	↓	↑	↓	↓	↓	↑	↓	↓	↓	↑
	10		↑	↑	↑	↓	↓	↑	↓	↓	↓	↓	↑
	40		↑	↑	↓	↑	↓	↓	↑	↓	↑	↓	↓
	80		↓	↑	↓	↓	↓	↑	↑	↓	↓	↓	↓
	160		↑	↑	↑	↑	↓	↑	↓	↓	↓	↓	↓
RM Shallow v. Deep GW	5	↓	↑	↑	↓	↑	↑	↓	↓	↓	↑	↑	↓
	10		↓	↑	↓	↑	↓	↓	↓	↓	↑	↑	↓
	20		↓	→	↑	↓	↑	↓	↓	↑	↑	↑	↑
	40		↓	↓	↑	↓	↓	↑	↓	↑	↓	↑	↑
	80		↓	↑	↓	↑	↓	↑	↓	↑	↑	↑	→
TX Grazed v. Ungrazed	5	↑	↑	→	↓	↑	↓	↓	↓	↓	↓	↓	↓
	10		↓	↑	↓	↓	↓	↓	↓	↑	↓	↓	↓
	20		↓	↑	↓	↓	↑	↑	↓	↓	↓	↓	→
	50		↓	↑	↓	↑	↑	↓	↑	↑	↑	↓	→
OZ Crop v. Grass v. Grazed	3	↓	-	-	-	-	-	-	-	-	-	-	-
	4		↓	→	↓	↑	↓	↑	↓	↑	↑	↑	↓
	15		↓	↑	↓	↑	↓	↑	↑	↑	↑	↓	↓
	45		↑	↑	↓	↑	↓	↑	↓	↓	↑	↑	↑
	75		↑	↑	↓	↑	↓	↑	↑	↓	↑	↑	↑

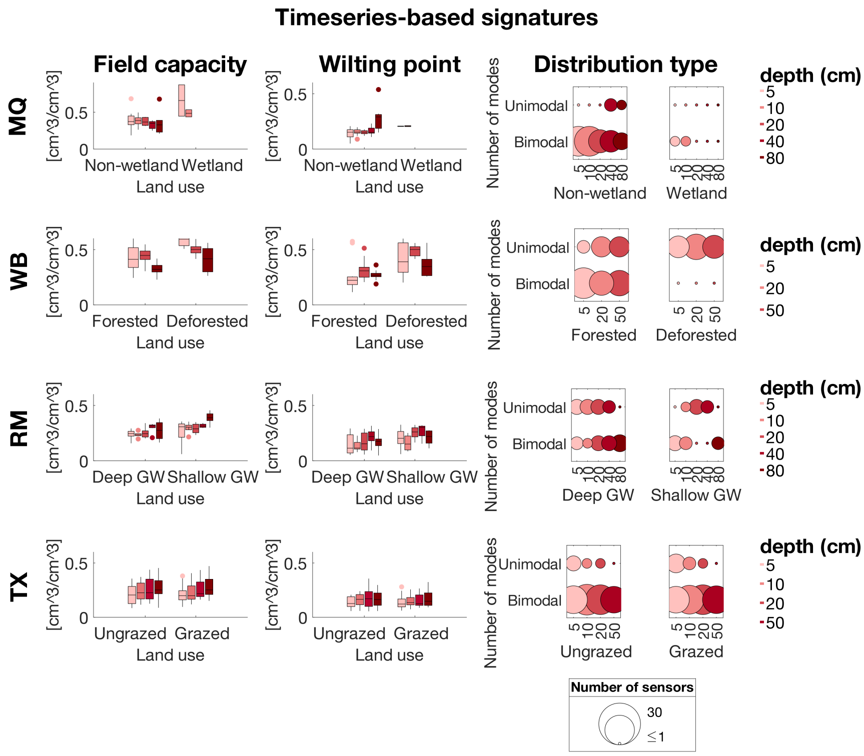
-20 0 20
% change in sequential responses

0 0.05 0.1 ≥0.15
P-value color scale

-100 0 100
% change in unimodal distribution

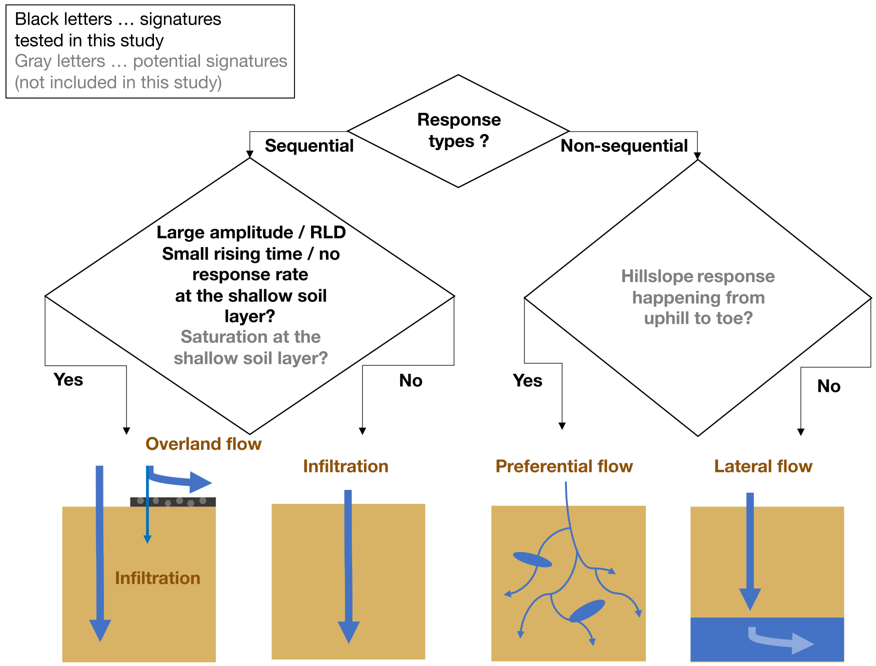


Event-based signatures
Normalized amplitude
Rising time
Rising limb density
No response rate
TX
HB
WB
[Amplitude/(FC-WP)]
[hours]
[1/hours]
[#No response/#Events]
Ungrazed Grazed
Green space Housing
Forested Deforested
Land use
depth (cm)
Season-based signatures
Start of dry to wet transition
Duration of dry to wet transition
Start of wet to dry transition
Duration of wet to dry transition
RM
[Day of the year]
[Days]
Deep GW Shallow GW



Site		Dominant response type	Ampli-tude	Rising time	RLD	No res rate	Dry-to-wet transition: Start Day	Dry-to-wet transition: Duration	Wet-to-dry transition: Start Day	Wet-to-dry transition: Duration	FC	WP	Distribution type (% of unimodal)
		Signatures											
		Event signatures					Season-based signatures				Timeseries-based signatures		
WB forested	Expected processes	Preferential flow (Wiekenkamp et al., 2016; Graham and Lin, 2011)					Tandem transition (Grayson et al., 1997; Clark et al., 2011)				Soil properties (Trimble, 2007; Wiekenkamp et al., 2016)		
	Expected sig	Non-sequential	→	→	→	→	→	→	→	→	→	→	↗
	Observed sig	Non-sequential	→	→	↗	↗	→	↘	→	↗	↘	→	↗
HB green-space	Expected processes	Vertical infiltration (Graham and Lin, 2011)					Tandem transition (Grayson et al., 1997; Clark et al., 2011)				Soil properties (Trimble, 2007)		
	Expected sig	Sequential	↘	↗	↘	↗	→	→	→	→	→	→	↗
	Observed sig	Sequential	↘	↗	↘	↗	↗	↘	↗	↗	→	→	↘
RM Deep GW	Expected processes	Vertical infiltration (Graham and Lin, 2011)					Tandem transition (Grayson et al., 1997; Clark et al., 2011)				Capillary effects		
	Expected sig	Sequential	↘	↗	↘	↗	→	→	→	→	↗	↗	↗
	Observed sig	Sequential	↘	↗	↘	↗	↗	→	↗	→	↗	→	→
TX Ungrazed	Expected processes	Vertical infiltration (Woodruff and Wilding, 2008; Graham and Lin, 2011)					Episodic response due to deep drying (Bureau of Economic Geology, 2020; Long et al., 2013)				Evaporative drying (Chandler et al., 2017)		
	Expected sig	Sequential	↘	↗	↘	↗	↗	↗	↗	↗	→	↗	↗
	Observed sig	Sequential	↘	↗	↘	↗	↗	↘	→	↗	↗	↗	↘
MQ Non-wetland	Expected processes	Vertical infiltration (Dente et al., 2012; Graham and Lin, 2011)					Tandem transition (Grayson et al., 1997; Clark et al., 2011)				No capillary effect (Dente et al., 2012)		
	Expected sig	Sequential	↘	↗	↘	↗	→	→	→	→	→	→	↗
	Observed sig	Sequential	↘	↗	↘	↗	↗	↘	↗	↗	↘	↗	↗
OZ Grass	Expected processes	Vertical infiltration (Shakesby et al., 2000; Letey, 2001; Graham and Lin, 2011)					Episodic response due to deep drying (Grayson et al., 2006)				Evaporative drying (Chandler et al., 2017; Grayson et al., 2006)		
	Expected sig	Sequential	↘	↗	↘	↗	↗	↗	↗	↗	↗	↗	↗
	Observed sig	Sequential	↘	↗	↘	↗	→	↗	→	↗	↗	↗	-

		Signatures											
		Event-based signatures					Season-based signatures				Timeseries-based signatures		
							Dry-to-wet		Wet-to-dry transition				
		Res type (sequential)	Amplitude	Rising time	RLD	No res rate	Start Day	Duration	Start Day	Duration	FC	WP	Dist type (% of unimodal)
WB Deforested vs. forested	Expected processes	Sequential flow ↑; More responsive due to storage ↑ (Wiekenkamp et al., 2019)					Transition speed ↓ due to T ↓ interception ↓ (Rosenbaum et al., 2012; Wiekenkamp et al., 2016a; Laio, 2002) and/or Seasonal persistence ↑ due to surface connectivity ↑ (Lehmann et al., 2007; McGuire and McDonnell, 2010)				Storage ↑ due to T & interception ↓ (Rosenbaum et al., 2012; Wiekenkamp et al., 2016a; Bruijnzeel, 2004)		
	Expected sig	↑	↑	↓	↑	↓	→ and/or ↓	↑ and/or ↓	→ and/or ↑	↑ and/or ↑	↑	↑	↑
	Observed sig	↑	↑	↓	↑	↓	↓	↓	→	↑	↑	↑	↑
HB Housing vs. greenspace	Expected processes	Vertical infiltration -> overland-flow due to surface sealing (Scalenghe and Ajmone-Marsan, 2009; Ziegler et al., 2001)					Transition speed ↓ due to ET & interception ↓(Laio, 2002) and/or Transition speed ↑ due to sporadic infiltration & drainage due to constraction waste (Wiesner et al., 2016)				Storage ↑ due to infiltration ↓ (Bruijnzeel, 2004)		
	Expected sig	↑	↑	↑	↑	↑	→ and/or →	↑ and/or →	→ and/or ↓	↑ and/or ↓	↓	↓	↑
	Observed sig	↑	↑	↑	↑	↓	↓	→	→	↓	↓	↓	↑ and ↓
RM Shallow vs. deep GW	Expected processes	Vertical infiltration -> lateral flow; Less responsive due to saturation (Soylu and Bras, 2020)					Transition speed and timing ↑ due to thickness of effective soil layer ↓ (Laio, 2002; Wu et al., 2002) and/or Seasonal persistence ↑ due to surface connectivity ↑ due to capillary rise (Lehmann et al., 2007; McGuire and McDonnell, 2010)				Storage ↑ due to capillary rise		
	Expected sig	↓	↓	↓	↓	↑	↓ and /or ↓	↓ and/or ↓	↓ and/or ↑	↓ and/or ↑	↑	↑	↑ but ↓ at GW interface
	Observed sig	↓	↓	↑	↓	↑	↓	↑	↓	↑	↑	↑	↑ but ↓ at GW interface
TX Grazed vs. ungrazed	Expected processes	Vertical infiltration -> overland-flow due to compaction (Woodruff and Wilding, 2008; Alaoui et al., 2018; Ziegler et al., 2001)					Seasonal persistence ↓ due to surface connectivity ↓ due to compaction (Lehmann et al., 2007; McGuire and McDonnell, 2010)				Storage ↓ due to compaction and overland flow (Bormann and Klaassen, 2008; Bruijnzeel, 2004; Selassie and Ayanna, 2013)		
	Expected sig	↑	↑	↑	↑	↑	↓	↓	↑	↑	↓	↓	↓
	Observed sig	↑	↓	↑	↓	→	→	↓	↓	→	↓	↓	↑
MQ Wetland vs Non-wetland	Expected processes	Vertical infiltration --> Lateral flow; Less responsive due to saturation (Soylu and Bras, 2020; Dente et al., 2012)					Seasonal persistence ↑ due to heat capacity ↑				Storage ↑ due to soil organic matter (Dente et al., 2012); More persistent freeze/thaw		
	Expected sig	↓	↓ and/or ↑	↓	↓	↑	↓	↓	↑	↑	↑	↑	↓ and/or ↑
	Observed sig	↓	→	→	↓	↑	→	→	→	→	↑	↑	↑
OZ Crop vs. grazed vs. grass	Expected processes	Vertical infiltration --> Overland-flow due to compaction (Alaoui et al., 2018; Ziegler et al., 2001); Less responsive due to transpiration ↑					Seasonal persistence ↓ due to surface connectivity ↓ due to compaction (Lehmann et al., 2007; McGuire and McDonnell, 2010)				Storage ↓ due to compaction and T↑ (Bormann and Klaassen, 2008; Bruijnzeel, 2004; Selassie and Ayanna, 2013) and/or Storage ↑ due to irrigation (Smith et al., 2012)		
	Expected sig	↑	↑ and/or ↓	↑	↑	↑	↓	↓	↑	↑	↓	↓ and/or ↑	↓ and/or ↑
	Observed sig	↑	→	↑	↓	↑	↓	↑	→	→	↑	↑	→



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