Supplementary information

Drought decreases streamflow response to precipitation especially in arid regions

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Method – Mixed effect panel data model

Regression equations used in the mixed effect panel data model:

$$(\frac{Q}{P})_{ct} = (\alpha + \alpha_c) + \sum_i^p (\beta_i + \beta_{ic}) * D_{iD_{(t)}} + \varepsilon \quad (1)$$

$$\sum_i^p D_{iD_{(t)}} = D_{M_{D\,(t)}} + D_{SM_{D\ (t)}} + D_{HY_{D\ (t)}} + D_{NDVI_{D\ (t)}} \quad (2)$$

$$(\frac{Q}{P})_{ct} = (\alpha + \alpha_c) + \sum_i^p (\beta_i + \beta_{ic}) * D_{iSV_{(t)}} + \varepsilon \quad (3)$$

$$\sum_i^p D_{iSV_{(t)}} = D_{M_{SV\,(t)}} + D_{SM_{SV\ (t)}} + D_{HY_{SV\ (t)}} + D_{NDVI_{SV\ (t)}} \quad (4)$$

$$(\frac{Q}{P})_{ct} = (\alpha + \alpha_c) + \sum_i^p (\beta_i + \beta_{ic}) * D_{iSV_{(t)}} + \sum_i^p (\gamma_i + \gamma_{ic}) * D_{iSV_{(t-1)}} + \varepsilon \quad (5)$$

$$\sum_i^p D_{iSV_{(t-1)}} = D_{M_{SV\,(t-1)}} + D_{SM_{SV\ (t-1)}} + D_{HY_{SV\ (t-1)}} + D_{NDVI_{SV\ (t-1)}} \quad (6)$$

$$(\frac{Q}{P})_{ct} = (\alpha + \alpha_c) + \sum_z^n (\beta_z + \beta_{zc}) * D_{zSV_{(t)}} + \varepsilon \quad (7)$$

$$\sum_z^p D_{z_{(t)}} = D_{M_{SV\,(t)}} + D_{SM_{SV\ (t)}} + D_{STR_{SV\ (t)}} + D_{SW_{SV\ (t)}} + D_{TWS_{SV\ (t)}} + D_{NDVI_{SV\ (t)}} \quad (8)$$

Where:

$(\frac{Q}{P})_{ct}$: Ratio between average streamflow [mm/d] and precipitation [mm/d] calculated for the year t in catchment *c*;

α: Intercept;

D_{i_D}: Max cumulative drought duration in a year [number of drought months in a year] (M: meteorological; SM: soil moisture, HY: hydrological drought);

$D_{i_{SV}}$: Max cumulative drought severity *i* in a year (*i* is M: meteorological; SM: soil moisture, HY: hydrological drought);

$D_{z_{SV}}$: Max cumulative drought severity *z* in a year (*z* is M: meteorological; SM: soil moisture; STR: streamflow; SW: surface water extent; TWS: total water storage and NDVI anomalies);

β_i: Unique effect of drought on the ratio between streamflow and precipitation;

ε: Error term.

Variables were standardized by subtracting the catchment mean and dividing by the standard deviation, ensuring consistency in units and facilitating comparisons across coefficients.

Method – Trend analysis

We applied linear and quadratic models using generic *lm* functions in R (the former also without a slope term to check the fit without a trend). and a step model using the R package *chngpt* (Fong et al., 2017). This package is designed to work with threshold regression models, also known as regime-switching models, with the aim of modelling the relationship between variables that change at a certain threshold (i.e., change point). Within the analysed time period, multiple state transitions might occur.

By using the *chngpt* package, we only investigated the largest transition that occurred within the analysed time frame.

Tables

Table S1 – Spatial resolution and temporal coverage of the data used in this study

Dataset	Temporal resolution	Spatial resolution	Temporal coverage
In-situ river streamflow data – GSIM (Do et al., 2018; Gudmundsson et al., 2018)	Daily statistics per month (MAX, MIN, MEAN)	nodes (catchment outlets/ hydrometric stations)	Varying (1900 - 2016)
Precipitation – MSWEP (Beck et al., 2019)	monthly	11 km	1979 - 2022
Soil Moisture - GLEAM (Global Land Evaporation Amsterdam Model) v3.6a (Martens et al., 2017)	monthly	25 km	1980 - 2020
Surface water extent (Global Surface Water) (Donchyts et al., 2016)	monthly	polygons/ centroids	1984-2020
No noise (smoothed) Normalized Difference Vegetation Index (NOAA, 2022)	7-day composite	4km	1981 - 2022
Total Water Storage (TWS) anomaly is computed as standardized deviation of the GRACE satellite Liquid Water Equivalent (GRACE) (Boergens et al., 2019)	monthly	50 km	2002 - 2020

Table S2. Fixed effects of the mixed panel data model with max consecutive severity and max consecutive duration as independent variables (Equation 1 and 2). Significant result are indicated with asterisks: * p < 0.1;** p < 0.01; *** p < 0.001.

Anomalies	**Severity** (max severity accounting for consecutive anomalies)	**Severity** (max of that year)	**Duration** (max duration accounting for consecutive anomalies)
Meteorological	-0.160*** (0.003)	-0.113*** (0.003)	-0.132*** (0.003)
Soil Moisture	-0.201*** (0.005)	-0.209 *** (0.004)	-0.202*** (0.004)
Hydrological	-0.277*** (0.005)	-0.266*** (0.003)	-0.263*** (0.005)
NDVI	0.065***	0.035***	0.062***

	(0.003)	(0.004)	(0.003)
num. obs.			142974

Table S3. Fixed effects from the mixed effect panel data model. Significant results are indicated with asterisks: * p < 0.1;** p < 0.01; *** p < 0.001.

Anomalies	**Severity** (max of that year)
Meteorological	-0.114*** (0.003)
Soil Moisture	-0.207*** (0.004)
Hydrological	-0.264*** (0.003)
NDVI	0.036*** (0.002)
Meteorological lag 1	-0.039*** (0.002)
Soil Moisture lag 1	-0.019*** (0.003)
Hydrological lag 1	-0.002 (0.003)
NDVI lag 1	0.023*** (0.002)
num. obs.	142974

Table S4. Fixed effects of the mixed panel data model and effects from the fixed panel data model with max severity as independent variables (Equation 4). For this analysis, we only considered the period between 2002 to 2016 to guarantee overlap among the variables. Significant result are indicated with asterisks: * p < 0.1;** p < 0.01; *** p < 0.001.

	Severity (max severity in a year)	
Anomalies	Mixed panel data model	Fixed panel data model
Meteorological	-0.134*** (0.002)	-0.131*** (0.011)
Soil Moisture	-0.220*** (0.015)	-0.223*** (0.015)
Streamflow	-0.241*** (0.013)	-0.247*** (0.013)
Total water storage	-0.139*** (0.009)	-0.128*** (0.020)
Surface water extent	- 0.010 (0.011)	-0.009 (0.014)
NDVI	- 0.020* (0.005)	- 0.016 (0.016)
num. obs.	142974	

Table S5. Fixed effect panel data model with clustered standard errors. Significant results are indicated with asterisks: * p < 0.1;** p < 0.01; *** p < 0.001.

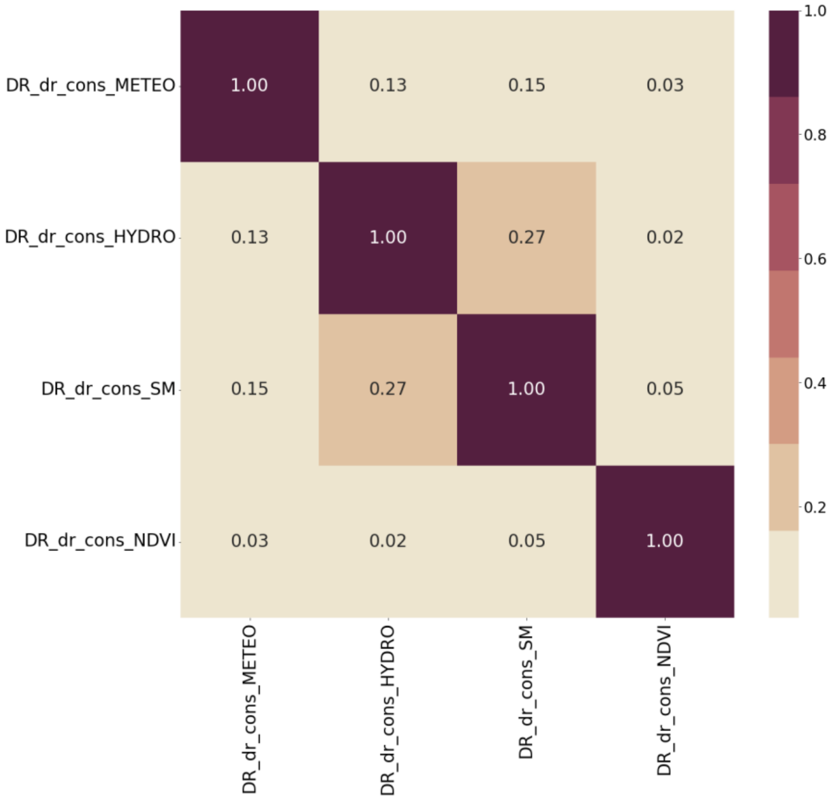
Anomalies		**Severity** (max of that year)				
	All	*Arid*	*Equatorial*	*Warm Temperate*	*Snow*	*Polar*
Meteorological	-0.113*** (0.0029)	-0.159*** (0.0116)	-0.077*** (0.008)	-0.115*** (0.005)	-0.126*** (0.005)	0.053*** (0.019)
Soil Moisture	-0.206*** (0.0037)	-0.310*** (0.0099)	-0.189*** (0.011)	-0.234*** (0.006)	-0.179*** (0.006)	-0.073*** (0.023)
Hydrological	-0.264*** (0.0032)	-0.226*** (0.011)	-0.280*** (0.008)	-0.285*** (0.005)	-0.254*** (0.005)	-0.177*** (0.025)
NDVI	0.035*** (0.0037)	-0.028** (0.013)	0.036*** (0.011)	0.048*** (0.006)	0.034*** (0.006)	0.055** (0.023)
Meteorological lag 1	-0.039*** (0.010)	-0.057*** (0.010)	-0.024** (0.007)	-0.026*** (0.005)	-0.051*** (0.004)	-0.015 (0.025)
Soil Moisture lag 1	-0.019*** (0.002)	-0.021* (0.012)	-0.013 (0.009)	-0.027*** (0.006)	-0.013* (0.006)	-0.031 (0.023)
Hydrological lag 1	-0.002 (0.021)	-0.001 (0.0113)	0.137 (0.093)	0.003 (0.005)	0.579 (0.005)	-0.019 (0.022)
NDVI lag 1	0.023*** (0.011)	0.001 (0.011)	0.034*** (0.009)	0.016** (0.005)	0.032*** (0.005)	-0.014 (0.023)
num. obs.	142974	10765	18906	53598	55817	3200

Table S6. Characteristics of catchments in north-west Brazil that experienced a change step in the Q/P relationship during the 2011 drought.

gsim.no	**Log.org**	**lat.org**	**area.est [km2]**	**climate.type**	**sto.volume [km3]**	**ele.min [m. amsl]**	**ele.max [m. amsl]**	**landcover.type**	**Q/P shift**
BR_0000495	-471.167	-16.522	360.891	Equatorial	0.0	0.0	94.0	Agriculture	Positive
BR_0000623	-405.492	-43.775	1.606.527	Equatorial	0.0	0.0	1074.0	Forest	Negative
BR_0000649	-395.086	-65.578	3.532.893	Arid	0.0	0.0	899.0	No dominant class	Negative
BR_0000659	-386.331	-58.997	39537.25	Arid	2695.0	0.0	998.0	No dominant class	Negative
BR_0000778	-363.036	-100.311	1.484.357	Arid	0.0	0.0	631.0	Agriculture	Negative

Figures

a.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DR_dr_cons_HYDRO
DR_dr_cons_SM
DR_dr_cons_NDVI
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0.13 1.00 0.27 0.02
0.15 0.27 1.00 0.05
0.03 0.02 0.05 1.00
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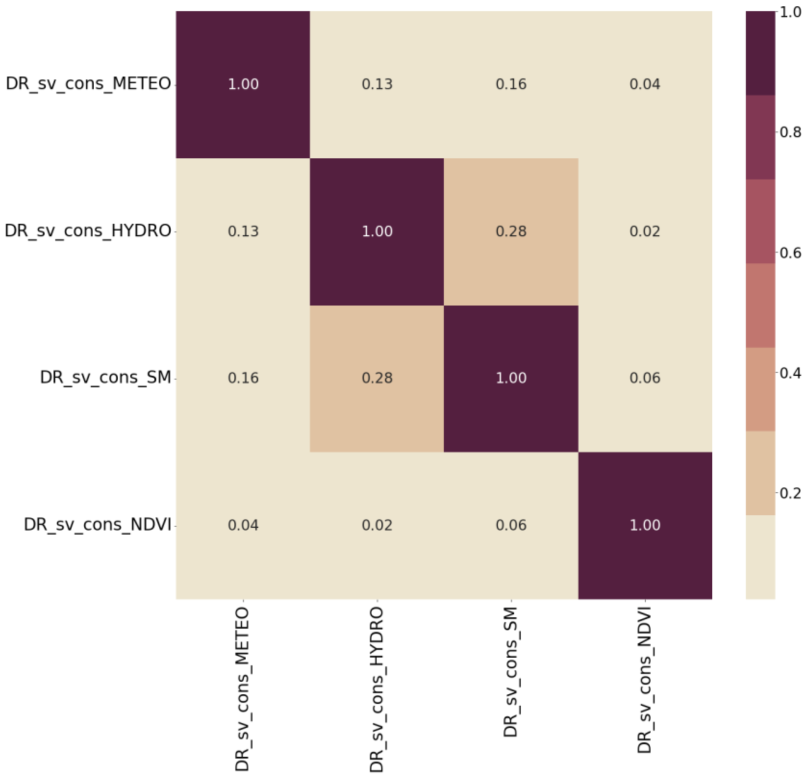
0.8
0.6
0.4
0.2

b.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DR_sv_cons_HYDRO
DR_sv_cons_SM
DR_sv_cons_NDVI
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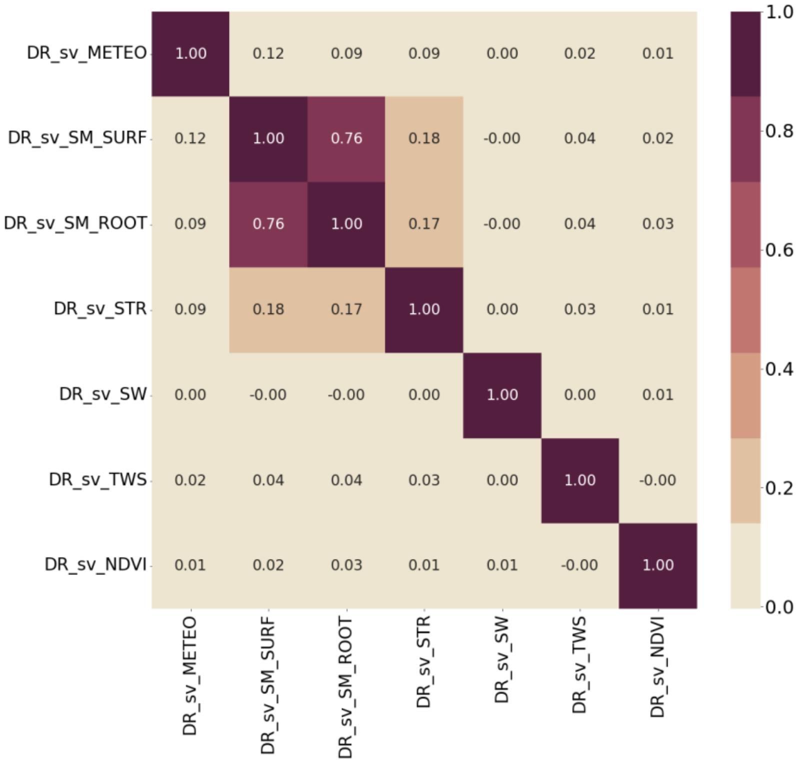
0.04 0.02 0.06 1.00
1.0
0.8
0.6
0.4
0.2

c.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DR_sv_SM_SURF
DR_sv_SM_ROOT
DR_sv_STR
DR_sv_SW
DR_sv_TWS
DR_sv_NDVI
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0.12 1.00 0.76 0.18 -0.00 0.04 0.02
0.09 0.76 1.00 0.17 -0.00 0.04 0.03
0.09 0.18 0.17 1.00 0.00 0.03 0.01
0.00 -0.00 -0.00 0.00 1.00 0.00 0.01
0.02 0.04 0.04 0.03 0.00 1.00 -0.00
0.01 0.02 0.03 0.01 0.01 -0.00 1.00
1.0
0.8
0.6
0.4
0.2
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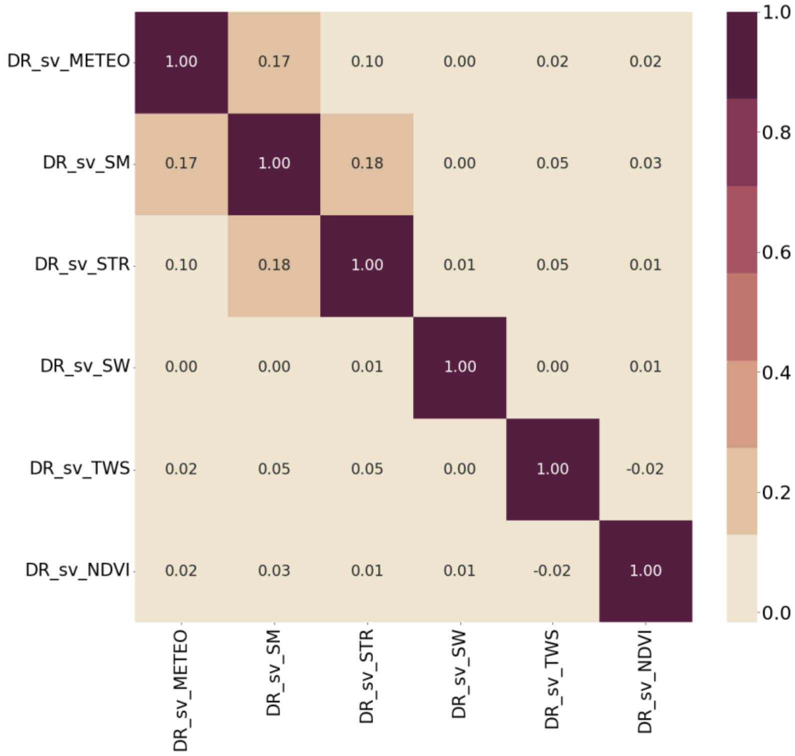
d.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DR_sv_SM
DR_sv_STR
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DR_sv_NDVI
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0.17 1.00 0.18 0.00 0.05 0.03
0.10 0.18 1.00 0.01 0.05 0.01
0.00 0.00 0.01 1.00 0.00 0.01
0.02 0.05 0.05 0.00 1.00 -0.02
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1.0
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0.6
0.4
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0.0

e.

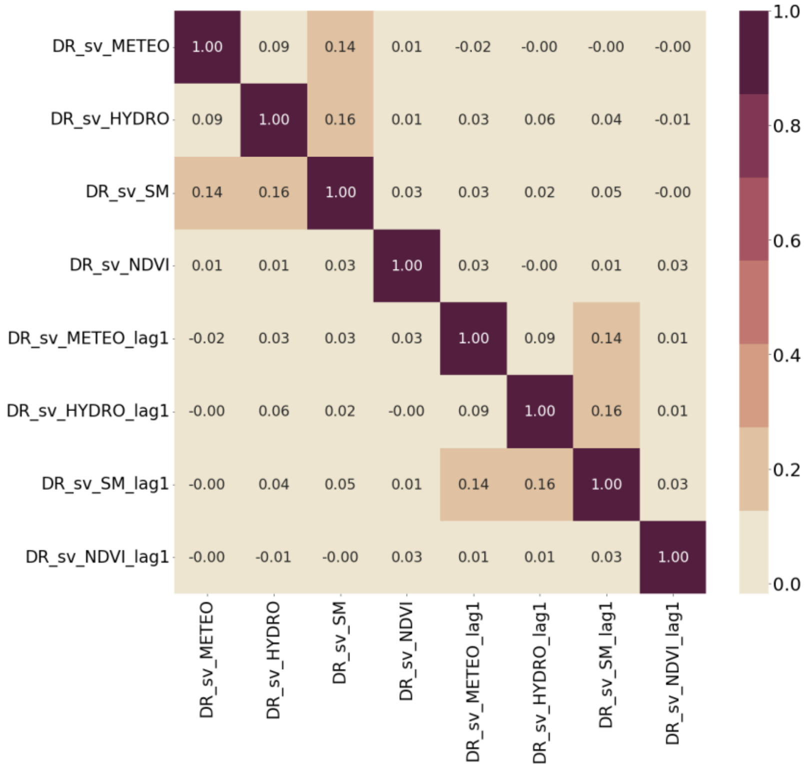
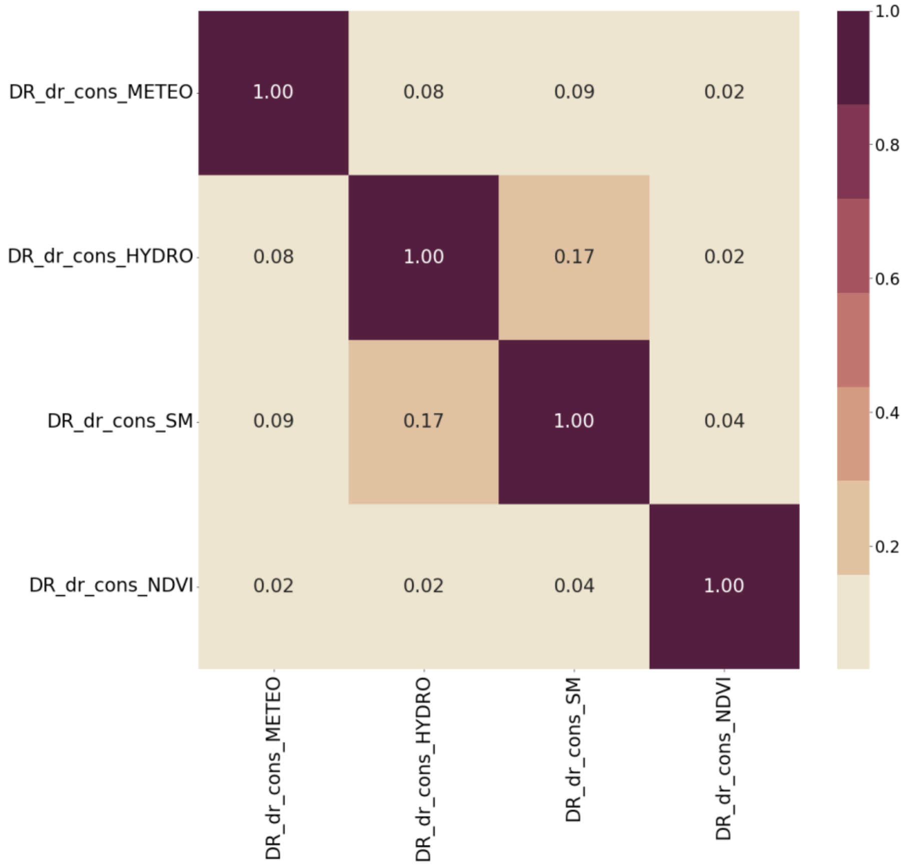


Figure S1. Pearson correlation analysis between drought anomalies used as explanatory variables in the mixed effect and fixed effect panel data model. The heatmaps, arranged from top to bottom (a,b,d,e), display correlation analyses for the variables in Equations 1, 3, 5, and 7.

a.



DR_dr_cons_METEO
DR_dr_cons_HYDRO
DR_dr_cons_SM
DR_dr_cons_NDVI
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0.08 1.00 0.17 0.02
0.09 0.17 1.00 0.04
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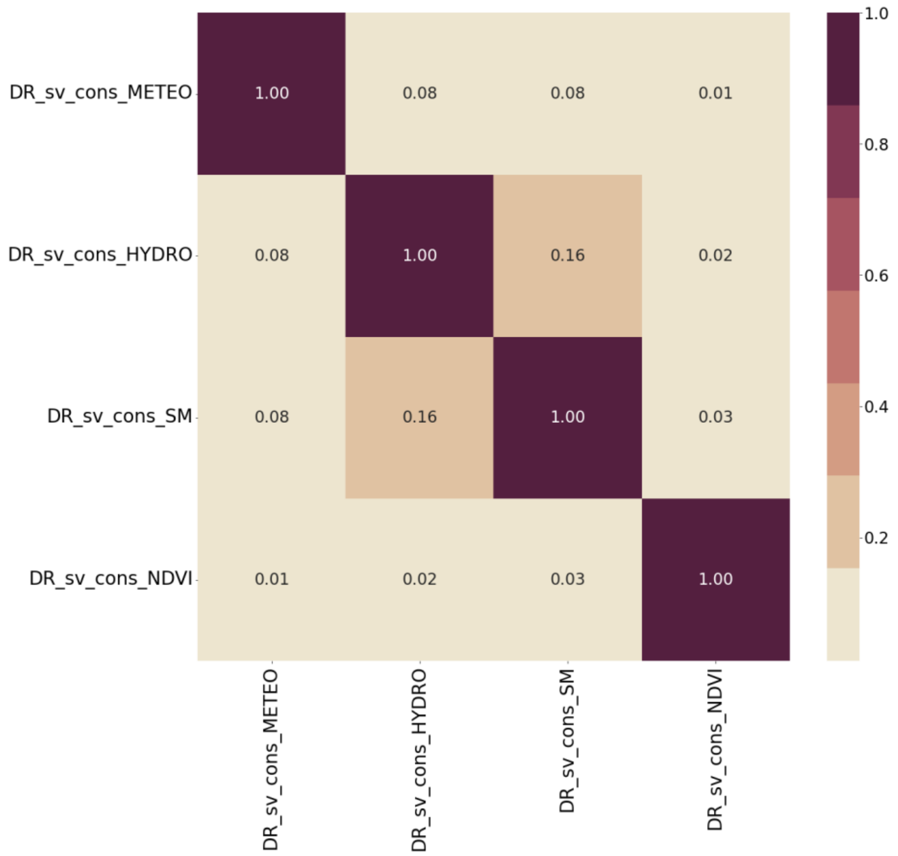
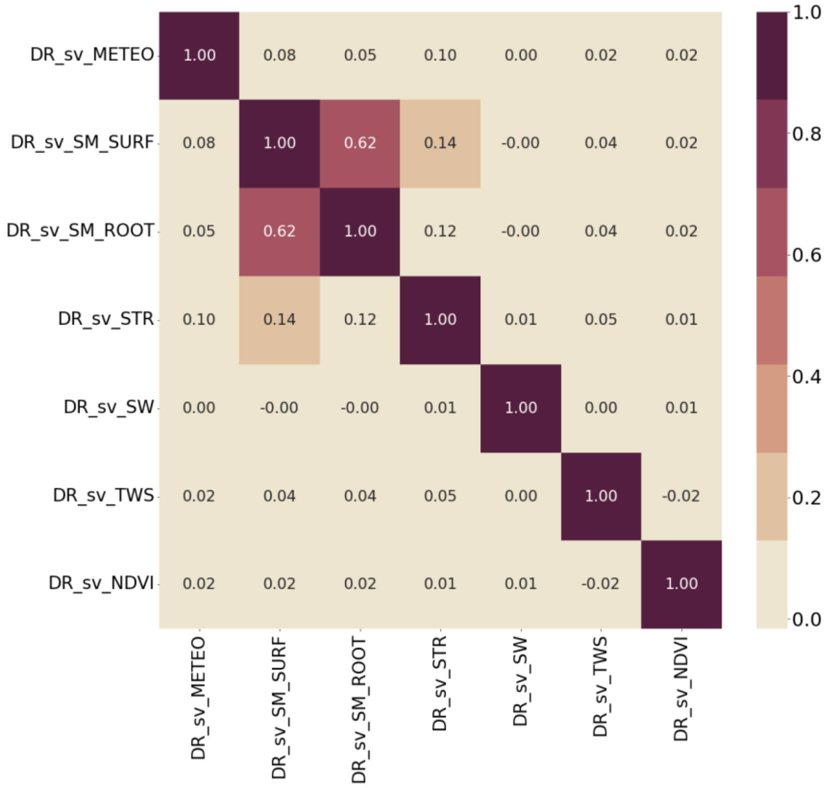
0.8
0.6
0.4
0.2

b.



DR_sv_cons_METEO
DR_sv_cons_HYDRO
DR_sv_cons_SM
DR_sv_cons_NDVI
1.00 0.08 0.08 0.01
0.08 1.00 0.16 0.02
0.08 0.16 1.00 0.03
0.01 0.02 0.03 1.00
1.0
0.8
0.6
0.4
0.2

c.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DR_sv_SM_SURF 0.08 1.00 0.62 0.14 -0.00 0.04 0.02
DR_sv_SM_ROOT 0.05 0.62 1.00 0.12 -0.00 0.04 0.02
DR_sv_STR 0.10 0.14 0.12 1.00 0.01 0.05 0.01
DR_sv_SW 0.00 -0.00 -0.00 0.01 1.00 0.00 0.01
DR_sv_TWS 0.02 0.04 0.04 0.05 0.00 1.00 -0.02
DR_sv_NDVI 0.02 0.02 0.02 0.01 0.01 -0.02 1.00
DR_sv_METEO
DR_sv_SM_SURF
DR_sv_SM_ROOT
DR_sv_STR
DR_sv_SW
DR_sv_TWS
DR_sv_NDVI
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0.4
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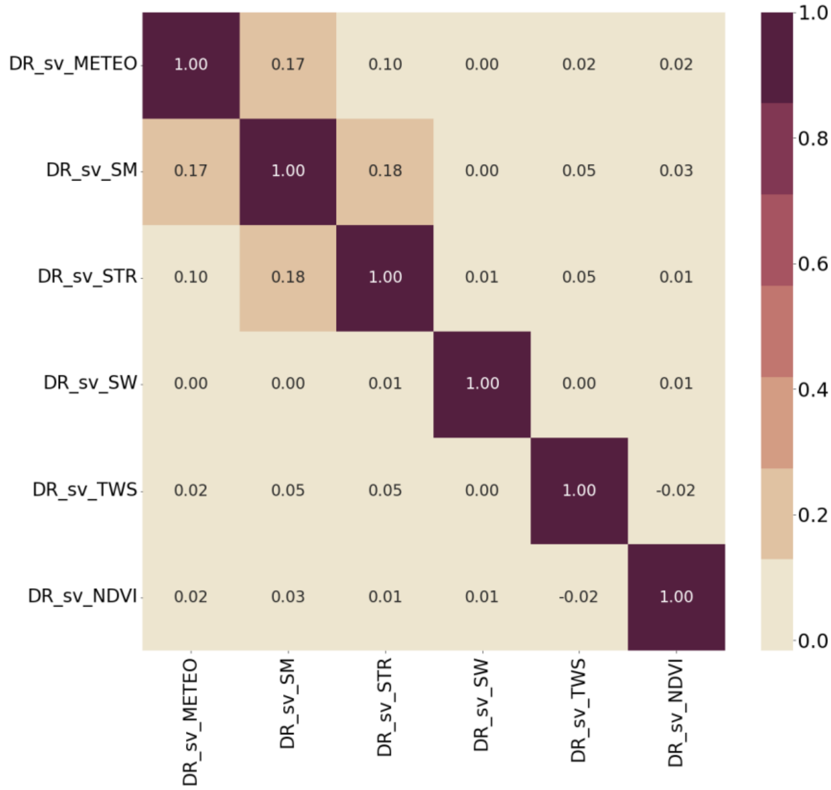
0.0

d.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DR_sv_SW 0.00 0.00 0.01 1.00 0.00 0.01
DR_sv_TWS 0.02 0.05 0.05 0.00 1.00 -0.02
DR_sv_NDVI 0.02 0.03 0.01 0.01 -0.02 1.00
DR_sv_METEO
DR_sv_SM
DR_sv_STR
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0.2
0.0

e.

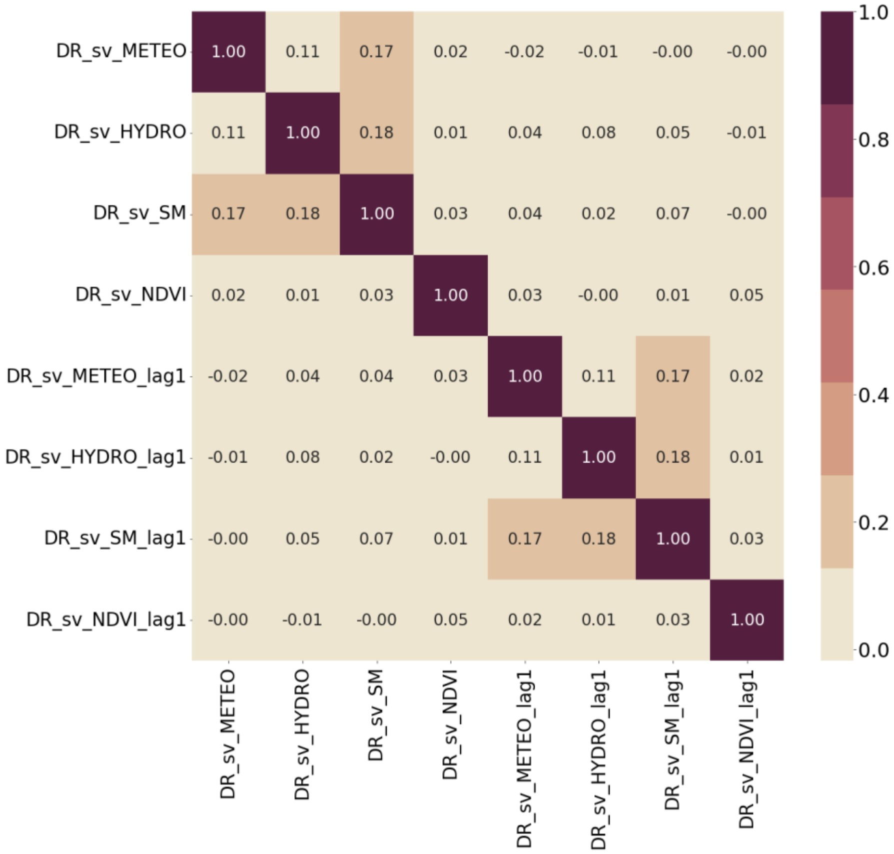

Figure S2. Spearman correlation analysis between drought anomalies used as explanatory variables in the mixed effect and fixed effect panel data model. The heatmaps, arranged from top to bottom (a,b,d,e), display correlation analyses for the variables in Equations 1, 3, 5, and 7.

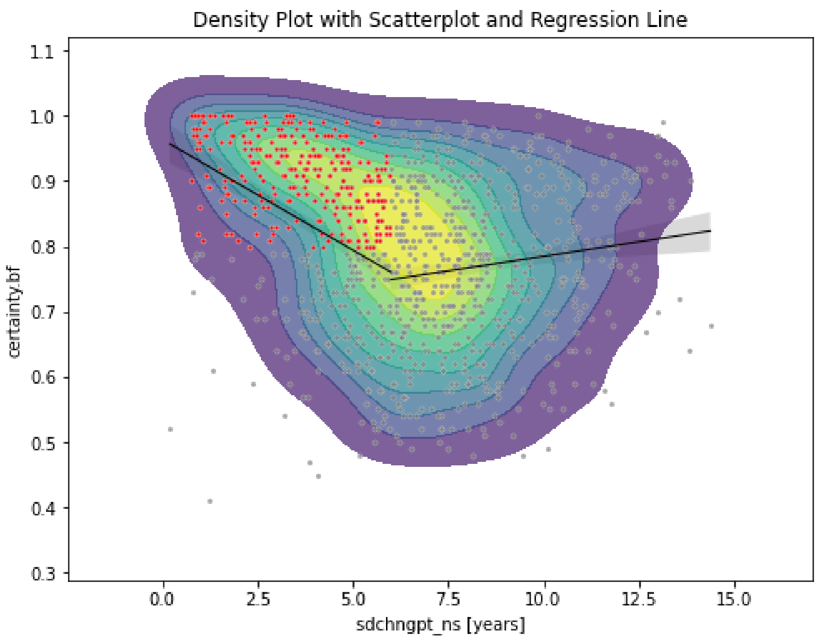

Figure S3. Scatter plot of the relationship between the standard deviation of change points (x-axis) detected at each bootstrap iteration and the confidence values in the bootstrap selection (percentage of times a particular trend type is identified as the best trend; y-axis). Red dots represent the catchments whose Q-P ratio step trend present a standard deviations below 6 and confidence values above 80%.

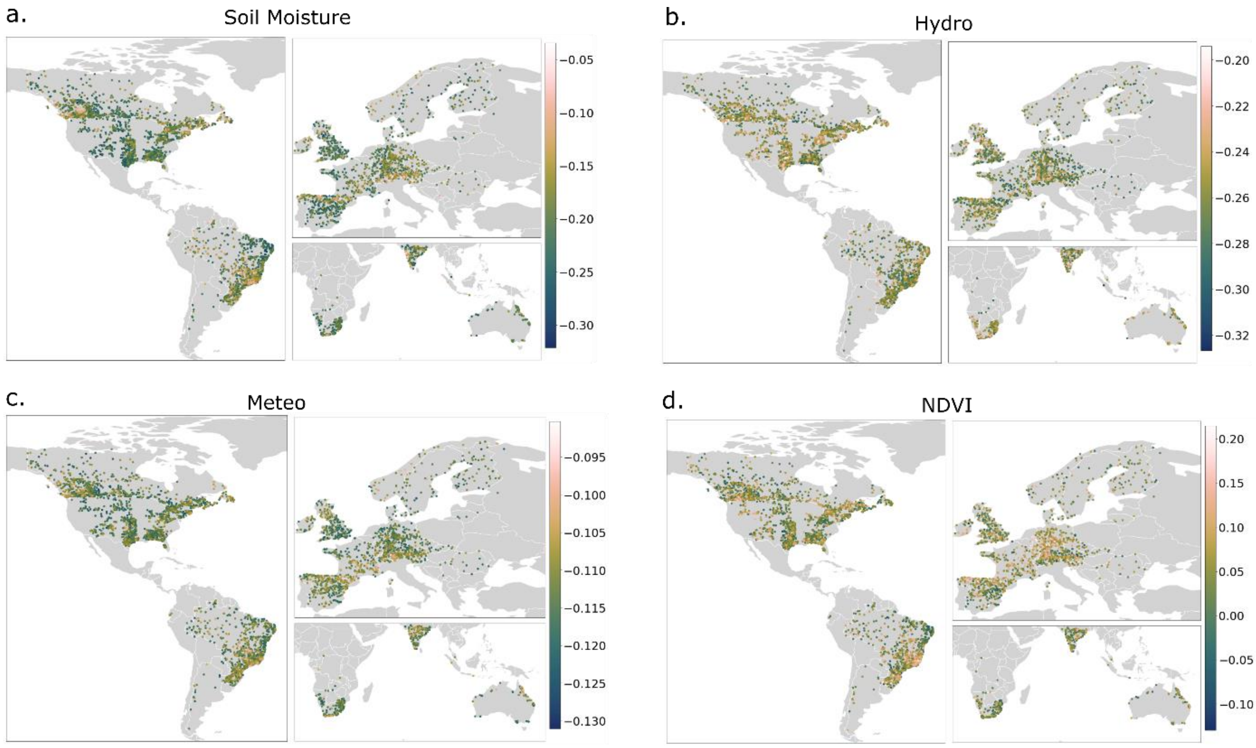

Figure S4. Influence of drought types on Q-P ratio timeseries according to the results of the mixed effect panel data model. Investigated drought types included Soil Moisture, Hydrological, Meteorological droughts and NDVI anomalies. Different ranges on the y-axis across the plots.

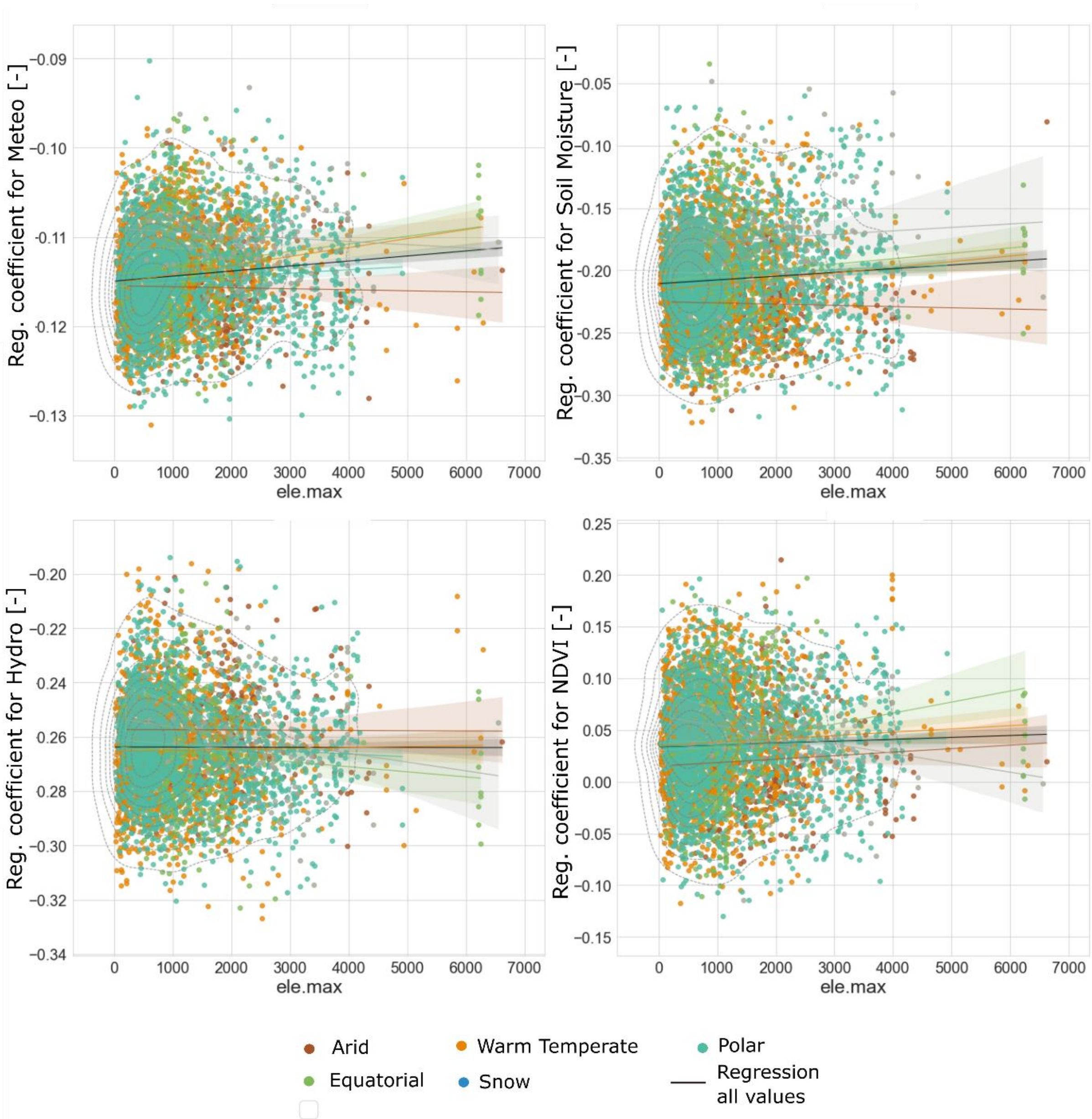

Figure S5. Scatter plots of catchment-effect of drought conditions on QP ratio according to the mixed-effect panel data model against max catchment elevation. Regression coefficients are presented for each drought type (panels a, b, c, d representing respectively Meteorological, Hydrological, Soil Moisture droughts and NDVI anomalies). Dot colors represents the climate type of the catchments, according to the five major Köppen-Geiger climate classes: Arid, Warm Temperate, Polar, Snow and Equatorial. Regression lines for each climate type are reported for each climate cluster using the same color code. The y-axis range varies for each plot.

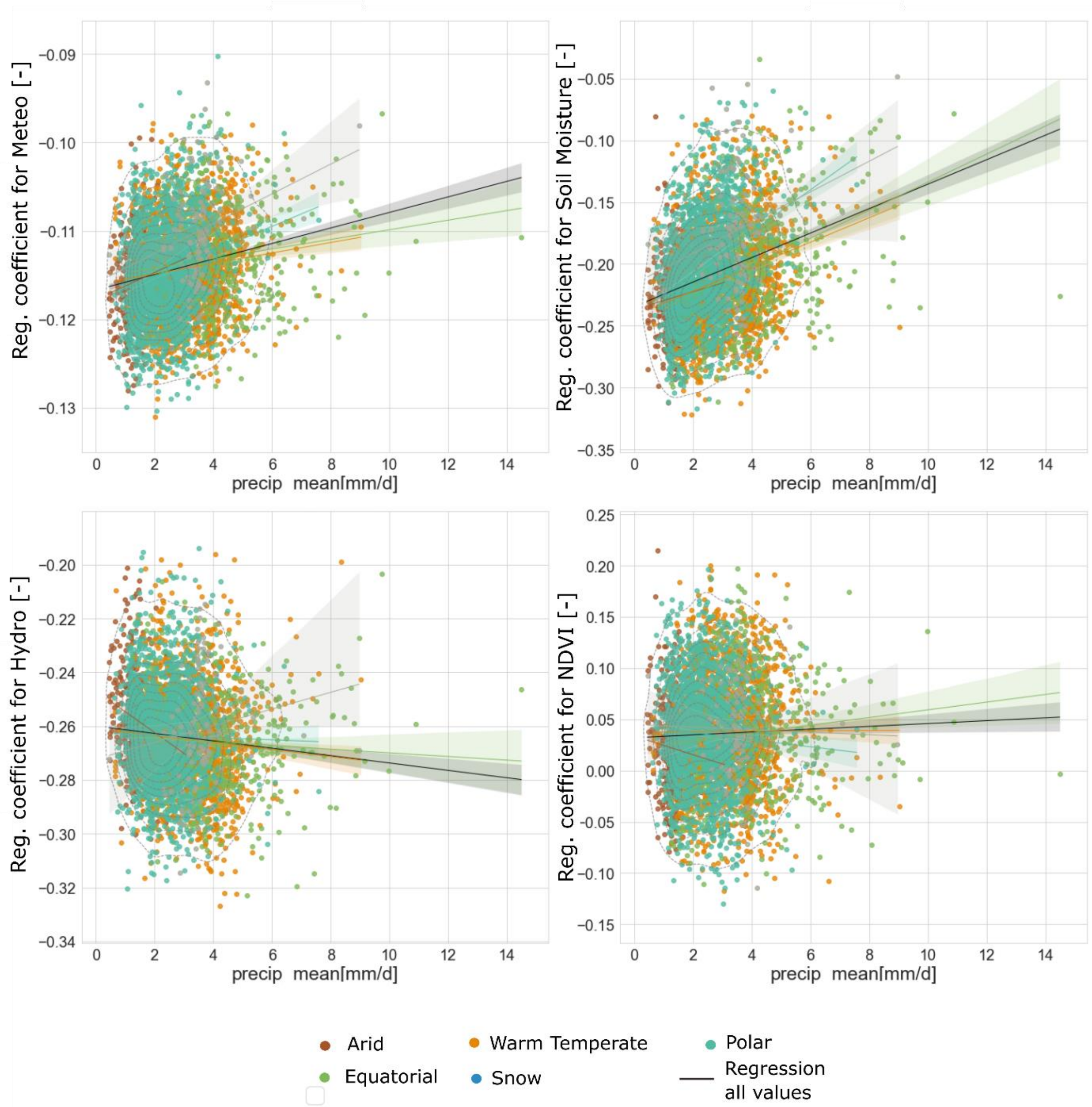

Figure S6. Scatter plots of catchment effect of drought conditions on Q-P ratio according to the mixed-effect panel data model against mean catchment precipitation. Regression coefficients are presented for each drought type (panels a, b, c, d representing respectively Meteorological, Hydrological, Soil Moisture droughts and NDVI anomalies). Dot colors represents the climate type of the catchments, according to the five major Köppen-Geiger climate classes: Arid, Warm Temperate, Polar, Snow and Equatorial. Regression lines for each climate type are reported for each climate cluster using the same color code. The y-axis range varies for each plot.

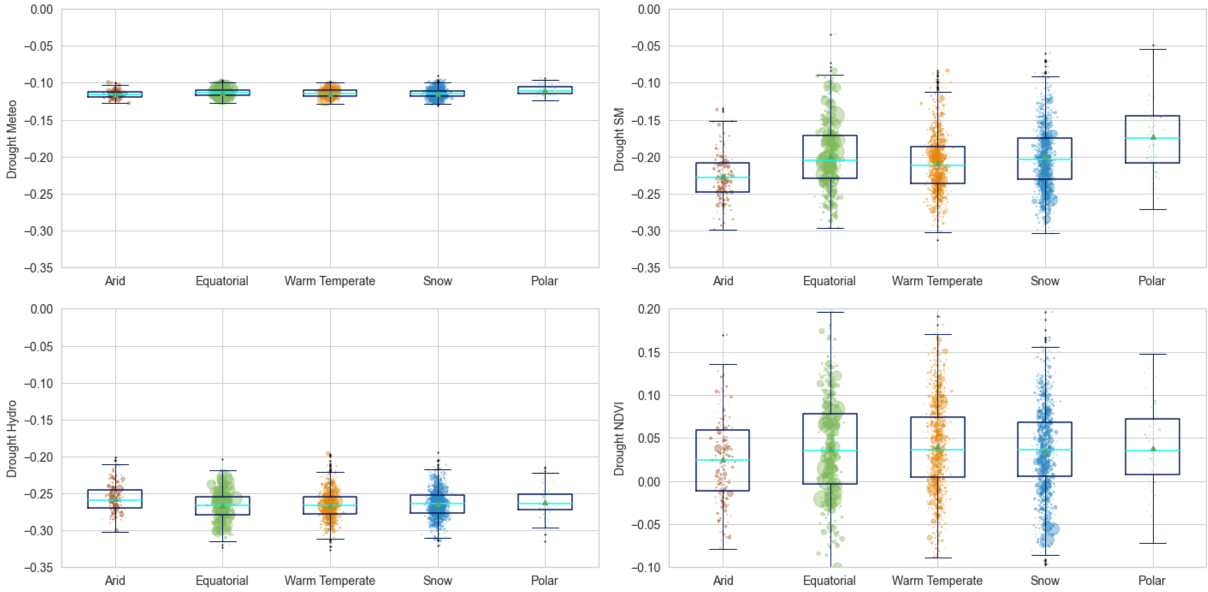

Figure S7. Box plots of catchment effect of drought events on streamflow sensitivity to precipitation according to the mixed-effect panel data model. Effects are clustered per climate region of the related catchment, according to the five major Köppen-Geiger climate classes: Arid, Warm Temperate, Polar, Snow and Equatorial. From the top left to the bottom right, the drought events considered are: meteorological, soil moisture, hydrological and NDVI anomalies. Size of the circle represents catchment size.

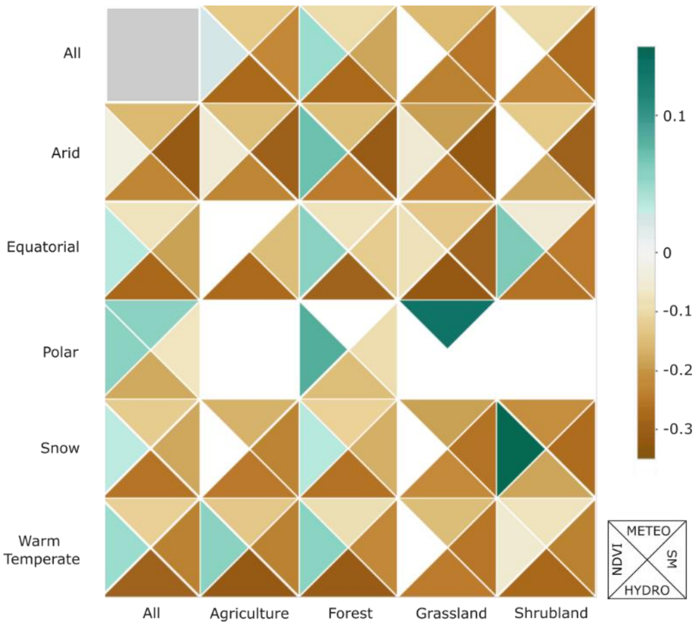

Figure S8. Fixed-effect of drought on Q-P relationship according to catchments clustered based on both climate and landcover types. Climate classifications follow the five major Köppen-Geiger climate classes: Arid, Warm Temperate, Polar, Snow, and Equatorial. Landcover classifications derived from the classification provided by GSIM dataset. Each square represents a distinct climate-landcover cluster, with triangles within squares denoting coefficient values obtained from the fixed-effect model with clustered standard errors. Starting from the top triangle in a clockwise direction, triangles represent

Meteorological, Soil Moisture, Hydrological, and NDVI coefficients derived from the panel data model. Triangle colour represents coefficient values according to the colorbar legend. Blank triangles indicate that coefficient values were not significant (p>0.01).

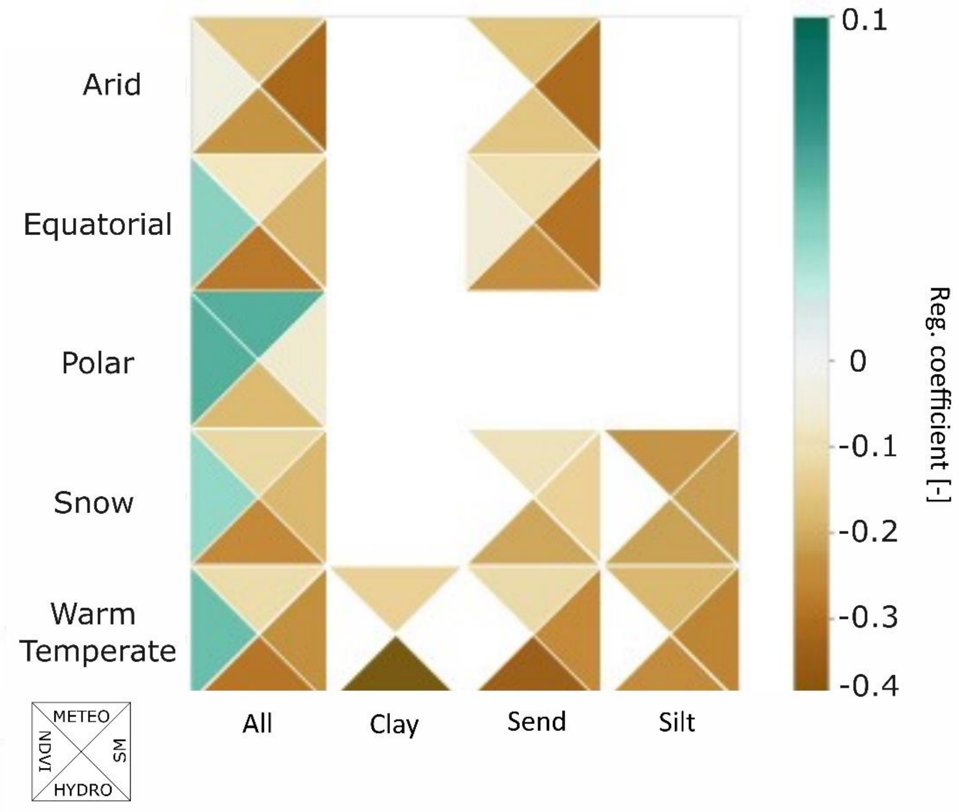

Figure S9. Fixed-effect of drought on Q-P relationship according to catchments clustered based on both climate and soil types. Climate classifications follow the five major Köppen-Geiger climate classes: Arid, Warm Temperate, Polar, Snow, and Equatorial. Soil classifications derived from information on the fraction of sand, silt, or clay in each analysed catchment as provided by GSIM dataset. Soil type has been identified as clay, sand or silt if their spatial percentage is greater than 33%. Each square represents a distinct climate-soil cluster, with triangles within squares denoting coefficient values obtained from the fixed-effect model with clustered standard errors. Starting from the top triangle in a clockwise direction, triangles represent Meteorological, Soil Moisture, Hydrological, and NDVI coefficients derived from the panel data model. Triangle color represents coefficient values according to the colorbar legend. Blank triangles indicate that coefficient values were not significant (p>0.01).

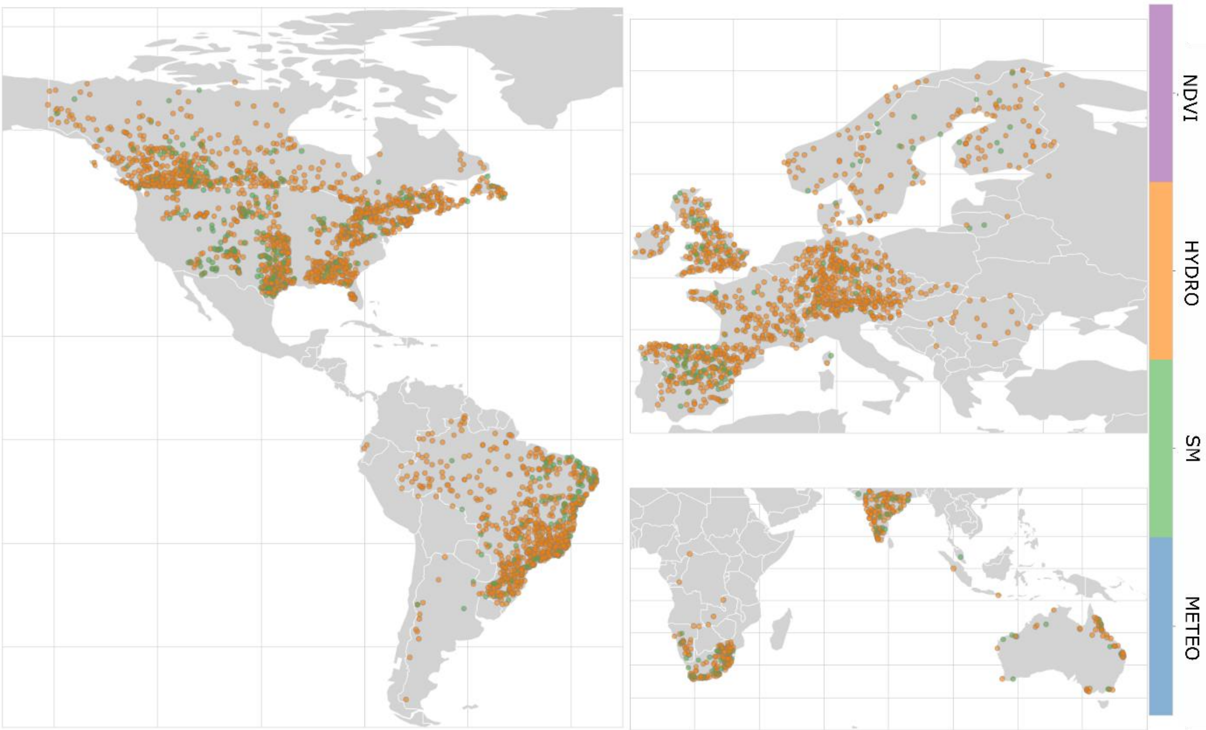

Figure S10. Global map displaying the highest regression coefficient per catchment, indicating the predominant drought type influencing streamflow sensitivity to precipitation, as determined by the mixed-effect panel data model. Circular markers represent a decrease in sensitivity of streamflow to precipitation, while triangle markers indicate an increase in sensitivity.

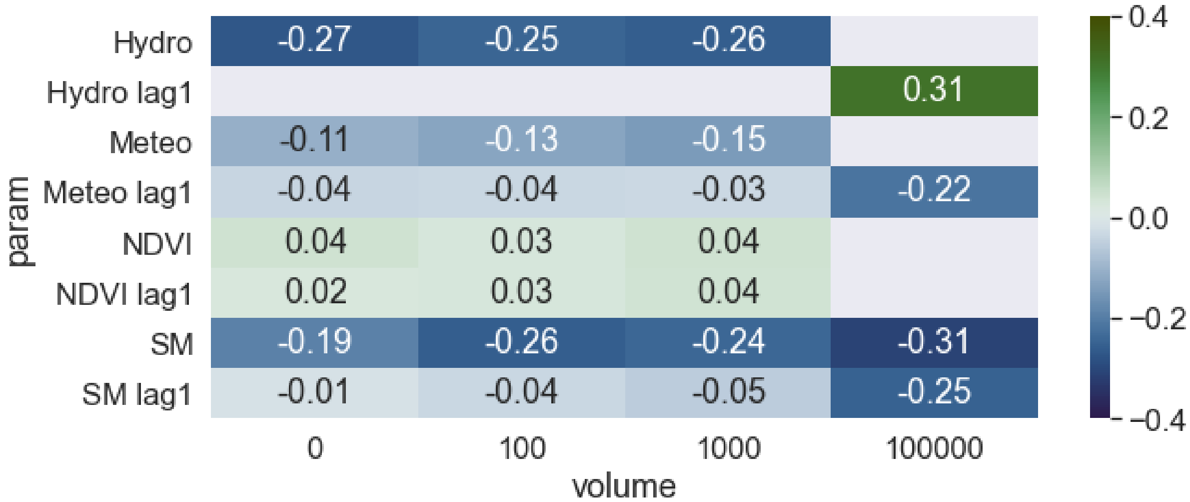

Figure S11. Fixed effect of drought on Q-P relationship according to catchment clusters based on human influence, computed as total storage volumes [km³] from all dams within the catchment boundary (0 values indicate no human influence on the river).

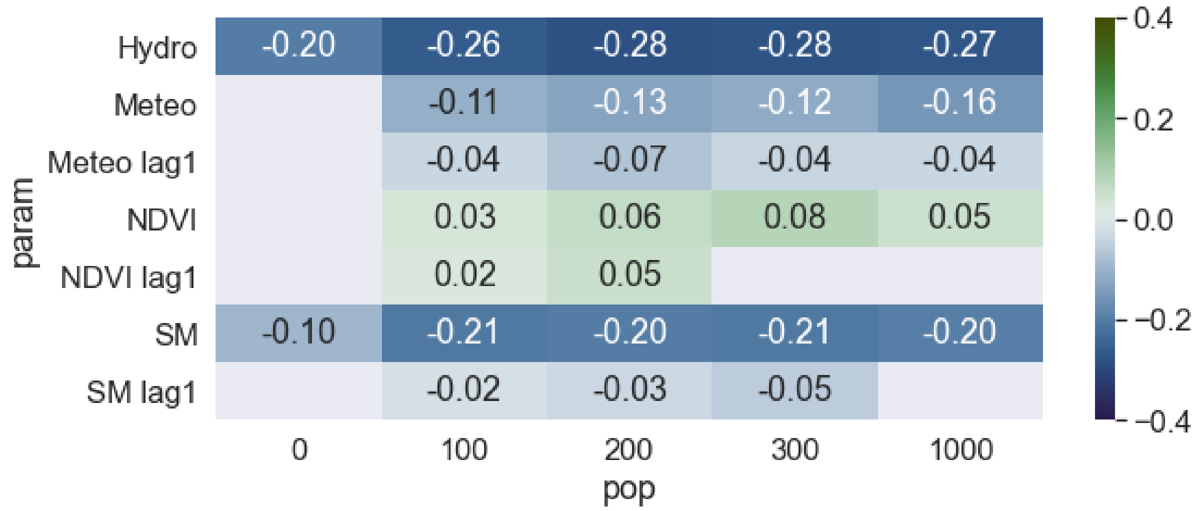

Figure S12. Fixed effect of drought on Q-P relationship according to catchment clusters based on catchment population density.

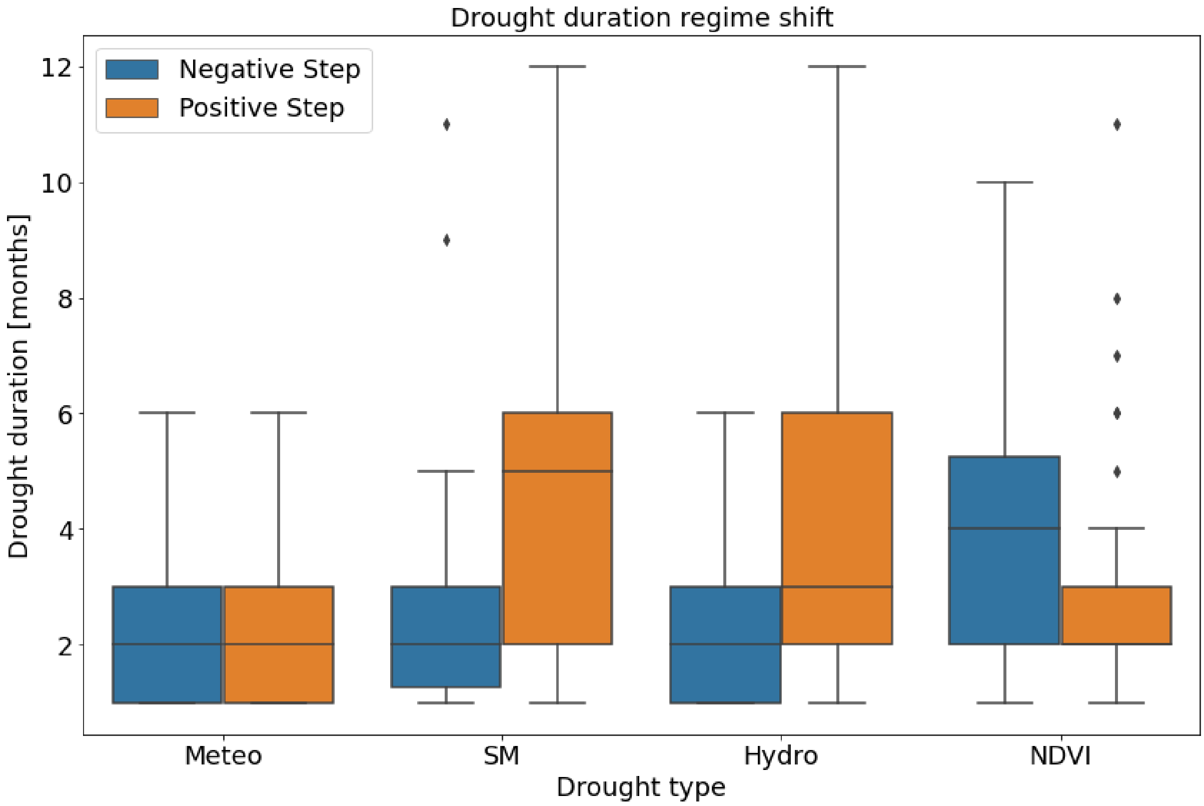

Figure S13. Drought duration [months] computed as the number of continuous months under drought until the change point (drought can continue after the change point).