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

Qianyi Wang, Jessica Wang, Even Li
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1 Introduction

Streamflow is a vital component of global water systems, supporting ecosystems, human livelihoods, and economic activities. However, climate change poses challenges to understanding streamflow due to its complex interactions with climatic, hydrological, and geographic factors. Alterations in streamflow dynamics—such as shifts in variability and hydrograph signatures—are closely tied to climatic conditions, including aridity, seasonality, and snowfall patterns.

Watersheds, which channel precipitation and snowmelt into larger water bodies, are essential units in hydrology. They integrate multiple climatic and geographic factors, making them vital for understanding runoff dynamics. This 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). Runoff efficiency quantifies how effectively watersheds convert precipitation into runoff, influenced by regional factors like climate trends in the north-central United States and groundwater withdrawals in the south-central United States.

2 Data

This study analyzes the relationship between climatic indices and streamflow signatures across 3,022 watersheds over a 38-year period (1981–2019). Watershed-scale annual and long-term averages of Snow Fraction, Aridity Index (AI), and Seasonality Index (SI) were derived from global datasets. Snow Fraction represents the proportion of precipitation falling as

cluster	Number of Watersheds	25th Percentile AI	Mean AI	75th Percentile AI	25th Percentile SI	Mean SI	75th Percentile SI	25th Percentile SF	Mean SF	75th Percentile SF	Runoff Efficiency
1	390	0.638	0.854	0.981	0.125	0.378	0.825	0.000	0.000	0.000	0.405
4	1037	0.548	0.734	0.860	-0.048	0.108	0.279	0.035	0.161	0.273	0.412
5	609	0.343	0.676	0.886	-0.293	-0.022	0.363	0.165	0.298	0.437	0.511
6	276	0.421	0.773	1.018	0.236	0.436	0.668	0.424	0.469	0.523	0.444
7	225	0.850	1.207	1.341	0.567	0.594	0.898	0.000	0.000	0.000	0.304
8	359	1.259	1.610	1.830	0.565	0.629	0.792	0.199	0.309	0.413	0.145
11	38	0.582	0.708	0.866	0.561	0.593	0.710	0.563	0.614	0.658	0.451
12	56	1.431	2.076	2.426	-0.918	-0.820	-0.767	0.000	0.052	0.004	0.190
13	32	2.272	3.533	3.372	-0.184	0.122	0.565	0.000	0.116	0.243	0.093

Figure 1: Cluster Level Summary Statistics

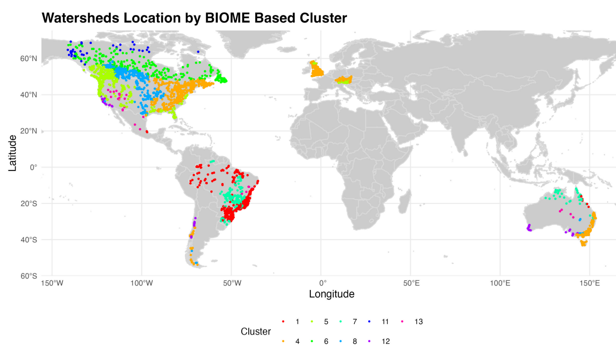
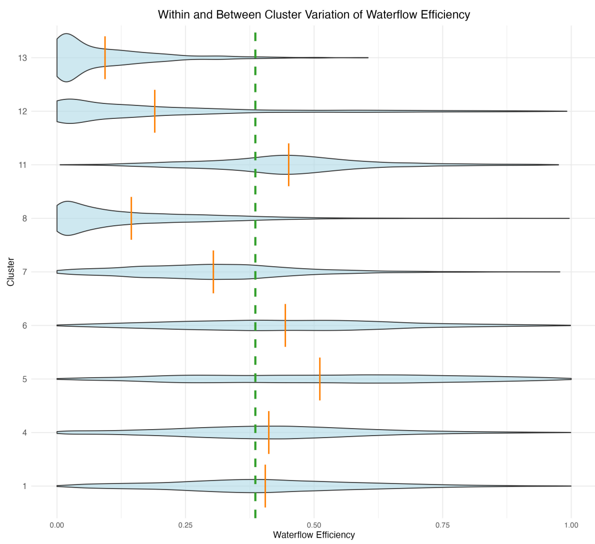


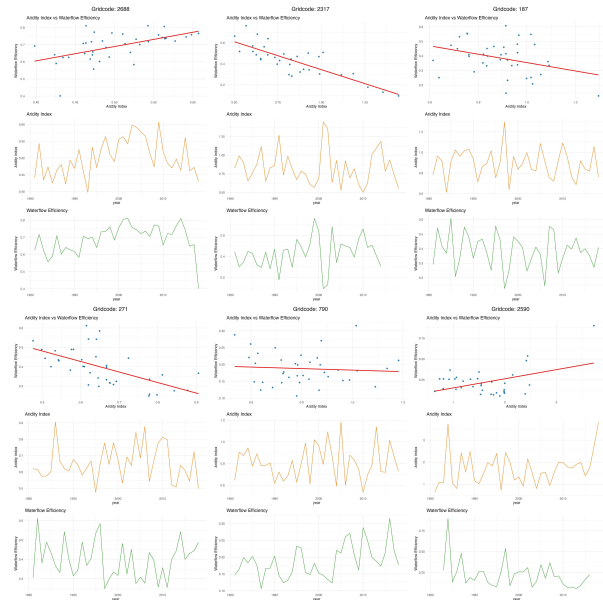
Figure 2: Geographical Location of Watersheds

snow, a key driver of seasonal water storage. AI, the ratio of potential evapotranspiration to total precipitation, reflects the balance between water supply and demand, while SI captures the synchronicity between precipitation and temperature, highlighting seasonal variations in watershed hydrology.

Streamflow data were collected from global gauge records and used to calculate runoff efficiency, the ratio of mean streamflow to precipitation). Watersheds were grouped into nine BIOME-based clusters, categorizing geographic regions by climate and physical characteristics. These clusters reflect differences in vegetation, soil type, and precipitation, enabling comparisons of watersheds within similar environmental contexts.



(a) Distribution of runoff efficiency by cluster



(b) Effect of aridity index on runoff efficiency for random selected watershed in cluster 1

Figure 3: Cluster and Catchment Level Variance

Table 1: Intraclass Correlation Coefficients (ICC) for Watershed and Cluster Levels

Level	**ICC**
Watershed	0.5024
Cluster	0.3648

3 Methods

The data reveals significant variability in runoff efficiency both within and between clusters. Figure 3a shows distinct distributions of runoff efficiency across clusters, with considerable overlap. Cluster-specific means, indicated by orange lines, highlight differences between clusters, while the green dashed line represents the overall mean. These patterns suggest substantial heterogeneity at the cluster level, supported by the ICC analysis, which attributes 36.5% of the total variability to cluster-level effects.

Figure 3b explores watershed-level variability, examining the relationship between runoff efficiency and one of the most influential climatic covariates aridity index (AI). Climate factors influence runoff efficiency differently across watersheds, with variability also observed within individual watersheds in response to climatic factors. This finding aligns with the ICC analysis, which attributes 50.2% of the variability to watershed-specific effects. Given the absence of temporal trends at the watershed level, deviations from average climatic values—both above and below—were analyzed to better capture within-watershed variation compared to relying solely on averages.

These findings underscore the need for a three-level hierarchical model. The first level captures year-to-year variability within watersheds driven by temporal fluctuations in climate. The second accounts for differences across watersheds due to geographic and hydrological factors. The third level represents clusters, grouping watersheds based on shared BIOME characteristics, such as vegetation, soil, and climate.

4 Model

A three-level model was developed to address three key research questions: (1) How does each climate covariate affect runoff efficiency within a watershed on a yearly basis? (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? The model captures variability at multiple levels, accounting for year-to-year fluctuations within watersheds, differences between watersheds, and broader patterns across regional clusters.

Level 1 - Yearly Variation Within Watersheds

At the first level, runoff efficiency ($\text{Runoff Efficiency}_{tik}$) for year t within watershed i and cluster k is modeled as:

$$\text{Runoff Efficiency}_{tik} = \beta_{0ik} + \beta_{1ik}(\text{ai}_{tik} - \overline{\text{ai}}_{ik}) + \beta_{2ik}(\text{si}_{tik} - \overline{\text{si}}_{ik}) + \beta_{3ik}(\text{sf}_{tik} - \overline{\text{sf}}_{ik}) + \epsilon_{tik}$$

where $\epsilon_{tik} \sim N(0, \sigma_\epsilon^2)$. The intercept term β_{0ik} represents the baseline runoff efficiency for watershed i within cluster k. The coefficients β_{1ik}, β_{2ik}, and β_{3ik} quantify the sensitivity of runoff efficiency to deviations in the climatic covariates: aridity index (ai_{tik}), seasonality index (si_{tik}), and snow fraction (sf_{tik}) from their respective watershed-specific means across all of its observations ($\overline{\mathrm{ai}}_{ik}$, $\overline{\mathrm{si}}_{ik}$, $\overline{\mathrm{sf}}_{ik}$). The residual term ϵ_{tik} captures random variation in runoff efficiency that is not explained by the climatic covariates or hierarchical structure.

Level 2 - Variability Between Watersheds Within Clusters

The second level models the watershed-specific baseline runoff efficiency (intercept, β_{0ik}) and slopes (β_{1ik}, β_{2ik}, and β_{3ik}) as functions of cluster level fixed effects and random effects:

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

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

Here, γ_{00k} is the cluster-specific intercept, influenced by watershed-level averages of aridity ($\overline{\mathrm{ai}}_{ik}$), seasonality ($\overline{\mathrm{si}}_{ik}$), and snow fraction ($\overline{\mathrm{sf}}_{ik}$), with corresponding fixed effects (γ_{01k}, γ_{02k}, and γ_{03k}). Random effects (u_{0ik}, u_{1ik}, u_{2ik}, and u_{3ik}) capture watershed-specific deviations from the cluster-level effects, with their variances and covariances structured as:

$$\begin{bmatrix} u_{0ik} \\ u_{1ik} \\ u_{2ik} \\ u_{3ik} \end{bmatrix} \sim N \left(\begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}, \begin{bmatrix} \sigma^2_{u_0} & \sigma_{u_0u_1} & \sigma_{u_0u_2} & \sigma_{u_0u_3} \\ & \sigma^2_{u_1} & \sigma_{u_1u_2} & \sigma_{u_1u_3} \\ & & \sigma^2_{u_2} & \sigma_{u_2u_3} \\ & & & \sigma^2_{u_3} \end{bmatrix} \right)$$

Level 3 - Variability Between Regional Clusters

At the cluster level, the cluster-specific fixed effects (γ_{00k}, γ_{10k}, γ_{20k}, γ_{30k}) are modeled as:

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

Here, (η_{000}) represents the grand mean intercept, and η_{100}, η_{200}, η_{300}) are the grand mean slopes for aridity, seasonality, and snow fraction, respectively. Random effects (r_{0k}, r_{1k}, r_{2k}, or r_{3k}) capture cluster-specific deviations, with their variances and covariances structured as:

$$\begin{bmatrix} r_{0k} \\ r_{1k} \\ r_{2k} \\ r_{3k} \end{bmatrix} \sim N\left(\begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}, \begin{bmatrix} \tau_{r_0}^2 & \tau_{r_0r_1} & \tau_{r_0r_2} & \tau_{r_0r_3} \\ & \tau_{r_1}^2 & \tau_{r_1r_2} & \tau_{r_1r_3} \\ & & \tau_{r_2}^2 & \tau_{r_2r_3} \\ & & & \tau_{r_3}^2 \end{bmatrix}\right)$$

Reduced Form

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

From the reduced form, we can clearly see that the runoff efficiency for a given year within a specific watershed and cluster is determined by several components. First, the baseline level of runoff efficiency for an individual watershed is influenced by the grand mean intercept (η_{000}) and the watershed's average covariate values ($\overline{\text{ai}}_{ik}, \overline{\text{si}}_{ik}, \overline{\text{sf}}_{ik}$). However, the watershed's mean level of runoff efficiency also reflects deviations from the grand mean effects of these averages, as expressed through cluster-specific fixed effects ($(\gamma_{01k}-\eta_{100})\overline{\text{ai}}_{ik}+(\gamma_{02k}-\eta_{200})\overline{\text{si}}_{ik}+(\gamma_{03k}-\eta_{300})\overline{\text{sf}}_{ik}$). This highlights how cluster membership modifies the influence of long-term climatic averages on runoff efficiency.

Second, runoff efficiency fluctuates in response to yearly deviations in climatic factors, represented by $(\text{ai}_{tik}-\overline{\text{ai}}_{ik}), (\text{si}_{tik}-\overline{\text{si}}_{ik}), (\text{sf}_{tik}-\overline{\text{sf}}_{ik})$. The sensitivity of runoff efficiency to these deviations is driven by regional grand mean estimates ($\eta_{100}, \eta_{200}, \eta_{300}$) and further shaped by cluster-level fixed effects, reflecting cluster-specific adjustments to these sensitivities. This framework captures the dynamic interactions between yearly climatic fluctuations and the hierarchical structure of the watersheds and clusters.

The model also accounts for variability at different levels through random effects. Cluster-level random effects ($r_{0k}+r_{1k}(\text{ai}_{tik}-\overline{\text{ai}}_{ik})+r_{2k}(\text{si}_{tik}-\overline{\text{si}}_{ik})+r_{3k}(\text{sf}_{tik}-\overline{\text{sf}}_{ik})$) capture differences between clusters, reflecting how clusters influence both the baseline and the sensitivities of runoff efficiency to yearly climatic deviations. Similarly, watershed-level random effects $(u_{0ik} + u_{1ik}(\mathrm{ai}_{tik} - \overline{\mathrm{ai}}_{ik}) + u_{2ik}(\mathrm{si}_{tik} - \overline{\mathrm{si}}_{ik}) + u_{3ik}(\mathrm{sf}_{tik} - \overline{\mathrm{sf}}_{ik}))$ capture unobserved variability within watersheds, such as local hydrological, geographic, or soil characteristics that are not explicitly modeled. Finally, the residual term (ϵ_{tik}) accounts for unexplained variability at the year-to-year observation level, representing short-term fluctuations and noise not captured by the fixed or random effects.

5 Results

Table 2: Fixed Effects Summary

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 3: Random Effects Summary

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	

Based on the model, we can see that the fixed effects indicate significant relationships between runoff efficiency and both average and individual climatic covariates. For the

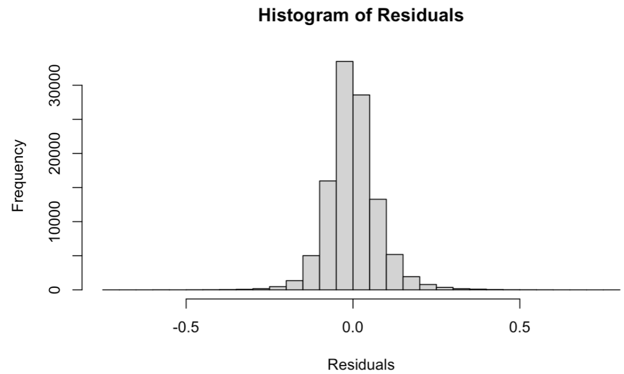


Figure 4: Residual Distribution

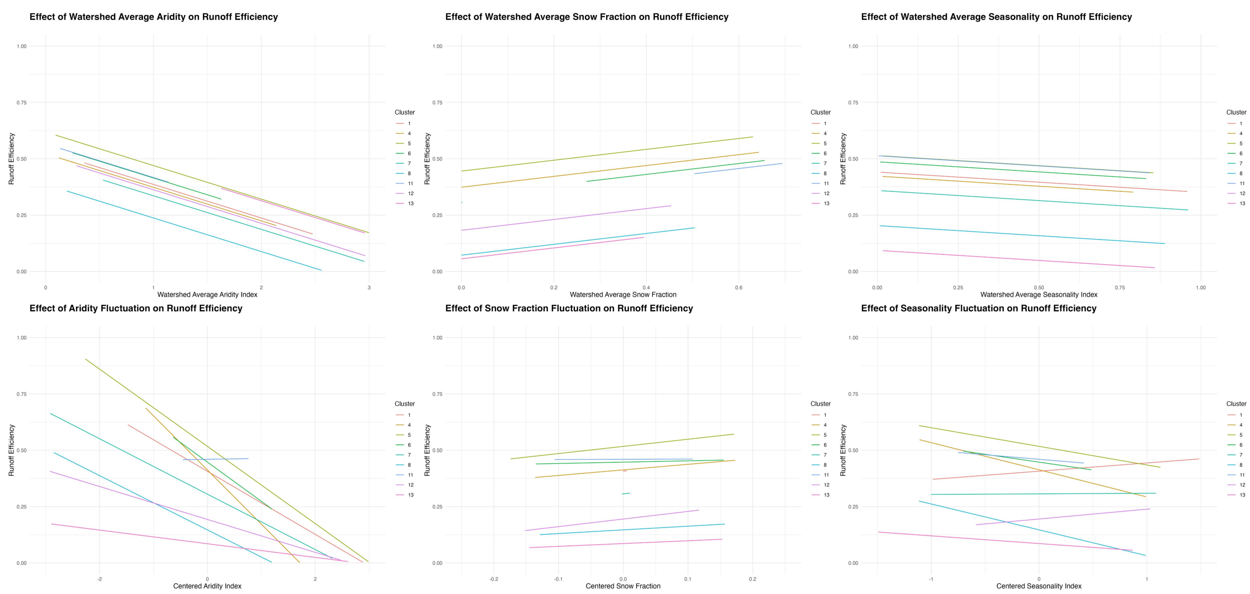


Figure 5: Fixed Effect of Climate Factors

watershed-level averages, the average aridity index has a strong negative effect (-0.149, $p < 0.001$). This suggests that watersheds with higher long-term aridity tend to exhibit lower runoff efficiency, likely due to increased water loss through evapotranspiration, which exceeds precipitation in arid conditions. Similarly, the average seasonality index shows a significant negative effect (-0.0899, $p < 0.001$), indicating that higher synchronization between precipitation and temperature reduces runoff efficiency, potentially by increasing evaporation when rainfall coincides with warmer temperatures. In contrast, the average snow fraction has a positive and significant impact (0.241, $p < 0.001$), reinforcing the critical role of snow in enhancing water availability through delayed runoff and storage.

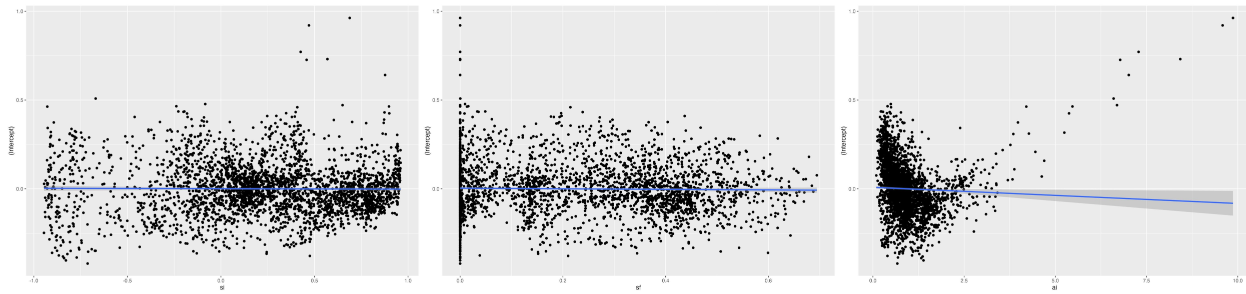


Figure 6: Random Effect and Level 2 Variables (Watershed Average SI, SF, AI)

Yearly deviations from the watershed-level means further highlight the importance of climatic variability. Individual aridity deviations negatively affect runoff efficiency (-0.119, $p = 0.002$), reflecting the hydrological stress imposed by short-term increases in aridity. For deviations in snow fraction, the positive effect (0.210, $p = 0.019$) emphasizes the role of above-average snowfall years in improving runoff efficiency by contributing to delayed water release. Interestingly, individual deviations in seasonality index show a marginally negative effect (-0.042, $p = 0.079$), which suggests that yearly fluctuations in seasonality may have less influence on runoff efficiency compared to long-term trends.

The random effects reveal substantial variability at both watershed and cluster levels. For watersheds, the variance in the intercept (0.022) and the slopes for *centered ai* (0.019), *centered si* (0.007), and *centered sf* (0.027) underscores the heterogeneity in how individual watersheds respond to climatic deviations. At the cluster level, the variance in the intercept (0.005) and slopes for *centered ai* (0.006), *centered si* (0.004), and *centered sf* (0.021) highlights the role of regional cluster characteristics in modifying runoff efficiency.

Residual diagnostics confirm that the model explains a substantial portion of the variability, with normally distributed errors supporting good model fit. These findings emphasize the importance of accounting for hierarchical and temporal variability in hydrological models and underscore the critical role of snow-dominated processes in sustaining runoff efficiency under climatic variability.

6 Conclusion

This study examined the relationships between climatic covariates and runoff efficiency across watersheds and clusters using a multilevel model. Both long-term climatic averages and yearly deviations significantly influence runoff efficiency, underscoring the interactions between climate, hydrology, and geography. The results also address three primary aspects of this study. First, runoff efficiency within a watershed is significantly influenced by yearly deviations in climatic covariates. Deviations in aridity index consistently show negative effects, reflecting reduced efficiency during drier-than-average years, while deviations in snow fraction positively affect efficiency, highlighting the buffering role of snow-dominated hydrological systems. Second, watershed-level averages of climatic covariates reveal long-term patterns that align with expectations based on hydrological theory. Higher average aridity and seasonality indexes reduce runoff efficiency, while higher average snow fraction enhances it, reinforcing the role of snow-dominated watersheds in providing sustainable water resources. Third, regional clusters exhibit substantial variability in baseline runoff efficiency and in the sensitivity of efficiency to both long-term averages and yearly deviations of climatic covariates. These findings suggest that regional characteristics, such as climate zones and ecological factors, play a crucial role in shaping hydrological responses.

However, the model has limitations. It assumes linear relationships, potentially oversimplifying hydrological processes, and omits non-climatic factors like land use, soil type, and human activities. Future work should incorporate additional covariates, such as vegetation and groundwater levels, and explore nonlinear methods or machine learning to capture complex interactions. Applying this framework to other regions and climate zones, alongside future climate scenarios, could refine predictions of runoff efficiency and inform water resource management.

A Model Results Appendix

```
lmer(formula = q_mean_p ~ avg_ai + cnt_ai + avg_si + cnt_si +
    avg_sf + cnt_sf + (1 + cnt_ai + cnt_si + cnt_sf | gridcode) +
    (1 + cnt_ai + cnt_si + cnt_sf | cluster), data = dat)
            coef.est coef.se
(Intercept)  0.50     0.03
avg_ai      -0.15     0.01
cnt_ai      -0.12     0.03
avg_si      -0.09     0.01
cnt_si      -0.04     0.02
avg_sf       0.24     0.02
cnt_sf       0.21     0.06

Error terms:
 Groups   Name        Std.Dev. Corr
 gridcode (Intercept) 0.15
          cnt_ai      0.14     -0.24
          cnt_si      0.08      0.02  0.25
          cnt_sf      0.16      0.13  0.34  0.50
 cluster  (Intercept) 0.07
          cnt_ai      0.08     -0.04
          cnt_si      0.06      0.27  0.43
          cnt_sf      0.14      0.15 -0.36  0.36
 Residual             0.08
---
number of obs: 107161, groups: gridcode, 3022; cluster, 9
AIC = -216960, DIC = -217105.1
deviance = -217060.7
```