Runoff Efficiency in a Changing Climate: A Multilevel Approach to Watersheds and Regional Clusters

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Study Background

Watershed

- A geographic area that channels precipitation and snowmelt into streams and rivers, ultimately directing water to a larger water body such as a lake, sea, or ocean.
- Watersheds are fundamental units in hydrology as they integrate multiple climatic and geographic factors, making them an essential focus for understanding runoff dynamics.

Runoff efficiency: how effectively watersheds convert precipitation into runoff

Our study examines global **relationships between runoff efficiency**—the ratio of water-year runoff to water-year precipitation—and three key climatic covariates: **the Aridity Index (AI), the Seasonality Index (SI), and the Snow Fraction (SF)**.

Research Questions

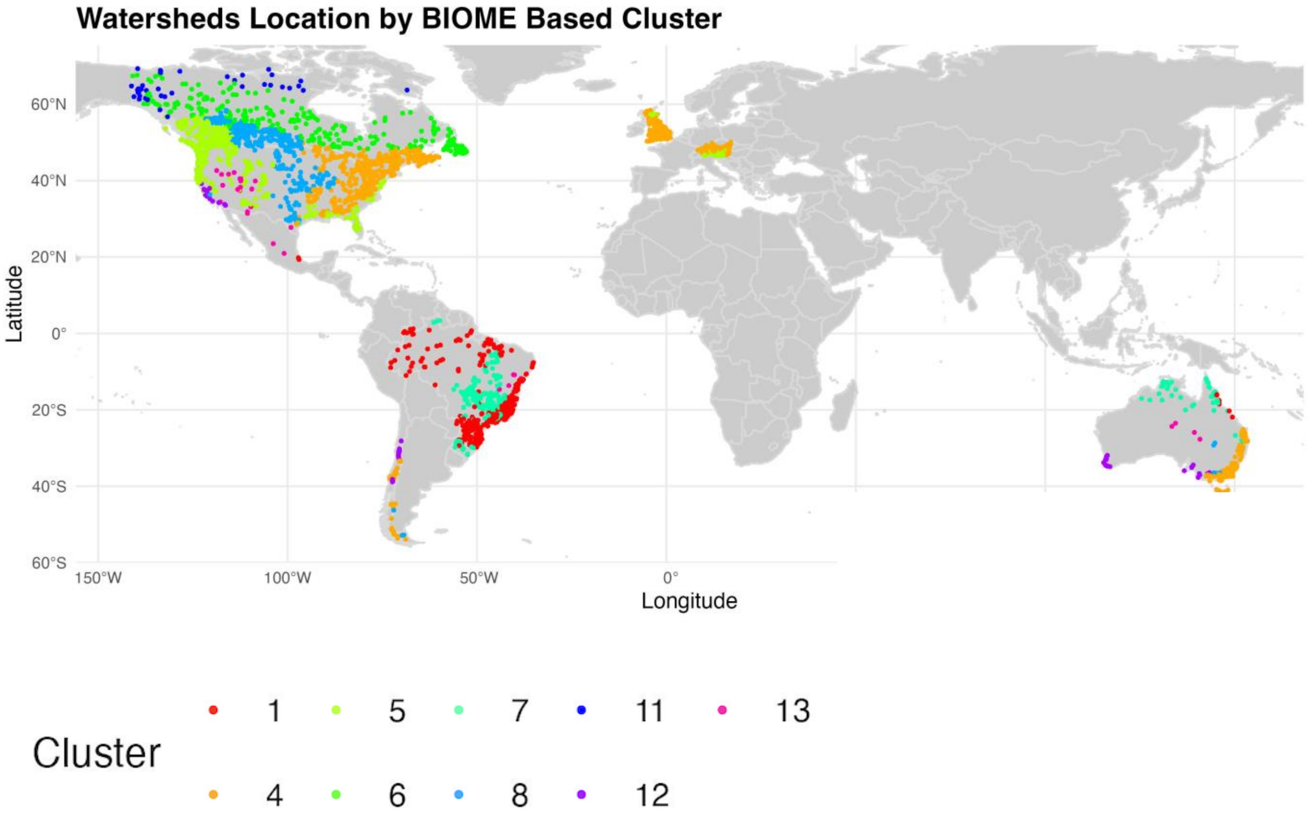
(1) How do climatic covariates affect runoff efficiency within a watershed?

(2) What is the average effect of climate covariates on runoff efficiency across watersheds?

(3) To what extent do regional clusters modify the relationship between climate covariates and runoff efficiency?

Data

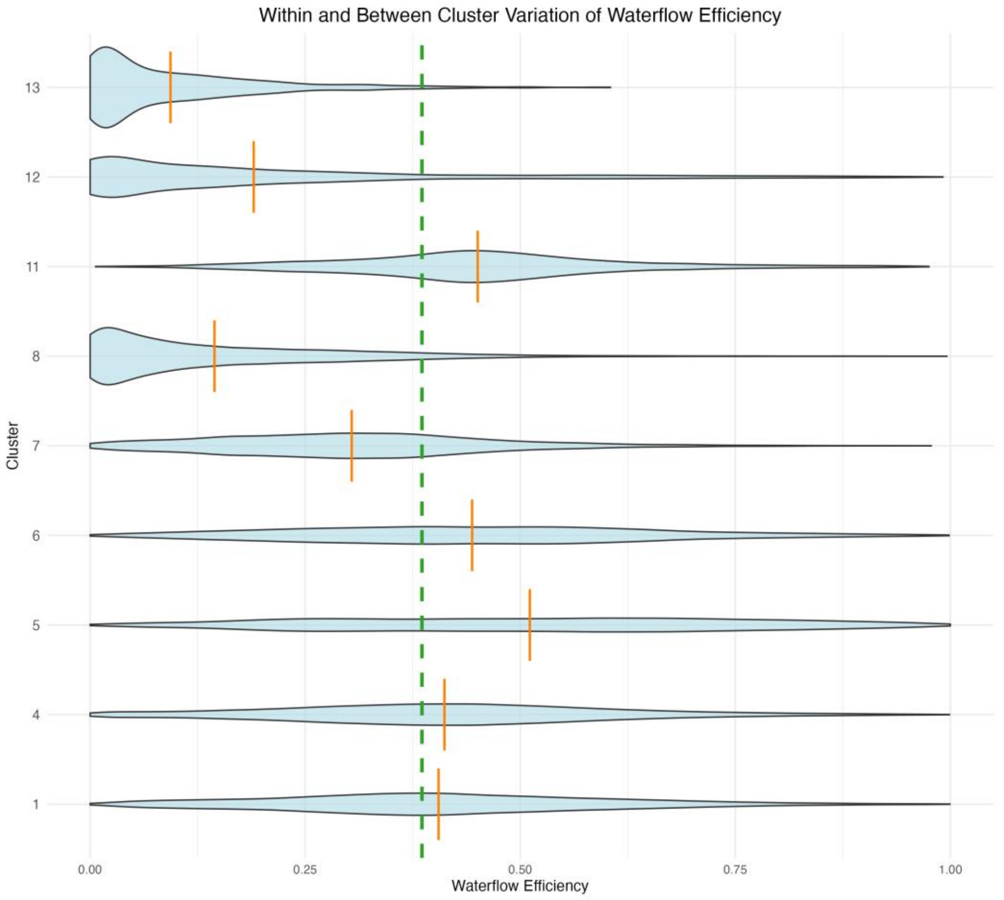
- Level 1 – Year: 38-year period 1981-2019
- Level 2 – watershed: 3022 watersheds
- Level 3 – BIOME based Clusters
- BIOME-based clusters: A biome is an area classified according to the species that live in that location. Which depends on. temperature range, soil type, and the amount of light and water which are unique to that place.
- E.g. Cluster 4 (Temperate Broadleaf and Mixed Forests, North America): Characterized by temperate climates with humid conditions, year-round precipitation, resulting in moderate to high runoff efficiency.



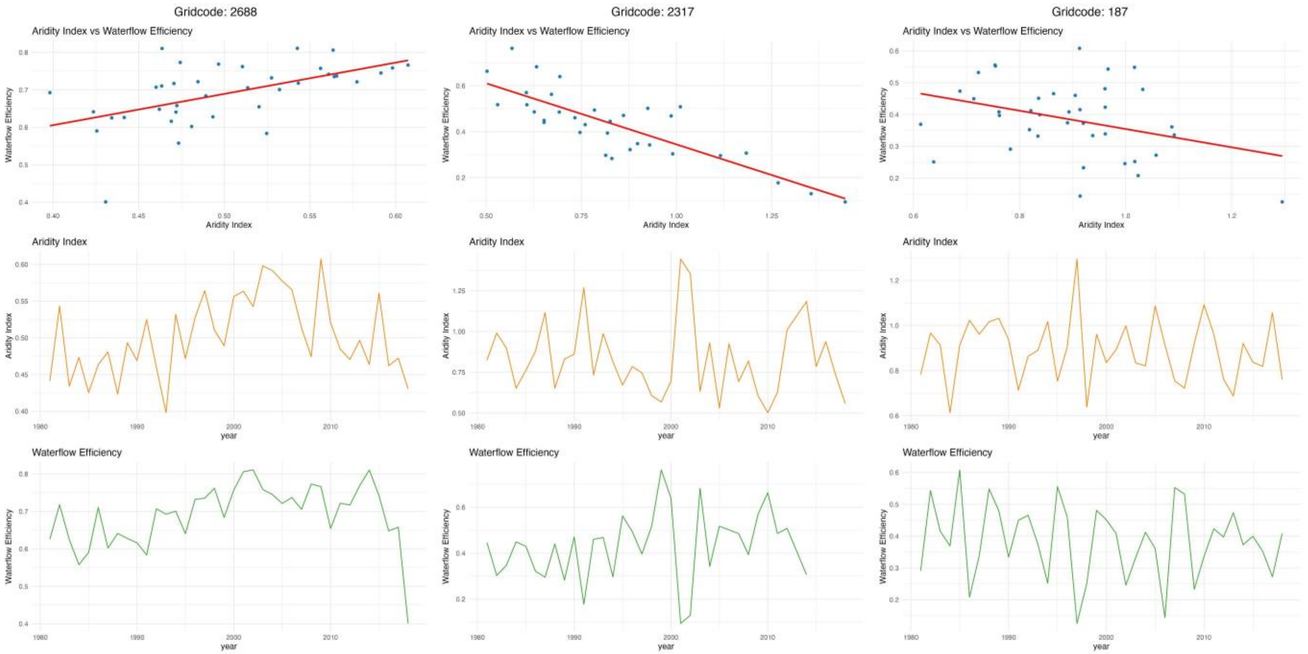
Edward Le, Joseph Janssen, John Hammond, and Ali A. Ameli. 2023. "The persistence of snow on the ground affects the shape of streamflow hydrographs over space and time: a continental-scale analysis." *Frontiers in Environmental Science*, 11. https://doi.org/10.3389/fenvs.2023.1207508

Data

Within and between clusters variability



Within and between watersheds variability



Level	ICC
Watershed	0.5024
Cluster	0.3648

Three-Level Model

Level 1 - Yearly Variation Within Watersheds

Yearly deviation from watershed mean level

$$Runoff\ Efficiency_{tik} = \beta_{0ik} + \beta_{1ik}(ai_{tik} - \overline{ai}_{ik}) + \beta_{2ik}(si_{tik} - \overline{si}_{ik}) + \beta_{3ik}(sf_{tik} - \overline{sf}_{ik}) + \varepsilon_{tik}$$

Level 2 - Variability Between Watersheds Within Clusters

Watershed specific average

$$\beta_{0ik} = \gamma_{00k} + \gamma_{01k}\overline{ai}_{ik} + \gamma_{02k}\overline{si}_{ik} + \gamma_{03k}\overline{sf}_{ik} + u_{0ik}$$

$$\beta_{1ik} = \gamma_{10k} + u_{1ik},\ \beta_{2ik} = \gamma_{20k} + u_{2ik},\ \beta_{3ik} = \gamma_{30k} + u_{3ik}$$

Level 3 - Variability Between Regional Clusters

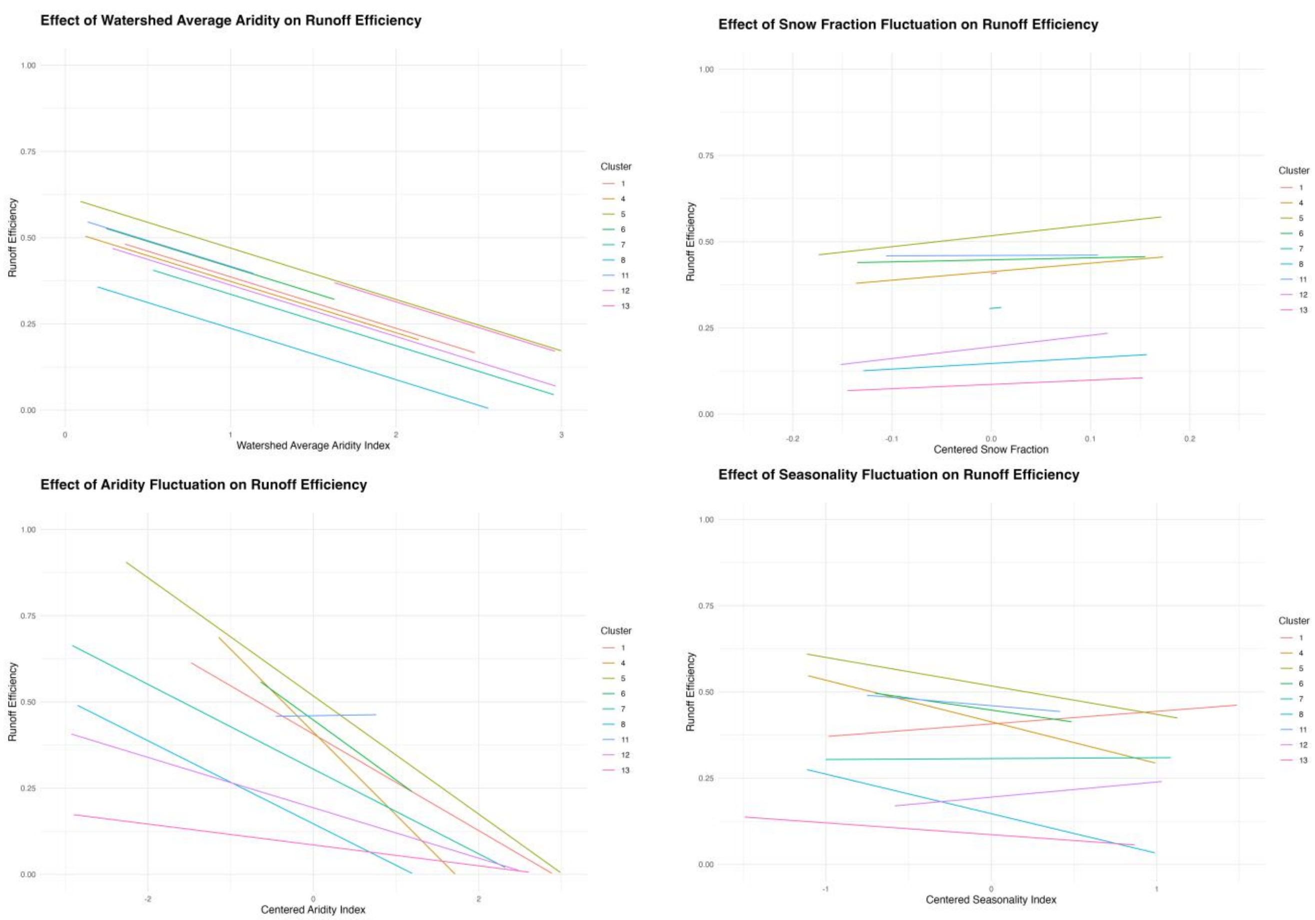
$$\gamma_{00k} = \eta_{000} + r_{0k}, \gamma_{10k} = \eta_{100} + r_{1k}, \gamma_{20k} = \eta_{200} + r_{2k}, \gamma_{30k} = \eta_{300} + r_{3k}$$

Model - Reduced Form

$$
\begin{aligned}
\text{Runoff Efficiency}_{tik} = & \eta_{000} + \gamma_{01k}\overline{\text{ai}}_{ik} + \gamma_{02k}\overline{\text{si}}_{ik} + \gamma_{03k}\overline{\text{sf}}_{ik} \\
& + \eta_{100}(\text{ai}_{tik} - \overline{\text{ai}}_{ik}) + \eta_{200}(\text{si}_{tik} - \overline{\text{si}}_{ik}) + \eta_{300}(\text{sf}_{tik} - \overline{\text{sf}}_{ik}) \\
& + r_{0k} + r_{1k}(\text{ai}_{tik} - \overline{\text{ai}}_{ik}) + r_{2k}(\text{si}_{tik} - \overline{\text{si}}_{ik}) + r_{3k}(\text{sf}_{tik} - \overline{\text{sf}}_{ik}) \\
& + u_{0ik} + u_{1ik}(\text{ai}_{tik} - \overline{\text{ai}}_{ik}) + u_{2ik}(\text{si}_{tik} - \overline{\text{si}}_{ik}) + u_{3ik}(\text{sf}_{tik} - \overline{\text{sf}}_{ik}) + \epsilon_{tik}
\end{aligned}
$$

$$
\begin{bmatrix} r_{0k} \\ r_{1k} \\ r_{2k} \\ r_{3k} \end{bmatrix} \sim N\left(\begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}, \begin{bmatrix} \tau_{r_0}^2 & \tau_{r_0 r_1} & \tau_{r_0 r_2} & \tau_{r_0 r_3} \\ & \tau_{r_1}^2 & \tau_{r_1 r_2} & \tau_{r_1 r_3} \\ & & \tau_{r_2}^2 & \tau_{r_2 r_3} \\ & & & \tau_{r_3}^2 \end{bmatrix} \right)
\quad
\begin{bmatrix} u_{0ik} \\ u_{1ik} \\ u_{2ik} \\ u_{3ik} \end{bmatrix} \sim N\left(\begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}, \begin{bmatrix} \sigma_{u_0}^2 & \sigma_{u_0 u_1} & \sigma_{u_0 u_2} & \sigma_{u_0 u_3} \\ & \sigma_{u_1}^2 & \sigma_{u_1 u_2} & \sigma_{u_1 u_3} \\ & & \sigma_{u_2}^2 & \sigma_{u_2 u_3} \\ & & & \sigma_{u_3}^2 \end{bmatrix} \right)
$$

Results
- Fixed Effect

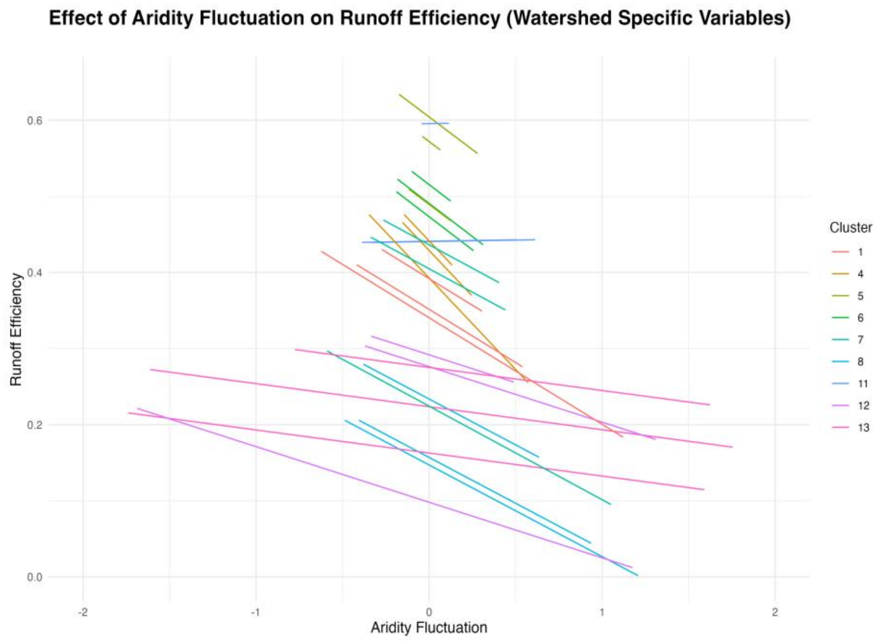


*Effect of Climate Factor on Runoff Efficiency of an '**Average**' Watershed From Each Cluster*

- All other climate factors held at cluster average level
- No yearly fluctuations in all other covariates

Term	Estimate	Std. Error	t-value	p-value
(Intercept)	0.498	0.026	18.983	<0.001
mean ai	-0.149	0.005	-29.067	<0.001
centered ai	-0.119	0.026	-4.524	0.002
mean si	-0.089	0.007	-12.161	<0.001
centered si	-0.042	0.021	-2.012	0.079
mean sf	0.241	0.022	10.787	<0.001
centered sf	0.210	0.056	3.757	0.019

Table.1 Fixed Effects Summary

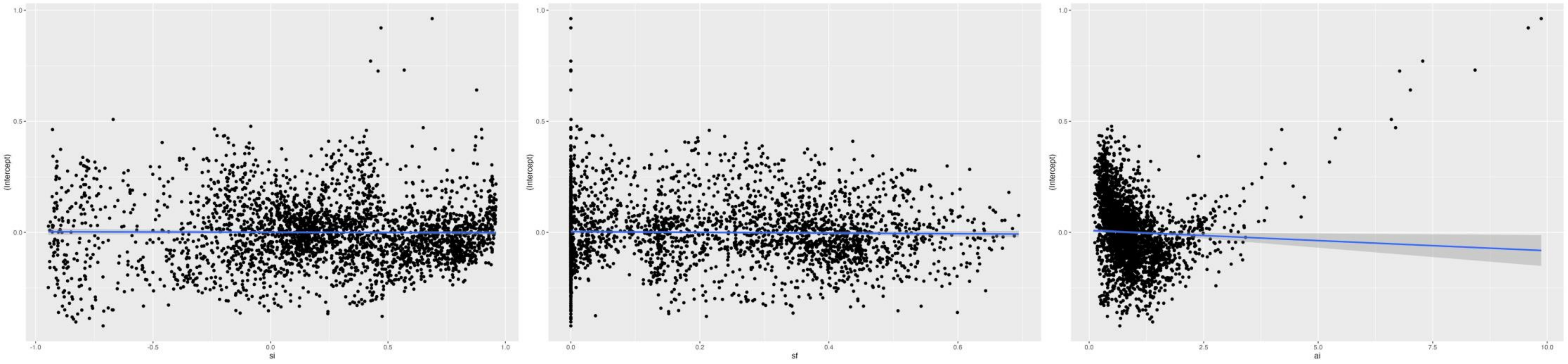


- Some watersheds have greater fluctuations (wider range of x)
- Some clusters are less prone to climate fluctuation (y changes a lot when x change a little, depends on cluster)

Results
– Random Effect

Group	Effect	Variance	Std. Dev.	Correlation
watershed	(Intercept)	0.022	0.148	
watershed	centered ai	0.019	0.138	-0.24
watershed	centered si	0.007	0.084	0.02 0.25
watershed	centered sf	0.027	0.164	0.13 0.34 0.50
cluster	(Intercept)	0.005	0.073	
cluster	centered ai	0.006	0.078	-0.04
cluster	centered si	0.004	0.062	0.27 0.43
cluster	centered sf	0.021	0.144	0.15 -0.36 0.36
Residual		0.006	0.079	

- *Table.2 Random Effects Summary*



Conclusions

Both long-term climatic averages and yearly deviations significantly influence runoff efficiency

1. How do climatic covariates affect runoff efficiency within a watershed?

Yearly deviations in climatic covariates significantly influence runoff efficiency. For example, deviations in aridity index negatively impact runoff efficiency, while deviations in snow fraction positively influence it.

2. What is the average effect of climatic covariates on runoff efficiency across watersheds?

Watersheds with higher average aridity and seasonality exhibit lower runoff efficiency, whereas those with higher average snow fractions demonstrate improved efficiency.

3. To what extent do regional clusters modify the relationship?

Clusters introduce additional variability, as indicated by random effects at the cluster level, which modify the sensitivity of runoff efficiency to both long-term averages and yearly climatic deviations.

Thank you !