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Propagation from meteorological to hydrological drought in the Horn of Africa using both standardized and threshold-based indices

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Supplementary materials

S1. Data

Catchment characteristics

Table S 1: Catchment characteristics (based on BasinATLAS) (Linke et al., 2019), Africa Groundwater ATLAS (BGS, 2021; O Dochartaigh, 2021), Copernicus Landcover 100m resolution (Buchhorn et al., 2020)

Variable(Name of variable in heatmap)	Unit	Description	Resolution	Source data
Sub catchment area (SUB_AREA)	km^2	Area enclosing the sub-catchment	polygon	HydroBASINS
Upstream area (Upstream_area(m2)	m^2	Upstream area including the individual sub-catchment	0.1 degree	GloFAS
Upstream Annual mean precipitation (annual_prec_mean(mm/yr)	mm	Calculated by averaging the monthly precipitation values based on the upstream contributing area	0.1 degree	MWEP
Climate zones (climate_zones)	classes (18)	Statistically derived 125 environmental strata based on 42 variables and aggregated to 18 environmental zones	Polygons	Global Environmental Stratification (GEnS)
Upstream average elevation (Upstream_Avg_Elevation (m))	meters a.s.l.	Obtained from the EarthEnv-DEM90 which is a digital elevation model derived from CGIAR-CSI SRTM v4.1 and ASTER GDEM v2 data products representing conditions of 2000-2010. Originally in 3 arc-second grid (approx. 90m at the equator) then aggregated to 15 arc-second grid using mean statistics	15 arc-second grid	EarthEnv-DEM90
Terrain slope (Terrain_slope)	degrees (x10)	Similar as above. Slope values were calculated based on Horn's method. Latitudinal corrections for the distortion in XY spacing of geographic coordinates were done by approximating the geodesic distance between cell centers	15 arc-second grid	EarthEnv-DEM90
Groundwater table depth (Avg_GW_table(cm))	centimeters	Obtained from compiled global observations of water depth from government archives and literature (1927-2009). Data gaps and inferred patterns and processes filled using a groundwater model forced by modern climate, terrain, and sea level	30 arc-second grid	Global Groundwater Map
Average soil water content (Avg_soilwater%_uyr)	percent	Percentage of the maximum soil soil water content per year, which is a measure of soil stress, and equal to soil water stress coefficient as a percentage. Primary inputs are based on WorldClim and Global-PET databases.	30 arc-second grid	Global High-Resolution Soil-Water Balance
Clay fraction (Clay_fraction%(top5cm))	percent	Fraction predictions are based on global spatial prediction models fitted, per soil variable, using a combination of major international soil profile databases and assortment of global environmental covariates representing soil forming factors. Represents the top 0-5cm	30 arc-second grid	SoilGrids1km
Sand fraction (Sand_fraction%(top5cm))	percent	Same as above	30 arc-second grid	SoilGrids1km

Silt fraction (Silt_fraction%(top5cm))	percent	Same as above	30 arc-second grid	SoilGrids1km
Global aridity index (Global_avg_aridity_index(x100))	index value (x100)	Modelled from WorlClim data parameters. Calculated as mean precipitation over mean annual PET. The aridity value increases with more humid regions and decreases with more arid regions. 0 no precipitation, 1 precipitation=PET, >1 precipitation>PET	30 arc-second grid	Global Aridity Index v1
Landcover classes (landcover_classes)	classes (5)	Landcover maps were based on daily data from PROBA-Vegetation sensor	100m resolution, global	Copernicus: Global Land Cover 2019
Average population density (Avg_Pop_density/km2)	people per km²	Based on 2010 round of censuses and provides the distributions of people on a continuous global surface	30 arc-second grid	Gridded Population of the World (GPW) v4
Geology	map	Overview of hydrogeology from multiple sources	polygons	Africa Groundwater Atlas: Country hydrogeology maps

S2. Methodology

S2.1 Standardized indices

We applied different distributions and picked the one with the best fit to calculate each of the indices. By doing this, we are not consistent between catchments, which causes uncertainties when comparing values between different catchments. Bur as we are only looking to compare within catchments, we prefer the better fits to the spatial consistency.

By the nature of the different indices, different distributions are best suited to fit the different data types. This is recognized in literature, and as such, we used the distributions suggested by Stagge et al., (2015) for calculation of SPI, distributions suggested by Ryu and Famiglietti, (2005) for calculation of SSMI and distributions suggested by Vicente-Serrano et al., (2012) for calculation of SSI.

Like with fitting a different distribution for each variable, also that fitting a different distribution for each catchment causes differences, especially in the tails (i.e. drought extremes). However, this is only relevant if one is directly comparing drought onset or severity of the same event between catchments. In our case we do not map and analyse the droughts themselves, but instead we look at the propagation in the hydrological system. To do this, we correlated the time series of the meteorological indices with several accumulation periods to the hydrological indices to find the best correspondence. In our opinion, in this case the benefits of having the best fit to the data for each catchment outweigh the differences in extreme droughts between catchments.

Another way to verify our results is the comparison with threshold-based indices. The results of the propagation analysis done with the threshold-based duration ratios is very similar to that based on accumulation periods of standardized indices. This indicates that the distribution fitting is expected to have a minor role.

To give more details about the distribution fitting, we here include some extra analysis. For example looking at the fitting of precipitation data for calculation of SPI-1 for the different catchments, we can see in the figures below that the depiction of the drought months is not different. This was similar for the other indices i.e. SSMI and SSI

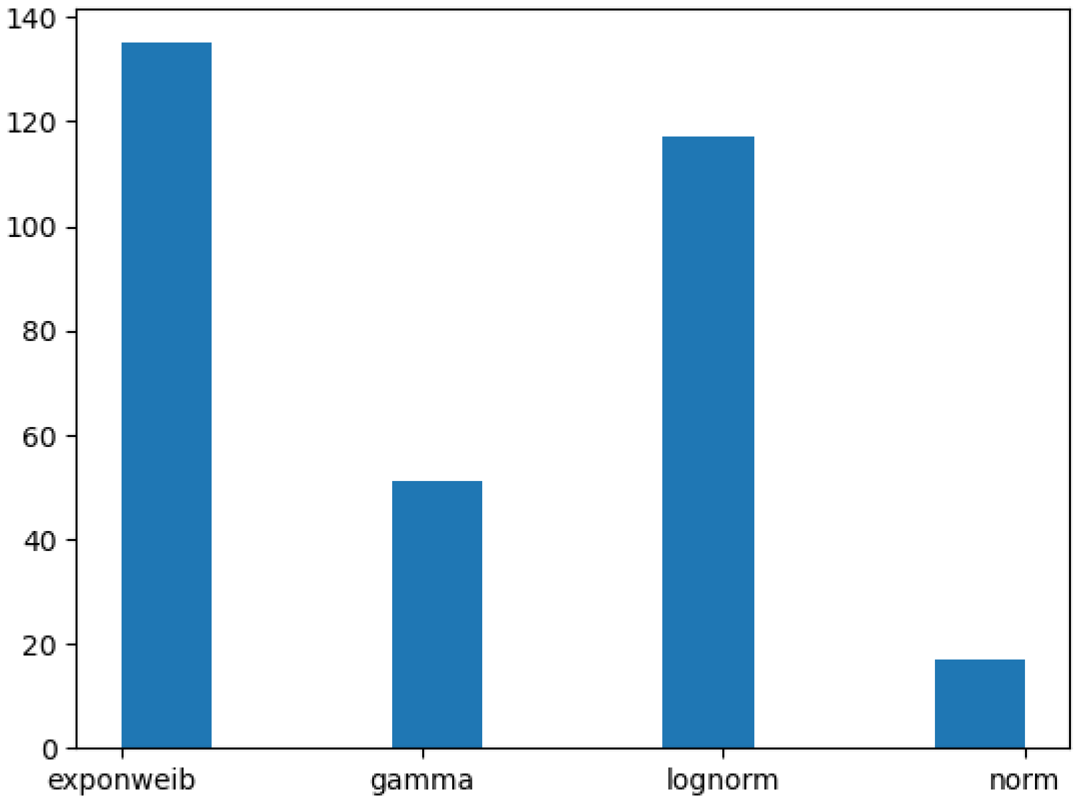


Figure S1: Histogram showing the number of times each distribution was used in the calculation of SPI-1

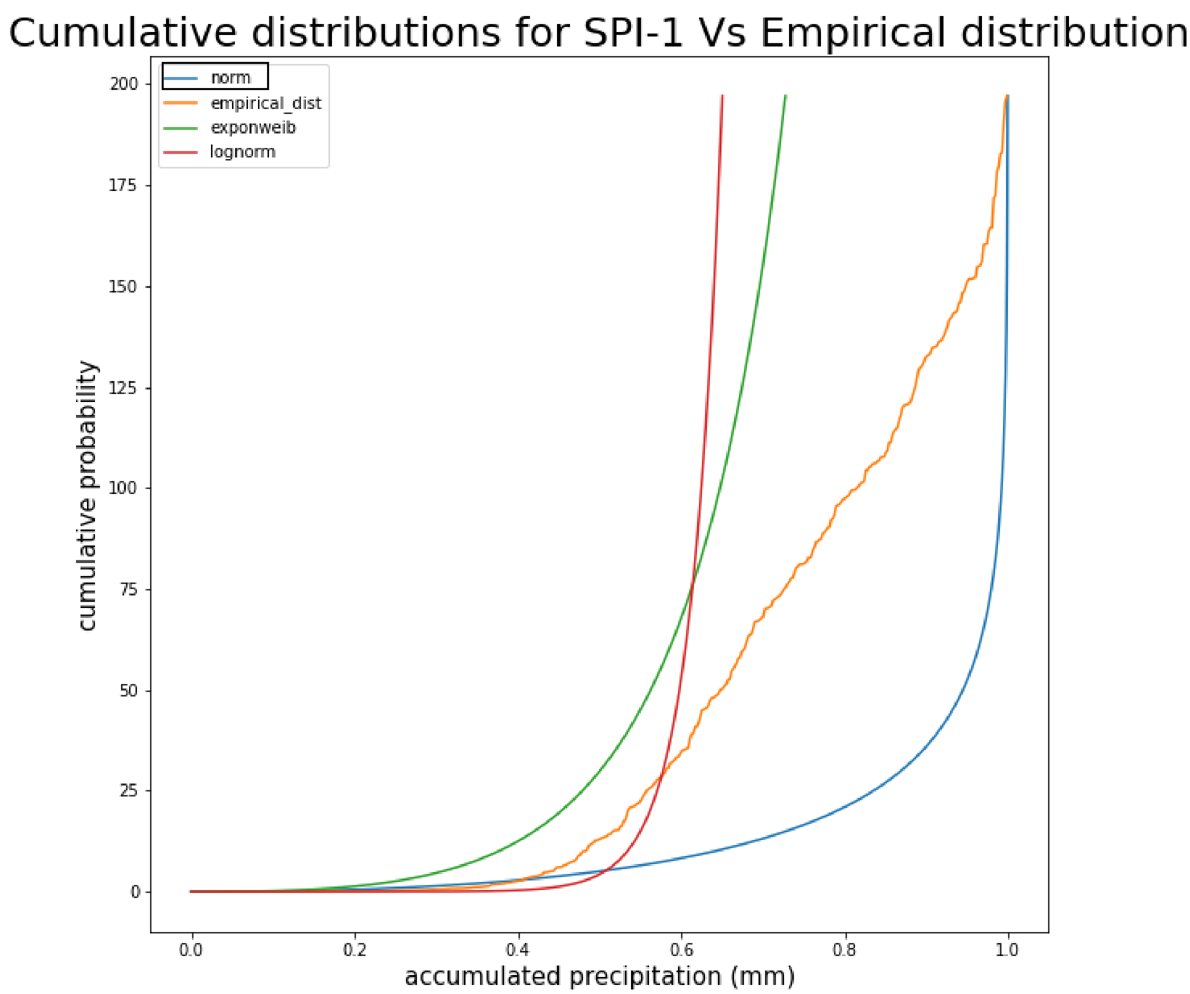


Figure S2: the fitting of the distribution for the calculation of SPI-1 in a catchment in (semi-)arid Ethiopia. The best distribution is framed in black

The fittings for the distributions in the catchments in general were not very good, as shown for one example catchment in Figure S2, hence we decided to not force fit data for each catchment into the same distribution to avoid introducing artifacts. This is because if we do force fit a consistent distribution throughout the catchments, especially in dry catchments with lots of zero values, we anticipate worse fitting distributions and even worse results. Additionally, we are rather more interested in the catchment propagation than the spatial pattern existing among the catchments, because we would like to better identify the droughts accurately within each catchment.

See Figure S3 below for four different catchments.

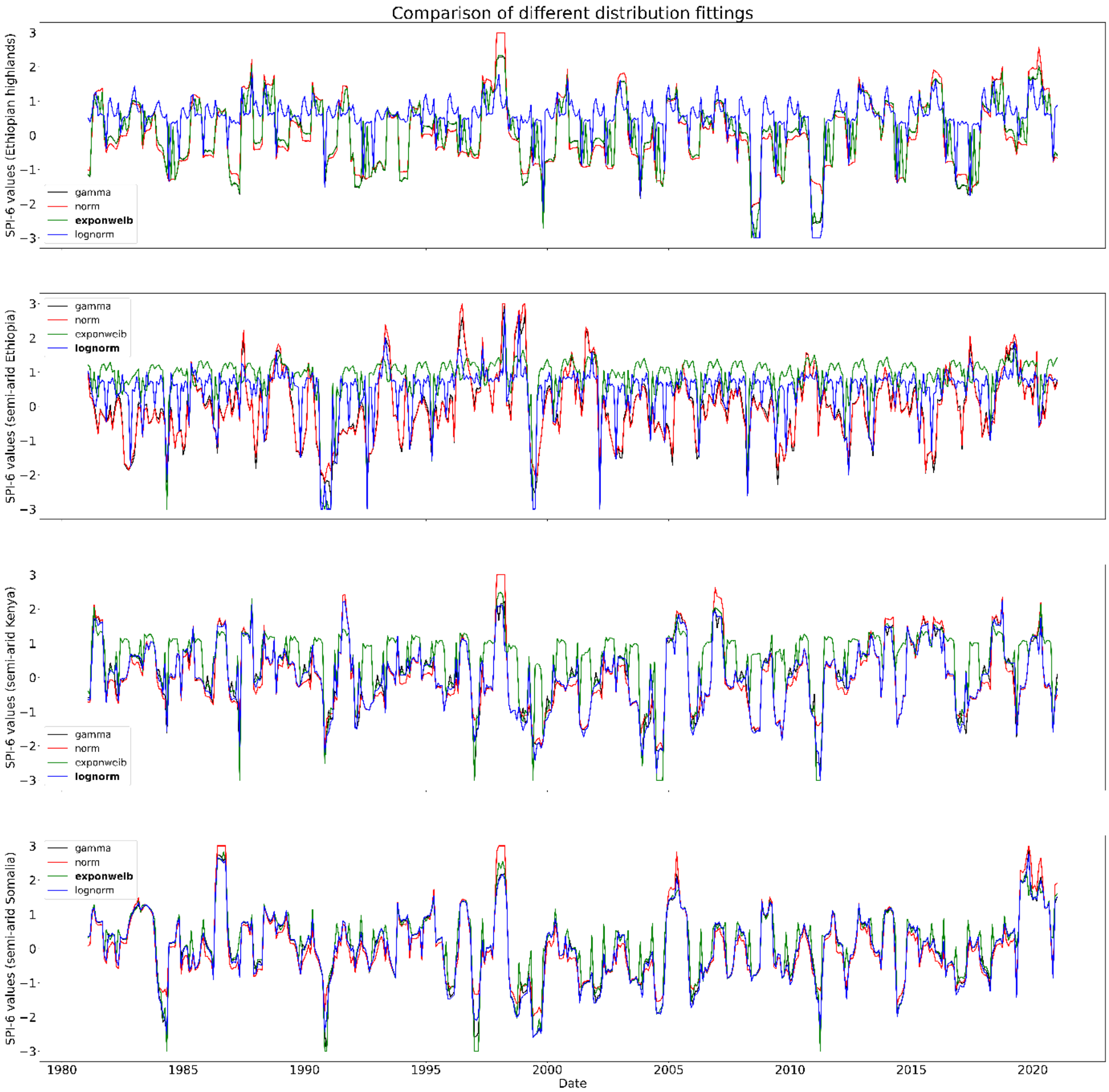


Figure S3: shows the SPI-6 after fitting different distribution through the precipitation data for four catchments (locations indicated on the y-axis). The best distributions are bold

There was a similar representation when looking at the SSMI-3 distribution fitting. There is very minor difference in the distributions (Figure S4). Therefore, we concluded that the use of the different distributions will not affect the results in the long run.

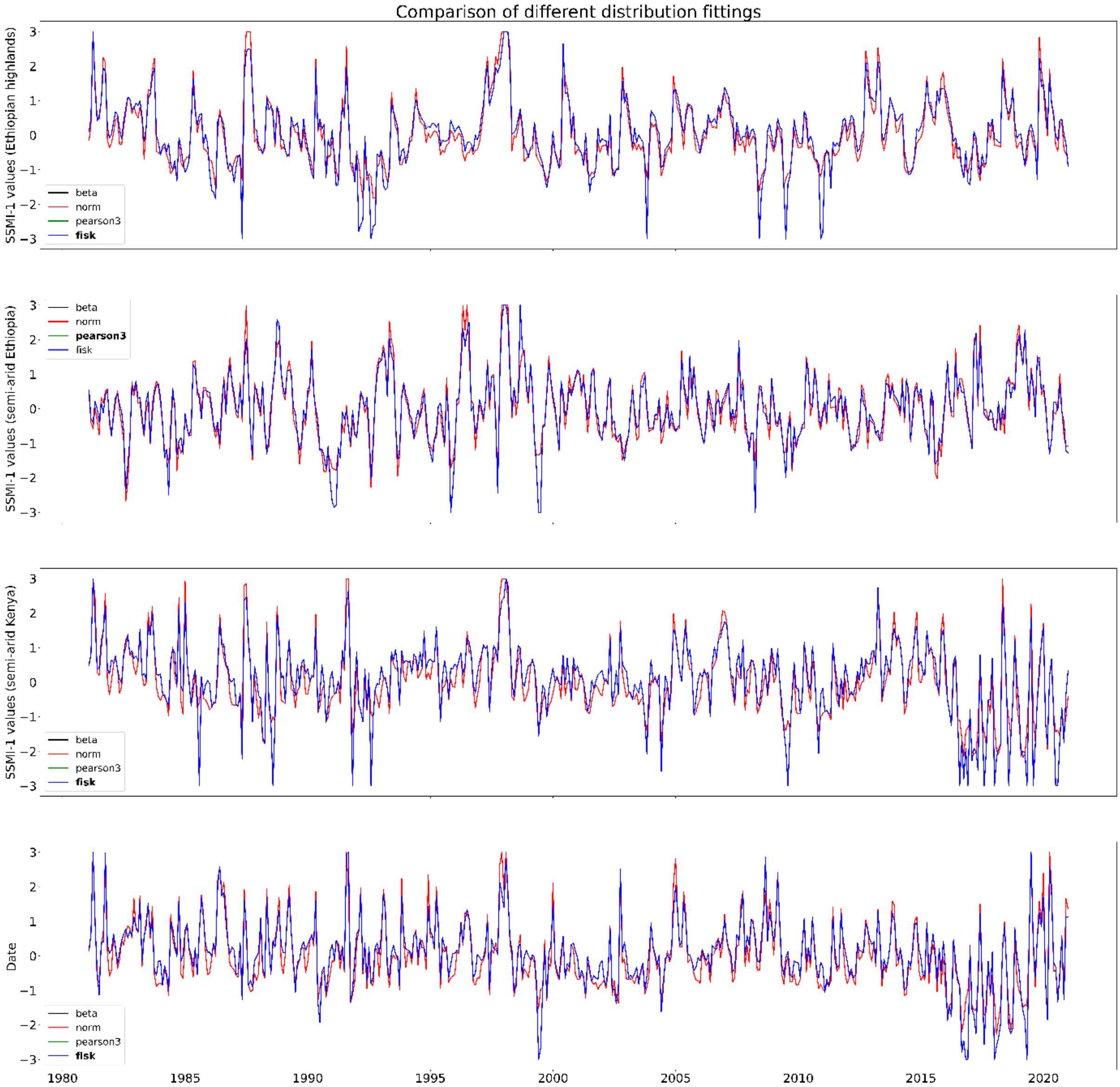


Figure S4: shows the SSMI-1 after fitting different distribution through the soil moisture data for four catchments (locations indicated on the y-axis). The best distributions are in bold.

S2.2 Threshold-based indices

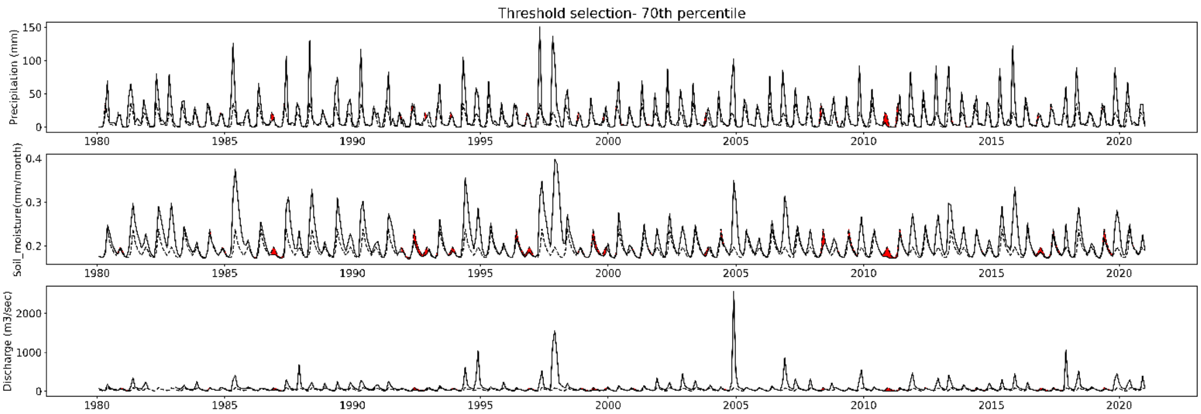


Figure S5: shows the 70th percentile threshold applied to catchment in the (semi-)arid region in Somalia

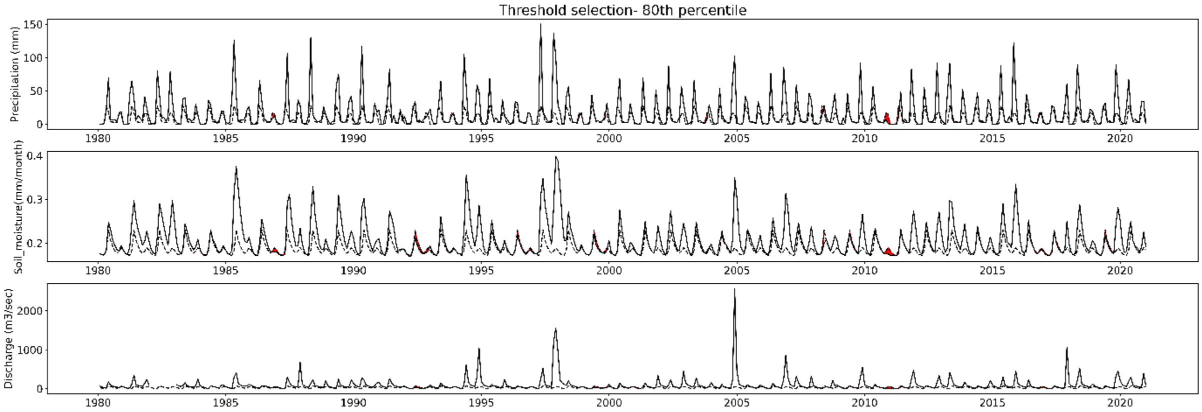


Figure S6: shows the 80th percentile threshold applied to catchment in the (semi-)arid region in Somalia

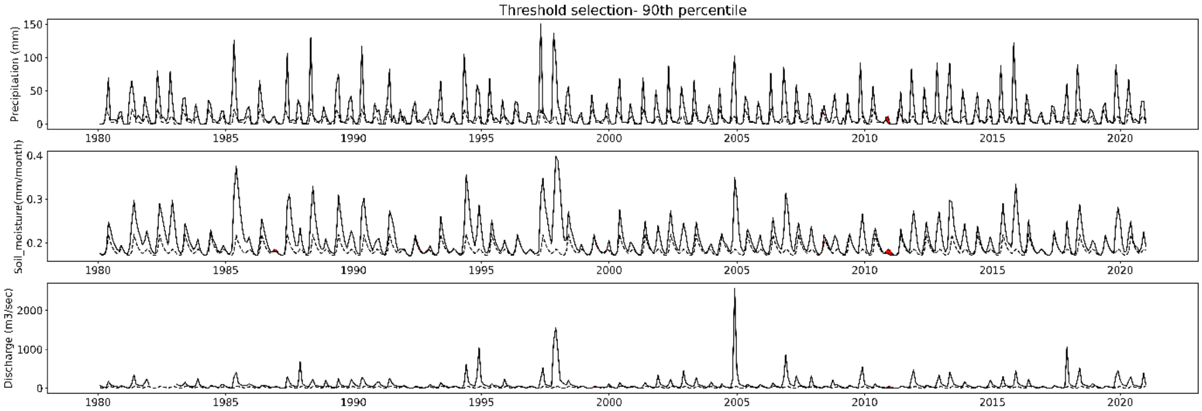


Figure S7: shows the 90th percentile threshold applied to catchment in the (semi-)arid region in Somalia

S3. Results and Discussion

S3.1 Propagation

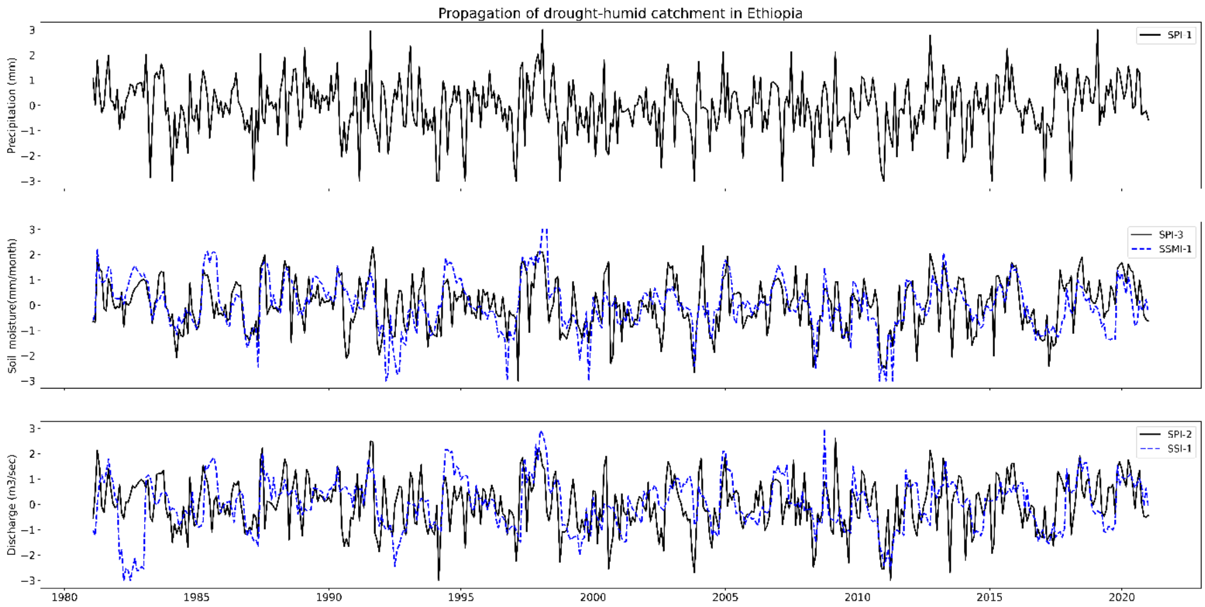


Figure S8 Quantitative time series propagation of the drought signal through the hydrological cycle in a humid catchment in Ethiopia highlands

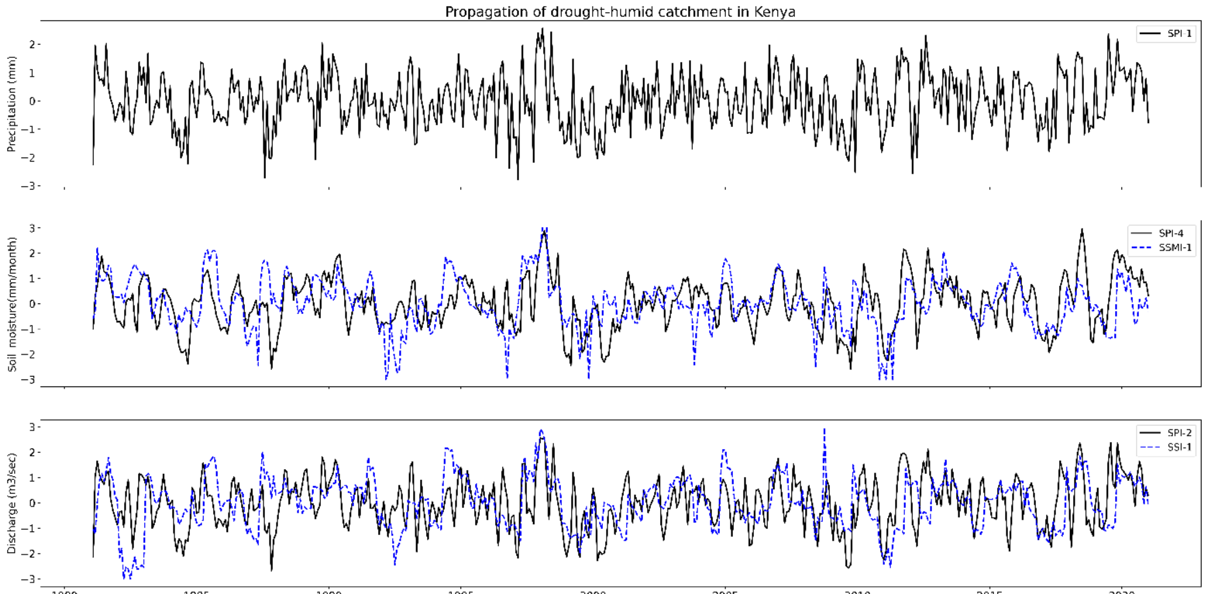


Figure S9: Quantitative time series propagation of the drought signal through the hydrological cycle in a humid catchment in Kenya

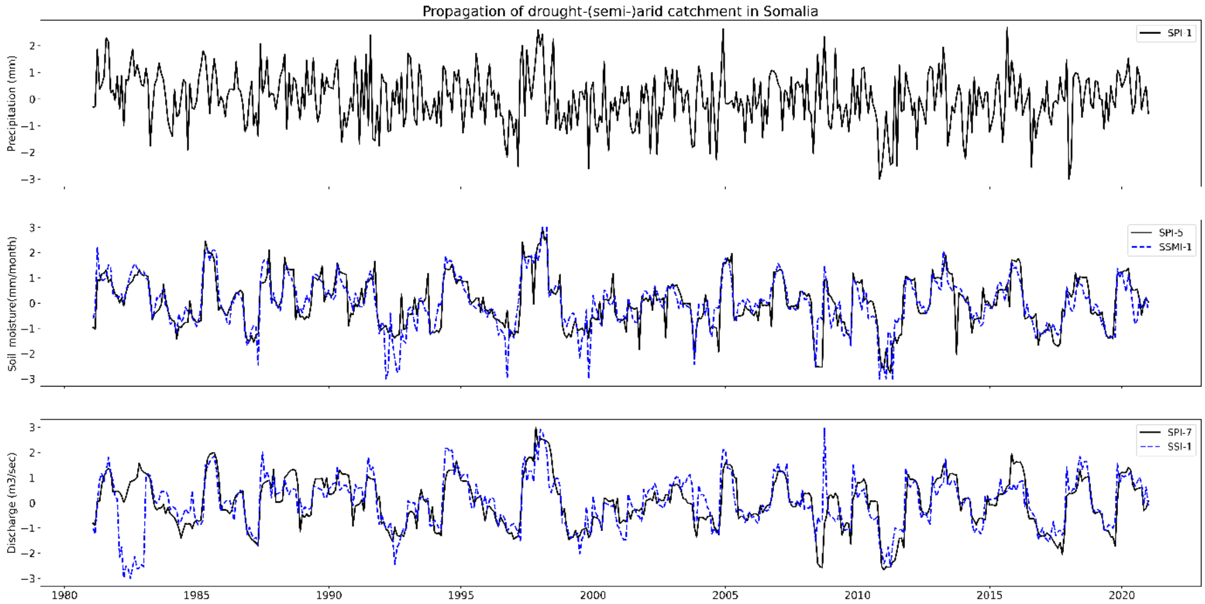
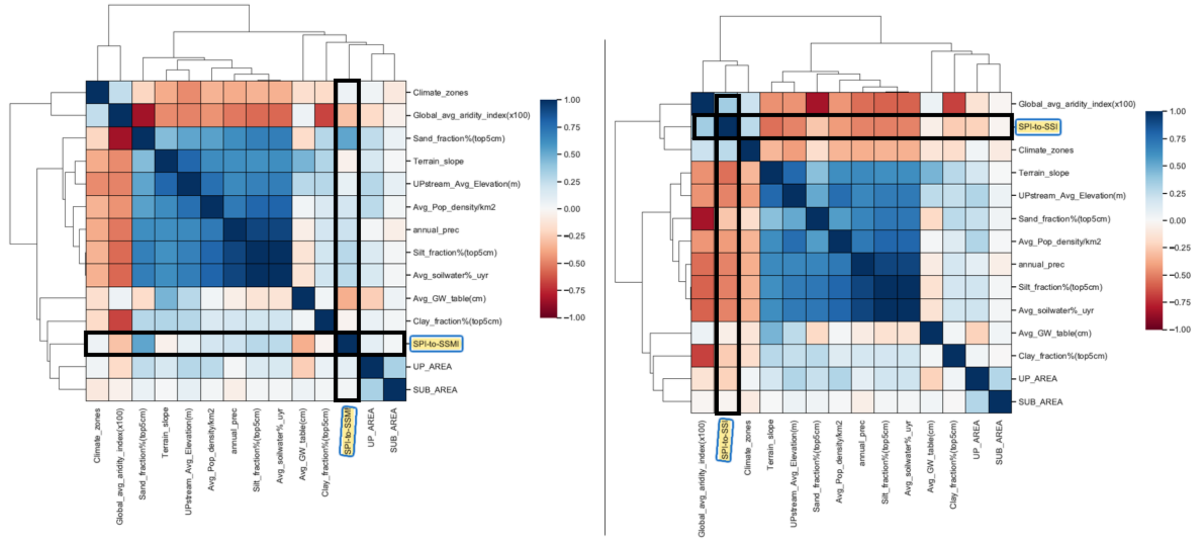


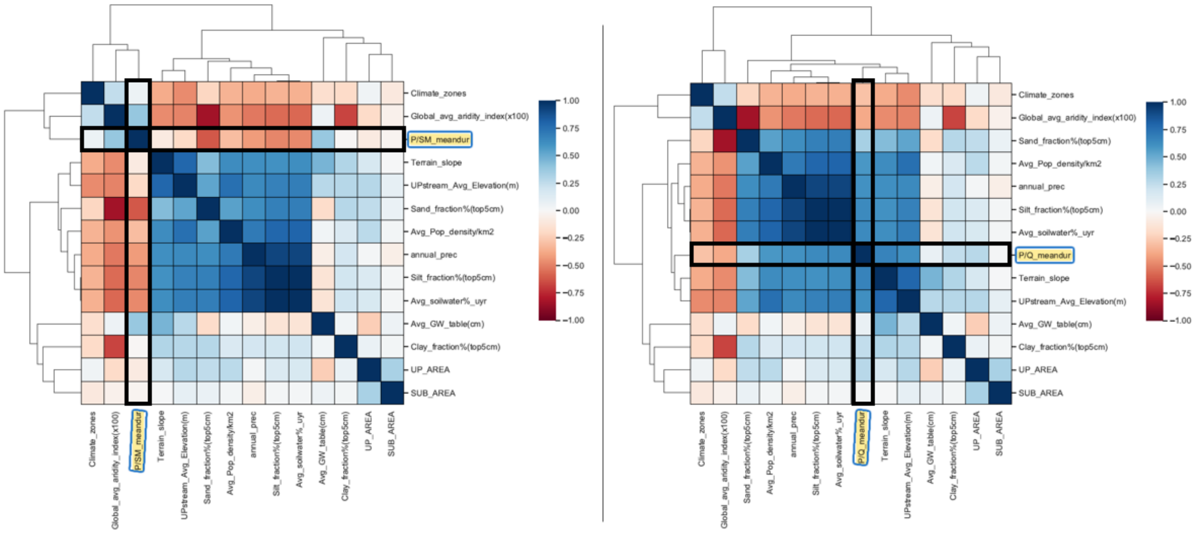
Figure S10: Quantitative time series propagation of the drought signal through the hydrological cycle in a (semi-)arid catchment in Somalia

S3.2 Linking with catchment characteristics



a) b)

Figure S11: Heatmap of Spearman correlations between the propagation indices and catchment characteristics ; a) the SPI-to-SSMI, b) SPI-to-SSI. Euclidean distances used for clustering variables with interchangeable correlations



a) b)

Figure S12: Heatmap of Spearman correlations between the threshold mean duration and catchment characteristics ; a) the P/SM mean duration ratio, b) P/Q mean duration ratio. Euclidean distances used for clustering variables with interchangeable correlations

Table S 2: Mean average accumulation period per average catchment characteristics range based on equal interval (quantile)

	Equal interval (quantile) range	*SPI-to-SSMI*	*SPI-to-SSI*
Terrain slope (degrees)	0-7	4.5	6.2
	7-22.8	4.2	5.9
	22.8-40	4.7	5.2
	40-66.6	4.6	4.0
	66.6-151	4.4	3.4
Global average aridity index (x100)	31-39	4.8	4.2
	39-41	5.5	4.5
	41-45	4.6	4.8
	45-49	4.2	5.9
	49-79	3.4	5.9
Upstream Elevation (meters a.s.l)	3-402	3.9	6.0
	402-731	4.4	6.0
	732-1043	4.7	4.9
	1044-1544	5.1	4.8
	1545-2493	4.3	3.1
Percent sand fraction (%)	11-26	3.1	5.5
	26-29	4.4	5.6
	29-32	4.8	5.1
	32-35	5.1	4.0
	35-40	5.8	4.6
Percent clay fraction (%)	8-23	4.4	6.0
	23-25	4.7	5.0
	25-26	4.5	4.5
	26-27.6	4.7	4.0
	27.6-32	4.2	4.7
Percent silt fraction (%)	0-12	3.1	6.3
	12-21	4.6	5.7
	21-31	5.0	4.4
	31-47.6	5.5	4.9
	47.6-77	4.4	3.2
Average annual soil water content (%)	1-15	3.1	6.3
	15-25	4.6	5.7
	25-37	5.0	4.3
	37-57	5.5	4.9
	57-112	4.3	3.2

Table S 3: Mean average accumulation period per climate zone

Name	**SPI-to-SSMI**	**SPI-to-SSI**
Tropical, rainforest	2.4	4.1
Tropical, monsoon	5.0	2.0
Tropical, savannah	4.8	1.8
Arid, desert, hot	5.1	3.5
Arid, desert, cold	3.9	5.2
Arid, steppe, hot	2.0	5.3
Arid, steppe, cold	5.0	4.3
Temperate, dry summer, hot summer	4.2	2.7
Temperate, dry summer, warm summer	3.7	4.5

Temperate, dry summer, cold summer	4.6	2.5
Temperate, dry winter, warm summer	4.8	0.9
Temperate, dry winter, cold summer	4.0	2.4
Temperate, no dry season, hot summer	3.0	4.0
Temperate, no dry season, cold summer	5.0	2.7
Cold, dry summer, hot summer	5.0	3.0
Polar, tundra	4.7	2.4

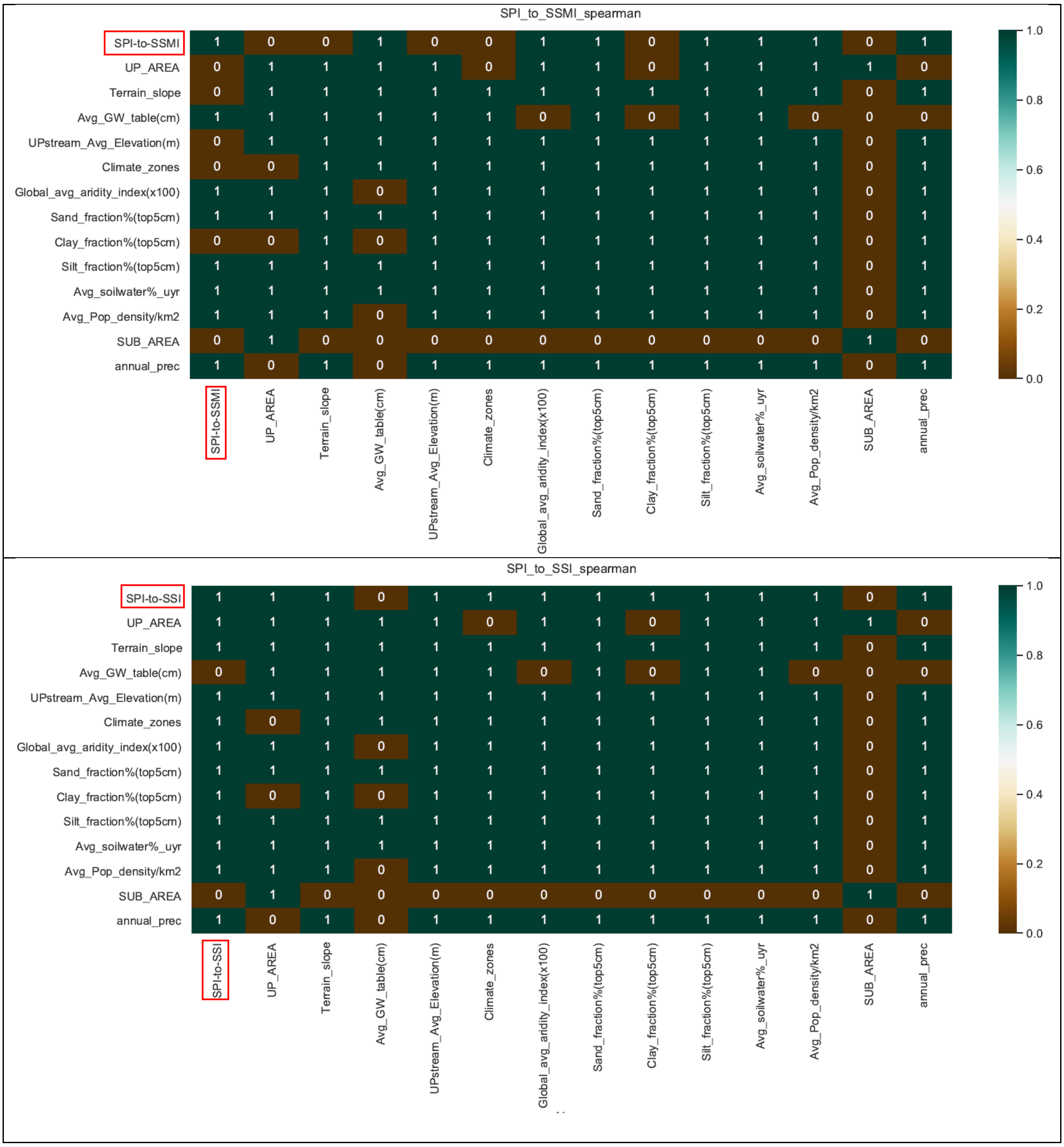
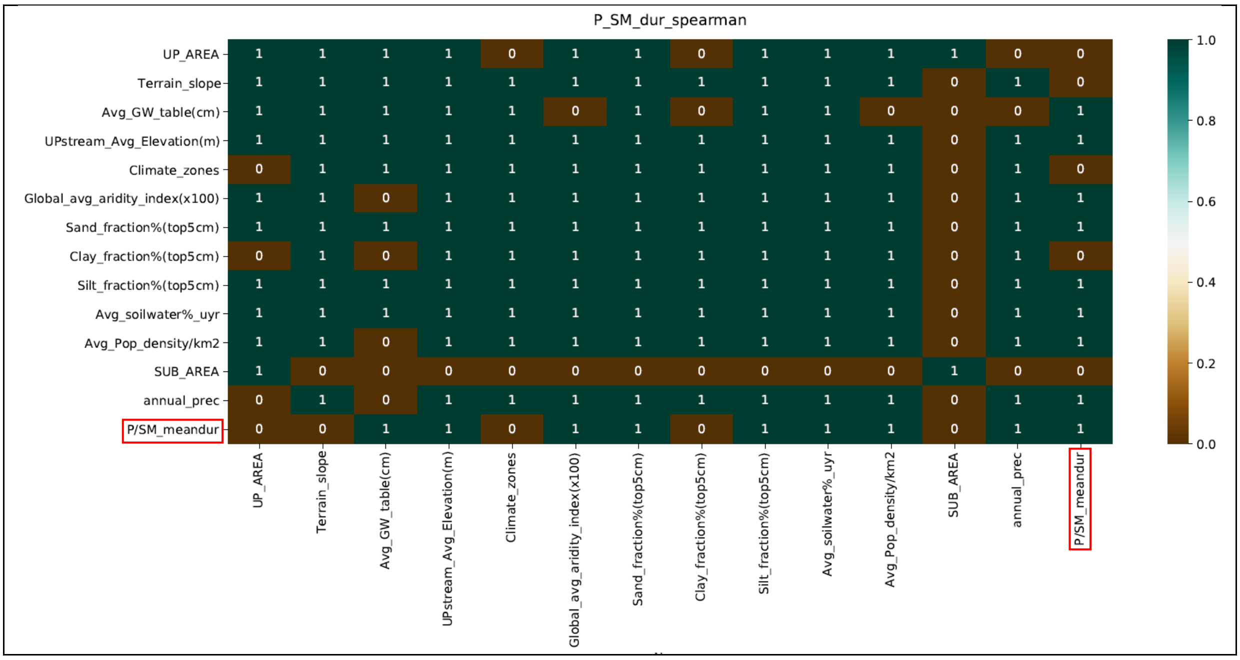


*Figure S13: Spearman significance test for the standardized propagation indices . *1 means significant relationship, *0 no significance*


P_SM_dur_spearman
UP_AREA
Terrain_slope
Avg_GW_table(cm)
UPstream_Avg_Elevation(m)
Climate_zones
Global_avg_aridity_index(x100)
Sand_fraction%(top5cm)
Clay_fraction%(top5cm)
Silt_fraction%(top5cm)
Avg_soilwater%_uyr
Avg_Pop_density/km2
SUB_AREA
annual_prec
P/SM_meandur
1.0
0.8
0.6
0.4
0.2
0.0

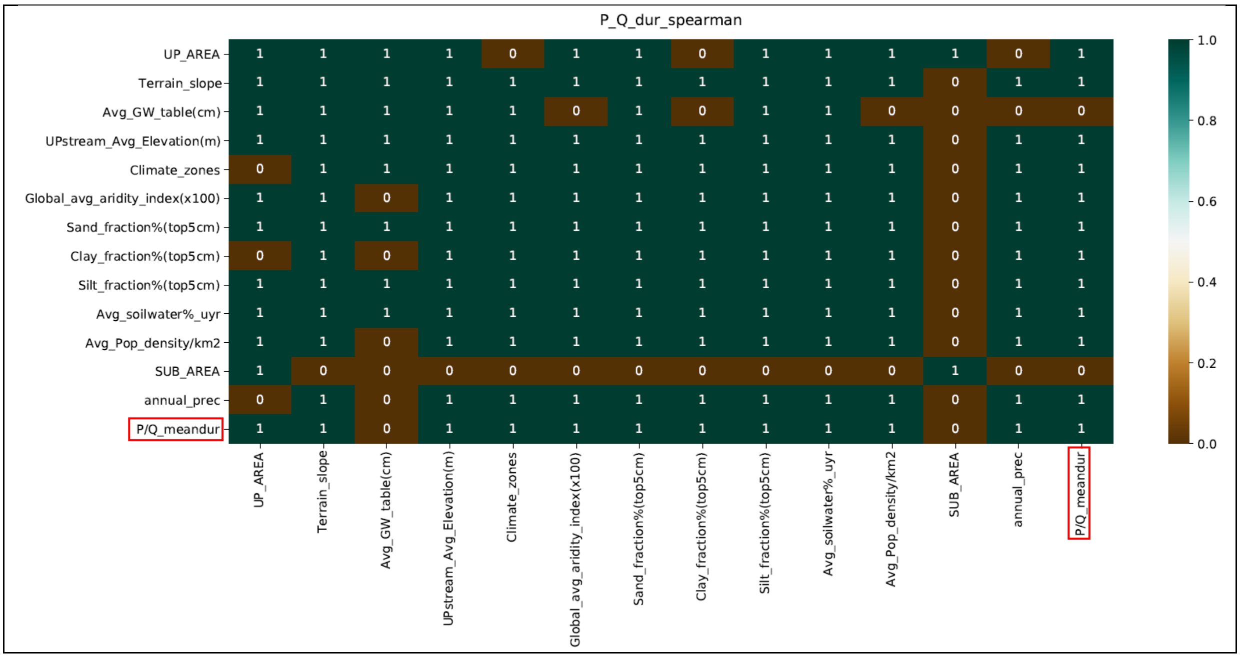


*Figure S14: Spearman significance test for the threshold-based duration indices . *1 means significant relationship, *0 no significance*

Table S 4: T-test significance test of the accumulation periods against catchment characteristics

	Accumulation periods	Upstream area	Terrain slope	Average groundwater table depth (cm)	Percent sand fraction (top5cm)	Upstream mean annual precipitation	Upstream average elevation (m)	Global average aridity index (x100)	Percent clay fraction (top5cm)	Percent silt fraction (top5cm)	Average annual soil water content	Average population density/km2
SPI-to-SSMI	1	0.13	0.17	0.00	0.00	0.00	0.21	0.00	0.00	0.09	0.07	0.03
	2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01
	6	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	7	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	9	0.08	0.01	0.01	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.25
SPI-to-SSI	1	nan	nan	nan	nan	nan	nan	nan	nan	nan	nan	nan
	2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	5	0.06	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	6	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	8	0.01	0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.23
	9	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02
	10	nan	nan	nan	nan	nan	nan	nan	nan	nan	nan	nan
	12	nan	nan	nan	nan	nan	nan	nan	nan	nan	nan	nan

*Table S 5: T-test significance test of the catchments groups per accumulation per catchment characteristics based on the number of pixels occupied by the catchment characteristic. **

			SPI-to-SSMI										SPI-to-SSI								
	Accumulation periods		1	2	3	4	5	6	7	8	9		1	2	3	4	5	6	7	8	9
		Type																			
Geology	1	Crystalline basement	1.00	0.02	0.00	0.16							1.00	0.07	0.02	0.19					
	2	Consolidated sedimentary rocks	0.02	1.00	0.05	0.97							0.07	1.00	0.00	0.98					
	3	Volcanic rocks	0.00	0.05	1.00	0.20							0.02	0.00	1.00	0.00					
	4	Unconsolidate sediments	0.16	0.97	0.20	1.00							0.19	0.98	0.00	1.00					
	5	Surface water																			
Landcover	1	Shrubland	1.00	0.21	0.00		0.01		0.00	0.01	0.04		1.00	0.06	0.00		0.00		0.63	0.04	0.00
	2	Herbaceous vegetation	0.21	1.00	0.23		0.05		0.00	0.03	0.04		0.06	1.00	0.02		0.01		0.02	0.84	0.01
	3	Cropland	0.00	0.23	1.00		0.13		0.00	0.00	0.00		0.00	0.02	1.00		0.13		0.00	0.01	0.15
	4	Built-up																			
	5	Permanent water bodies	0.01	0.05	0.13		1.00		0.02	0.02	0.04		0.00	0.01	0.13				0.00	0.03	0.44
	6	Herbaceous wetland																			
	7	Bare/sparse vegetation	0.00	0.00	0.00		0.02		1.00	0.00	0.00		0.63	0.02	0.00		0.00		1.00	0.03	0.00
	8	Open forests	0.01	0.03	0.00		0.02		0.00	1.00	0.66		0.04	0.84	0.01		0.03		0.03	1.00	0.03
	9	Closed forests	0.04	0.04	0.00		0.04		0.00	0.66	1.00		0.00	0.01	0.15		0.44		0.00	0.03	1.00
	*least pixels builtup and herbaceous wetland																				

*Table S 6: T-test significance test of the catchments groups per accumulation per catchment characteristics. *highlighted characteristics have significant relationship with the propagation from SPI-to-SSI*

SPI-to-SSI										
	Accumulation periods	1	2	3	4	5	6	7	8	9
Upstream area	1	nan	nan	nan	nan	nan	nan	nan	nan	nan
	2	nan	1.00	0.02	0.00	0.37	0.08	0.73	0.02	0.13
	3	nan	0.02	1.00	0.43	0.99	0.00	0.01	0.01	0.03
	4	nan	0.00	0.43	1.00	0.68	0.00	0.00	0.02	0.05
	5	nan	0.37	0.99	0.68	1.00	0.08	0.35	0.41	0.49
	6	nan	0.08	0.00	0.00	0.08	1.00	0.19	0.19	0.56
	7	nan	0.73	0.01	0.00	0.35	0.19	1.00	0.04	0.19
	8	nan	0.02	0.01	0.02	0.41	0.19	0.04	1.00	0.15
	9	nan	0.13	0.03	0.05	0.49	0.56	0.19	0.15	1.00
Terrain slope	1	nan	nan	nan	nan	nan	nan	nan	nan	nan
	2	nan	1.00	0.07	0.38	0.00	0.00	0.00	0.05	0.00
	3	nan	0.07	1.00	0.32	0.00	0.00	0.00	0.27	0.01
	4	nan	0.38	0.32	1.00	0.00	0.00	0.00	0.12	0.01
	5	nan	0.00	0.00	0.00	1.00	0.03	0.21	0.17	0.93
	6	nan	0.00	0.00	0.00	0.03	1.00	0.56	0.01	0.20
	7	nan	0.00	0.00	0.00	0.21	0.56	1.00	0.09	0.46
	8	nan	0.05	0.27	0.12	0.17	0.01	0.09	1.00	0.46
	9	nan	0.00	0.01	0.01	0.93	0.20	0.46	0.46	1.00
Average groundwater table depth (cm)	1	nan	nan	nan	nan	nan	nan	nan	nan	nan
	2	nan	1.00	0.61	0.42	0.48	0.94	0.02	0.77	0.46
	3	nan	0.61	1.00	0.19	0.83	0.68	0.08	0.53	0.29
	4	nan	0.42	0.19	1.00	0.17	0.41	0.00	0.84	0.75
	5	nan	0.48	0.83	0.17	1.00	0.52	0.19	0.52	0.32
	6	nan	0.94	0.68	0.41	0.52	1.00	0.03	0.78	0.50
	7	nan	0.02	0.08	0.00	0.19	0.03	1.00	0.07	0.03
	8	nan	0.77	0.53	0.84	0.52	0.78	0.07	1.00	0.73
	9	nan	0.46	0.29	0.75	0.32	0.50	0.03	0.73	1.00
Percent sand fraction (top5cm)	1	nan	nan	nan	nan	nan	nan	nan	nan	nan
	2	nan	1.00	0.98	0.95	0.00	0.00	0.00	0.37	0.00
	3	nan	0.98	1.00	0.93	0.00	0.00	0.00	0.32	0.00
	4	nan	0.95	0.93	1.00	0.00	0.00	0.00	0.37	0.00
	5	nan	0.00	0.00	0.00	1.00	0.73	0.60	0.35	0.13
	6	nan	0.00	0.00	0.00	0.73	1.00	0.34	0.27	0.16
	7	nan	0.00	0.00	0.00	0.60	0.34	1.00	0.44	0.04
	8	nan	0.37	0.32	0.37	0.35	0.27	0.44	1.00	0.14
	9	nan	0.00	0.00	0.00	0.13	0.16	0.04	0.14	1.00
Upstream mean annual precipitation	1	nan	nan	nan	nan	nan	nan	nan	nan	nan
	2	nan	1.00	0.01	0.38	0.00	0.00	0.00	0.05	0.01
	3	nan	0.01	1.00	0.21	0.00	0.00	0.00	0.56	0.10
	4	nan	0.38	0.21	1.00	0.00	0.00	0.00	0.26	0.07
	5	nan	0.00	0.00	0.00	1.00	0.01	0.25	0.13	0.61
	6	nan	0.00	0.00	0.00	0.01	1.00	0.20	0.00	0.03
	7	nan	0.00	0.00	0.00	0.25	0.20	1.00	0.03	0.23
	8	nan	0.05	0.56	0.26	0.13	0.00	0.03	1.00	0.39
	9	nan	0.01	0.10	0.07	0.61	0.03	0.23	0.39	1.00
Upstream average elevation (m)	1	nan	nan	nan	nan	nan	nan	nan	nan	nan
	2	nan	1.00	0.23	0.27	0.00	0.00	0.00	0.02	0.01
	3	nan	0.23	1.00	0.03	0.00	0.00	0.00	0.05	0.02
	4	nan	0.27	0.03	1.00	0.00	0.00	0.00	0.00	0.00
	5	nan	0.00	0.00	0.00	1.00	0.00	0.22	0.64	0.98
	6	nan	0.00	0.00	0.00	0.00	1.00	0.01	0.01	0.04
	7	nan	0.00	0.00	0.00	0.22	0.01	1.00	0.22	0.50
	8	nan	0.02	0.05	0.00	0.64	0.01	0.22	1.00	0.77
	9	nan	0.01	0.02	0.00	0.98	0.04	0.50	0.77	1.00
Global average aridity index (x100)	1	nan	nan	nan	nan	nan	nan	nan	nan	nan
	2	nan	1.00	0.62	0.43	0.00	0.00	0.00	0.18	0.00
	3	nan	0.62	1.00	0.67	0.00	0.00	0.00	0.02	0.00
	4	nan	0.43	0.67	1.00	0.00	0.00	0.00	0.09	0.00
	5	nan	0.00	0.00	0.00	1.00	0.90	0.97	0.63	0.00
	6	nan	0.00	0.00	0.00	0.90	1.00	0.86	0.63	0.00
	7	nan	0.00	0.00	0.00	0.97	0.86	1.00	0.60	0.00
	8	nan	0.18	0.02	0.09	0.63	0.63	0.60	1.00	0.04
	9	nan	0.00	0.00	0.00	0.00	0.00	0.00	0.04	1.00
Percent clay fraction (top5cm)	1	nan	nan	nan	nan	nan	nan	nan	nan	nan
	2	nan	1.00	0.28	0.19	0.31	0.09	0.23	0.21	0.00
	3	nan	0.28	1.00	0.73	0.07	0.02	0.02	0.04	0.00
	4	nan	0.19	0.73	1.00	0.05	0.01	0.02	0.06	0.00
	5	nan	0.31	0.07	0.05	1.00	0.66	0.97	0.64	0.00
	6	nan	0.09	0.02	0.01	0.66	1.00	0.58	0.81	0.00
	7	nan	0.23	0.02	0.02	0.97	0.58	1.00	0.53	0.00
	8	nan	0.21	0.04	0.06	0.64	0.81	0.53	1.00	0.05
	9	nan	0.00	0.00	0.00	0.00	0.00	0.00	0.05	1.00
Percent silt fraction (top5cm)	1	nan	nan	nan	nan	nan	nan	nan	nan	nan
	2	nan	1.00	0.01	0.13	0.00	0.00	0.00	0.01	0.00
	3	nan	0.01	1.00	0.26	0.00	0.00	0.00	0.11	0.07
	4	nan	0.13	0.26	1.00	0.00	0.00	0.00	0.06	0.04
	5	nan	0.00	0.00	0.00	1.00	0.00	0.80	0.33	0.46
	6	nan	0.00	0.00	0.00	0.00	1.00	0.01	0.00	0.01
	7	nan	0.00	0.00	0.00	0.80	0.01	1.00	0.24	0.36
	8	nan	0.01	0.11	0.06	0.33	0.00	0.24	1.00	0.88
	9	nan	0.00	0.07	0.04	0.46	0.01	0.36	0.88	1.00
Average annual soil water content	1	nan	nan	nan	nan	nan	nan	nan	nan	nan
	2	nan	1.00	0.00	0.48	0.00	0.00	0.00	0.01	0.01
	3	nan	0.00	1.00	0.06	0.00	0.00	0.00	0.08	0.08
	4	nan	0.48	0.06	1.00	0.00	0.00	0.00	0.04	0.04
	5	nan	0.00	0.00	0.00	1.00	0.01	0.84	0.42	0.44
	6	nan	0.00	0.00	0.00	0.01	1.00	0.01	0.01	0.01
	7	nan	0.00	0.00	0.00	0.84	0.01	1.00	0.32	0.34
	8	nan	0.01	0.08	0.04	0.42	0.01	0.32	1.00	0.99
	9	nan	0.01	0.08	0.04	0.44	0.01	0.34	0.99	1.00
Average population density/km2	1	nan	nan	nan	nan	nan	nan	nan	nan	nan
	2	nan	1.00	0.17	0.75	0.00	0.00	0.00	0.93	0.54
	3	nan	0.17	1.00	0.31	0.01	0.00	0.02	0.59	0.79
	4	nan	0.75	0.31	1.00	0.00	0.00	0.00	0.95	0.68
	5	nan	0.00	0.01	0.00	1.00	0.05	0.45	0.04	0.00
	6	nan	0.00	0.00	0.00	0.05	1.00	0.01	0.00	0.00
	7	nan	0.00	0.02	0.00	0.45	0.01	1.00	0.05	0.01
	8	nan	0.93	0.59	0.95	0.04	0.00	0.05	1.00	0.83
	9	nan	0.54	0.79	0.68	0.00	0.00	0.01	0.83	1.00

*Table S 7: T-test significance test of the catchments groups per accumulation per catchment characteristics. *highlighted characteristics have significant relationship with the propagation from SPI-to-SSMI*

		SPI-to-SSMI								
	Accumulation periods	1	2	3	4	5	6	7	8	9
Upstream area	1	1.00	0.71	0.12	0.19	0.37	0.21	0.31	0.90	0.65
	2	0.71	1.00	0.00	0.01	0.04	0.00	0.25	0.54	0.85
	3	0.12	0.00	1.00	0.05	0.84	0.31	0.14	0.04	0.26
	4	0.19	0.01	0.05	1.00	0.10	0.00	0.40	0.08	0.40
	5	0.37	0.04	0.84	0.10	1.00	0.38	0.38	0.24	0.51
	6	0.21	0.00	0.31	0.00	0.38	1.00	0.18	0.10	0.34
	7	0.31	0.25	0.14	0.40	0.38	0.18	1.00	0.12	0.62
	8	0.90	0.54	0.04	0.08	0.24	0.10	0.12	1.00	0.31
	9	0.65	0.85	0.26	0.40	0.51	0.34	0.62	0.31	1.00
Terrain slope	1	1.00	0.11	0.00	0.04	0.22	0.17	0.00	0.01	0.09
	2	0.11	1.00	0.00	0.13	0.96	0.97	0.00	0.03	0.53
	3	0.00	0.00	1.00	0.00	0.00	0.00	0.71	0.14	0.14
	4	0.04	0.13	0.00	1.00	0.10	0.08	0.00	0.30	0.96
	5	0.22	0.96	0.00	0.10	1.00	0.93	0.00	0.09	0.66
	6	0.17	0.97	0.00	0.08	0.93	1.00	0.00	0.05	0.58
	7	0.00	0.00	0.71	0.00	0.00	0.00	1.00	0.05	0.04
	8	0.01	0.03	0.14	0.30	0.09	0.05	0.05	1.00	0.44
	9	0.09	0.53	0.14	0.96	0.66	0.58	0.04	0.44	1.00
Average groundwater table depth (cm)	1	1.00	0.91	0.13	0.00	0.00	0.00	0.09	0.01	0.11
	2	0.91	1.00	0.01	0.00	0.00	0.00	0.01	0.00	0.01
	3	0.13	0.01	1.00	0.00	0.00	0.00	0.55	0.00	0.14
	4	0.00	0.00	0.00	1.00	0.41	0.65	0.03	0.80	0.77
	5	0.00	0.00	0.00	0.41	1.00	0.76	0.01	0.90	0.55
	6	0.00	0.00	0.00	0.65	0.76	1.00	0.01	0.98	0.64
	7	0.09	0.01	0.55	0.03	0.01	0.01	1.00	0.02	0.21
	8	0.01	0.00	0.00	0.80	0.90	0.98	0.02	1.00	0.64
	9	0.11	0.01	0.14	0.77	0.55	0.64	0.21	0.64	1.00
Percent sand fraction (top5cm)	1	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	2	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	3	0.00	0.00	1.00	0.20	0.61	0.12	0.00	0.00	0.11
	4	0.00	0.00	0.20	1.00	0.02	0.00	0.00	0.00	0.03
	5	0.00	0.00	0.61	0.02	1.00	0.16	0.00	0.00	0.09
	6	0.00	0.00	0.12	0.00	0.16	1.00	0.01	0.00	0.20
	7	0.00	0.00	0.00	0.00	0.00	0.01	1.00	0.03	0.73
	8	0.00	0.00	0.00	0.00	0.00	0.00	0.03	1.00	0.22
	9	0.00	0.00	0.11	0.03	0.09	0.20	0.73	0.22	1.00
Upstream mean annual precipitation	1	1.00	0.35	0.00	0.01	0.03	0.01	0.00	0.00	0.01
	2	0.35	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	3	0.00	0.00	1.00	0.04	0.00	0.00	0.88	0.59	0.99
	4	0.01	0.00	0.04	1.00	0.11	0.00	0.13	0.48	0.39
	5	0.03	0.00	0.00	0.11	1.00	0.08	0.01	0.10	0.13
	6	0.01	0.00	0.00	0.00	0.08	1.00	0.00	0.00	0.00
	7	0.00	0.00	0.88	0.13	0.01	0.00	1.00	0.38	0.91
	8	0.00	0.00	0.59	0.48	0.10	0.00	0.38	1.00	0.61
	9	0.01	0.00	0.99	0.39	0.13	0.00	0.91	0.61	1.00
Upstream average elevation (m)	1	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	2	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03
	3	0.00	0.00	1.00	0.00	0.00	0.00	0.60	0.01	0.08
	4	0.00	0.00	0.00	1.00	0.03	0.08	0.05	0.47	0.63
	5	0.00	0.00	0.00	0.03	1.00	0.87	0.00	0.79	0.88
	6	0.00	0.00	0.00	0.08	0.87	1.00	0.00	0.85	0.93
	7	0.00	0.00	0.60	0.05	0.00	0.00	1.00	0.00	0.02
	8	0.00	0.00	0.01	0.47	0.79	0.85	0.00	1.00	0.97
	9	0.00	0.03	0.08	0.63	0.88	0.93	0.02	0.97	1.00
Global average aridity index (x100)	1	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	2	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.11
	3	0.00	0.00	1.00	0.06	0.03	0.46	0.08	0.06	0.79
	4	0.00	0.00	0.06	1.00	0.88	0.10	0.00	0.00	0.63
	5	0.00	0.00	0.03	0.88	1.00	0.06	0.00	0.00	0.56
	6	0.00	0.00	0.46	0.10	0.06	1.00	0.00	0.00	0.99
	7	0.00	0.00	0.08	0.00	0.00	0.00	1.00	0.85	0.02
	8	0.00	0.00	0.06	0.00	0.00	0.00	0.85	1.00	0.01
	9	0.00	0.11	0.79	0.63	0.56	0.99	0.02	0.01	1.00
Percent clay fraction (top5cm)	1	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03
	2	0.00	1.00	0.01	0.07	0.86	0.34	0.07	0.42	0.34
	3	0.00	0.01	1.00	0.16	0.00	0.01	0.70	0.24	0.00
	4	0.00	0.07	0.16	1.00	0.01	0.25	0.26	0.89	0.05
	5	0.00	0.86	0.00	0.01	1.00	0.14	0.02	0.27	0.27
	6	0.00	0.34	0.01	0.25	0.14	1.00	0.04	0.61	0.04
	7	0.00	0.07	0.70	0.26	0.02	0.04	1.00	0.16	0.00
	8	0.00	0.42	0.24	0.89	0.27	0.61	0.16	1.00	0.03
	9	0.03	0.34	0.00	0.05	0.27	0.04	0.00	0.03	1.00
Percent silt fraction (top5cm)	1	1.00	0.95	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	2	0.95	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	3	0.00	0.00	1.00	0.16	0.01	0.00	0.19	0.62	0.89
	4	0.00	0.00	0.16	1.00	0.12	0.00	0.02	0.14	0.46
	5	0.00	0.00	0.01	0.12	1.00	0.05	0.00	0.02	0.20
	6	0.00	0.00	0.00	0.00	0.05	1.00	0.00	0.00	0.00
	7	0.00	0.00	0.19	0.02	0.00	0.00	1.00	0.30	0.43
	8	0.00	0.00	0.62	0.14	0.02	0.00	0.30	1.00	0.67
	9	0.00	0.00	0.89	0.46	0.20	0.00	0.43	0.67	1.00
Average annual soil water content	1	1.00	0.88	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	2	0.88	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	3	0.00	0.00	1.00	0.06	0.00	0.00	0.47	0.73	0.73
	4	0.00	0.00	0.06	1.00	0.07	0.00	0.03	0.37	0.69
	5	0.00	0.00	0.00	0.07	1.00	0.03	0.00	0.05	0.28
	6	0.00	0.00	0.00	0.00	0.03	1.00	0.00	0.00	0.00
	7	0.00	0.00	0.47	0.03	0.00	0.00	1.00	0.20	0.35
	8	0.00	0.00	0.73	0.37	0.05	0.00	0.20	1.00	0.72
	9	0.00	0.00	0.73	0.69	0.28	0.00	0.35	0.72	1.00
Average population density/km2	1	1.00	0.87	0.00	0.11	0.47	0.31	0.00	0.03	0.16
	2	0.87	1.00	0.00	0.00	0.07	0.01	0.00	0.00	0.00
	3	0.00	0.00	1.00	0.19	0.98	0.09	0.73	0.01	0.06
	4	0.11	0.00	0.19	1.00	0.47	0.44	0.62	0.28	0.39
	5	0.47	0.07	0.98	0.47	1.00	0.35	0.92	0.54	0.65
	6	0.31	0.01	0.09	0.44	0.35	1.00	0.43	0.61	0.64
	7	0.00	0.00	0.73	0.62	0.92	0.43	1.00	0.03	0.08
	8	0.03	0.00	0.01	0.28	0.54	0.61	0.03	1.00	0.63
	9	0.16	0.00	0.06	0.39	0.65	0.64	0.08	0.63	1.00

**1,10,12 Accumulation periods only had single catchments hence Nan values in the t-test*

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