

NM WRRI Student Water Research Grant Final Report

Characterizing the Spatial Coherence of Low Streamflow Events
across New Mexico and Colorado

NMWRRI-SG-FALL2024

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September 30, 2025

Abstract

Concurrent occurrences of low flow events across multiple watersheds pose significant challenges for water resources management. Understanding the spatial dependence and temporal variability of these hydrological extremes is crucial for the development of effective mitigation strategies and optimal water management. However, such dependence remains poorly quantified at the continental scale. This work aims to characterize the spatial coherence of low flow events across the Southwest United States. We use streamflow data from a set of minimally regulated stations with observations spanning from 1960 to 2024. To understand the temporal variability of low flow conditions, we employ a stochastic streamflow generator conditioned on the El Niño Southern Oscillation (ENSO) phase to simulate spatially coherent streamflow time series preserving the spatial and temporal correlation of the observed data. We define low flows as the fifth percentile of monthly streamflow and quantify their spatial dependence by examining the joint probability of low-flow events occurring simultaneously at each pair of watersheds in our dataset. Our results reveal that ENSO phases indeed modulate not only

the frequency of low flows, but also the spatial coherence of low flows in the Southwest. We further extended our analysis to the entire Conterminous United States to obtain large-scale information of the spatial dependence of low flow events.

1. Introduction

Understanding the spatial patterns of river flows is a long-standing challenge in hydrology. The spatial variability of streamflow directly impacts ecosystems, communities, and multiple human economic activities including agriculture and hydropower production which rely on streamflow [Postel and Richter, 2012, Rudd et al., 2017, Mohr et al., 2022]. Predicting the frequency, duration and spatial extents of low flow events is a key issue in water resources management, as these can pose significant risks to communities and to the local economy. Concurrent low flow events in multiple watersheds can be especially challenging, as they threaten water availability in extended regions. Due to the sparsity of the existing national network of streamflow gauge stations, the problem of characterizing the spatial dependence of river flows is tightly connected to that of predicting streamflow in ungauged basins [Blöschl, 2013] and to infer regional flow duration curves [Fennessey and Vogel, 1990, Castellarin et al., 2004, Mohamoud, 2008, Cheng et al., 2012]

Multivariate approaches have been developed to capture spatial dependencies in low flow events across multiple stations. Copula-based methods represent the most prominent framework, with Zhang et al. [2017] utilizing various copula families to quantify joint probabilities of concurrent hydrological droughts, and Brunner et al. demonstrating that Fisher copulas effectively represent spatial dependence and can be adapted for interpolation between gauged and ungauged locations. Zaerpour et al. [2021] investigated how teleconnection indices impact monthly streamflow from multiple watersheds using stochastic multi-site streamflow generators based on vine copulas.

Recent research has emphasized the importance of quantifying spatial coherence beyond individual basin scales. Berghuijs et al. [2019] introduced the concept of 'synchrony scales' for European floods, showing that spatial coherence extends far beyond individual drainage basins and varies across regions and time periods. Chagas et al. [2024] found that while catchment characteristics dominate low flow spatial variability at regional scales, climate and landscape controls become equally important at continental scales, suggesting that large-scale climate patterns should play a significant role in controlling low flow spatial coherence across the continental United States.

The El Niño-Southern Oscillation (ENSO) represents the dominant mode of interannual climate variability globally [Rasmusson and Wallace, 1983]. ENSO-driven tropical heating anomalies excite quasi-stationary Rossby waves that propagate globally, creating spatially coherent climate responses across North America through atmospheric teleconnections [Philander, 1989]. Early foundational work by Ropelewski and Halpert [1986] established the spatial patterns of ENSO teleconnections across North America, revealing that El Niño events typically increase precipitation in the southwestern United States while decreasing precipitation in the Pacific Northwest, with La Niña conditions producing opposite patterns. Chiew and McMAHON [2002] conducted comprehensive global analyses confirming spatially coherent ENSO-streamflow teleconnections across large geographical regions. How-

ever, ENSO's influence is not static and is modulated by other climate oscillations. Barnett et al. [1999] showed that Pacific Decadal Oscillation (PDO) operates independently from ENSO on longer timescales. Mo et al. [2009] found that Atlantic Multidecadal Oscillation (AMO) significantly modulates ENSO's impact on drought across the United States. Singh et al. [2021] demonstrated that decadal and multidecadal oscillations cause significant modulation of ENSO effects, showing that ENSO teleconnections can be enhanced or even reversed depending on the phases of these longer-term climate cycles. Regional studies have identified spatially coherent streamflow responses to ENSO events. Kahya and Dracup [1993] found particularly strong signals in the Gulf of Mexico, Northeast, North Central, and Pacific Northwest regions. Hidalgo and Dracup [2003] demonstrated that ENSO effects on streamflow vary significantly by season, while Jong et al. [2016] revealed that El Niño influence on precipitation strengthens from early to late winter with critical implications for regional streamflow patterns.

2. Data Sources

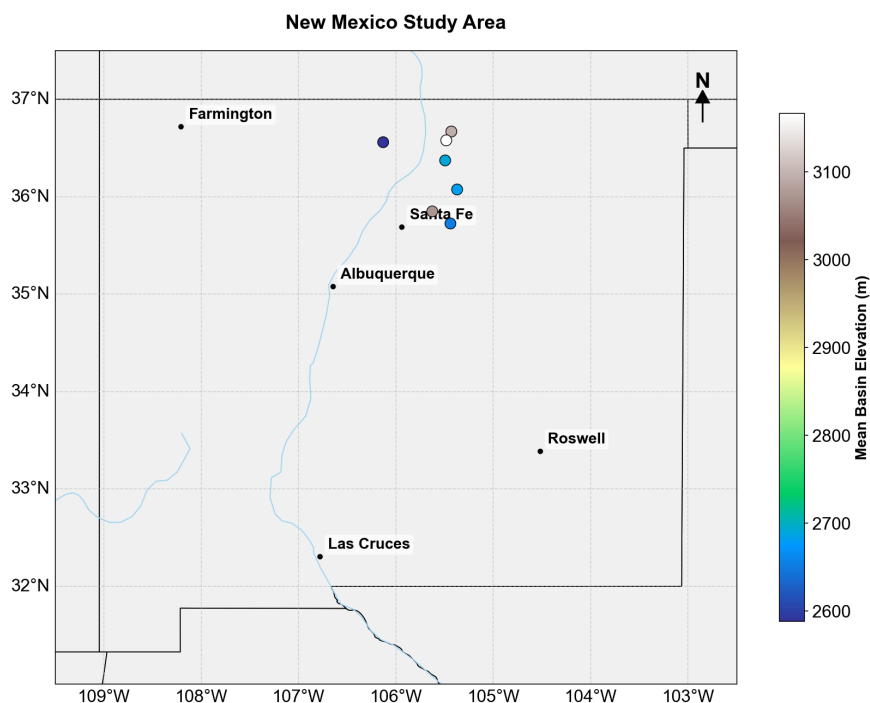


Figure 1: Study Area

This analysis utilized historical streamflow observations from the GAGES-II dataset [Falcone, 2011], which provides streamflow records alongside relevant watershed characteristics, station identifiers, and geographic coordinates. Streamflow data were obtained through the United States Geological Survey API [USGS, 2024], with complete records retrieved from all 8,839 available stations nationwide. Station selection followed three sequential filtering criteria to ensure data quality and study objectives. First, we applied a minimum catch-

ment area threshold of 25 km², excluding smaller watersheds from the analysis. Second, we selected only minimally regulated basins by calculating upstream reservoir storage duration for each station, defined as the ratio of total upstream dam storage volume to mean daily streamflow volume. Stations with calculated upstream dam storage exceeding 5 days were excluded to minimize anthropogenic flow alterations. Third, we imposed strict data completeness requirements: stations must have less than 0.5% missing data overall, no more than 7 consecutive missing observations, and continuous records spanning from 1960 to 2024. Following application of these filters, we focused our analysis on qualifying stations within New Mexico, as illustrated in Figure 1.

3. Methodology

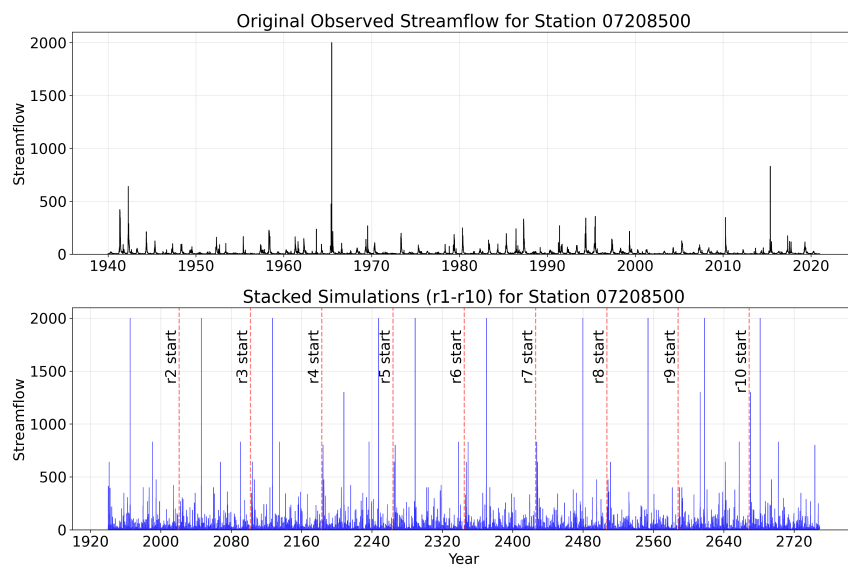


Figure 2: Comparison of original observed streamflow (top) and stacked simulations (bottom) for Station RAYADO CREEK NEAR CIMARRON, New Mexico, showing the temporal distribution of streamflow from 1940-2020 in the observed record and projected into the future through multiple simulations. Discharge units in cubic feet per second.

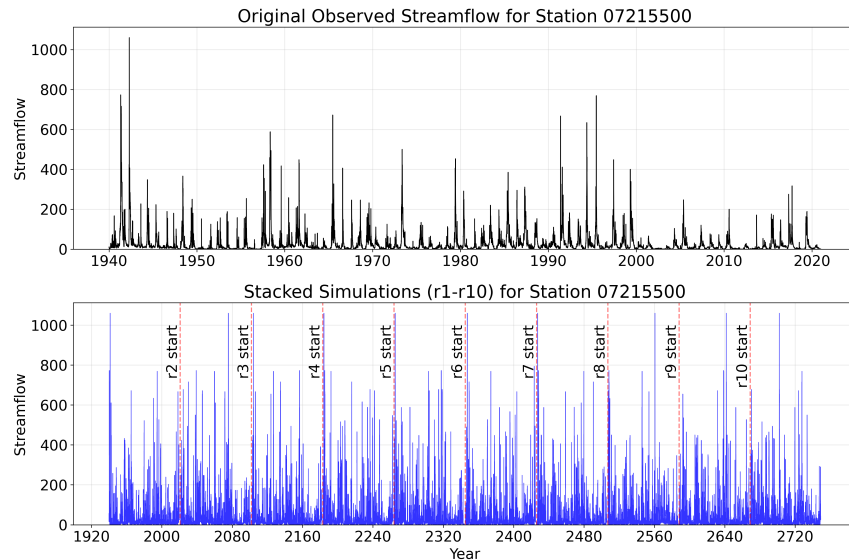


Figure 3: Comparison of original observed streamflow (top) and a set of simulations (bottom) for Station at MORA RIVER AT LA CUEVA, New Mexico, illustrating how the statistical properties of the historical record are preserved in the simulations. Discharge units in cubic feet per second.

This study presents a methodology for characterizing the spatial dependence of low-flow streamflow events and their interannual variability using an extensive dataset of historical streamflow records and climate indices, including the El Niño-Southern Oscillation (ENSO) index. We employ a wavelet-based phase randomization approach introduced by Brunner and Furrer to generate synthetic streamflow time series that preserve both temporal auto-correlations and spatial dependencies across multiple watersheds.

Figure 2 and 3 show the comparison of the simulation output to the original observed streamflows values of two stations in New Mexico. 10 realizations of the streamflow were obtained from the observed streamflow of each station using the procedure that is mentioned above. These multiple realizations can help us to extend our time series when they are stacked successively.

ENSO variability is incorporated into our simulations through a non-stationary modeling framework. We utilized historical El Niño-Southern Oscillation (ENSO) reconstructions from the Multivariate ENSO Index (MEI) dataset Wolter and Timlin [2011], which offers a more comprehensive characterization of ENSO variability than univariate indices by incorporating multiple atmospheric and oceanic variables. First, we remove the ENSO signal from observed streamflow data using linear regression analysis. Second, we simulate the residual streamflow components. Finally, we reintroduce the ENSO effects to generate conditional streamflow scenarios. This methodology enables us to distinguish between ENSO-driven changes in flow magnitude and the spatial synchronicity of streamflow events across the continental United States, thereby providing insights into the relative contributions of large-scale climate forcing versus local hydrological processes in determining regional streamflow patterns.

To evaluate the frequency of multiple stations being below a fixed low-flow threshold (e.g., the 5% of streamflow frequency distribution) we employ a stochastic streamflow generator

trained on the observed data. This approach allows us to i) generate long daily streamflow time series to evaluate the frequency of low flows, and ii) can be used to generate streamflow conditional to specific conditions (e.g., El Niño or La Niña years, which are known to impact precipitation and snowpack in Northern New Mexico and Colorado).

We define the simultaneous occurrence of low flows across stations as follows:

$$P(A_{ref} | A_k) = \frac{P(A_{ref} \cap A_k)}{P(A_k)} \quad (1)$$

provided that $P(A_k) > 0$.

We have $P(A_k) = 0.05$ because the low-flow event A_k (i.e., the threshold T_k) was defined using the 5th percentile (p_{05}) of the streamflow distribution at station S_k . By definition, the probability of observing a flow value less than or equal to the 5th percentile is 0.05, hence $P(Q_k \leq Q_{k,p05}) = 0.05$.

4. Spatial Integral length Scale

4.1 Correlation-Integral length Scale

For each station i , we quantify the spatial extent of streamflow synchrony using an integral length scale L_i , defined as:

$$L_i = \int_0^\infty \rho_i(r) dr \quad (2)$$

where $\rho_i(r)$ is the Spearman correlation coefficient between station i and other stations as a function of distance r (km).

4.2 Low-flow Conditional Probability Integral Scale

To quantify spatial coherence of drought events, we define an analogous integral scale based on conditional probabilities as described in equation 1. For each reference station i , the low-flow integral length scale L_i^{LF} is:

$$L_i = \int_0^\infty P_i(r) dr \quad (3)$$

where $P_i(r)$ is the conditional probability that a station at distance r from station i experiences a low-flow event given that station i is in low flow:

The integral length scale L_i can be interpreted as a characteristic distance over which streamflow remains constant with the reference station. Larger values indicate that the station's flow behavior is synchronized over longer distances.

5. Results and Discussion

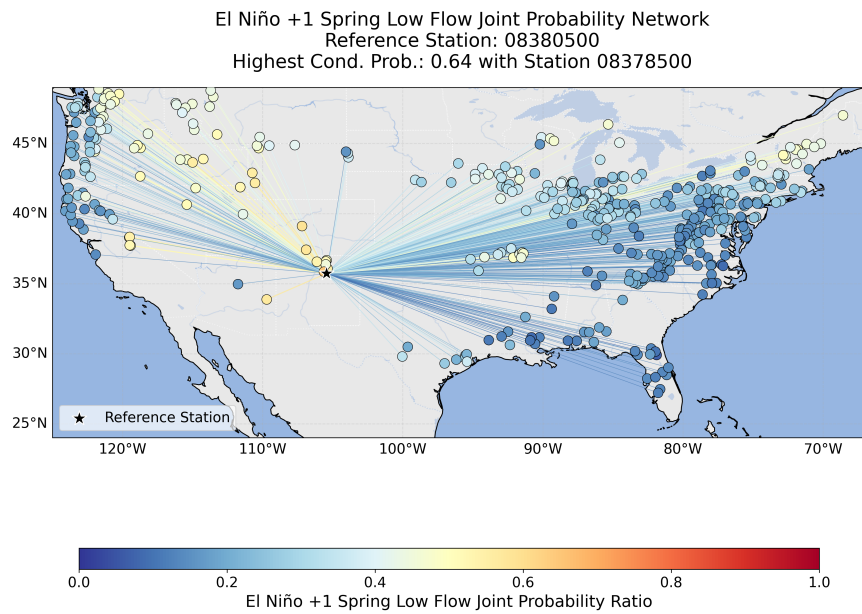


Figure 4: Low Flow Conditional Probability for Station 08380500 for El Niño phase, showing the spatial correlation of low flow events across multiple stations in the study region. Color scale represents the low flow joint probability i.e. probability of low flow in a station when we know another station is in low flow condition.

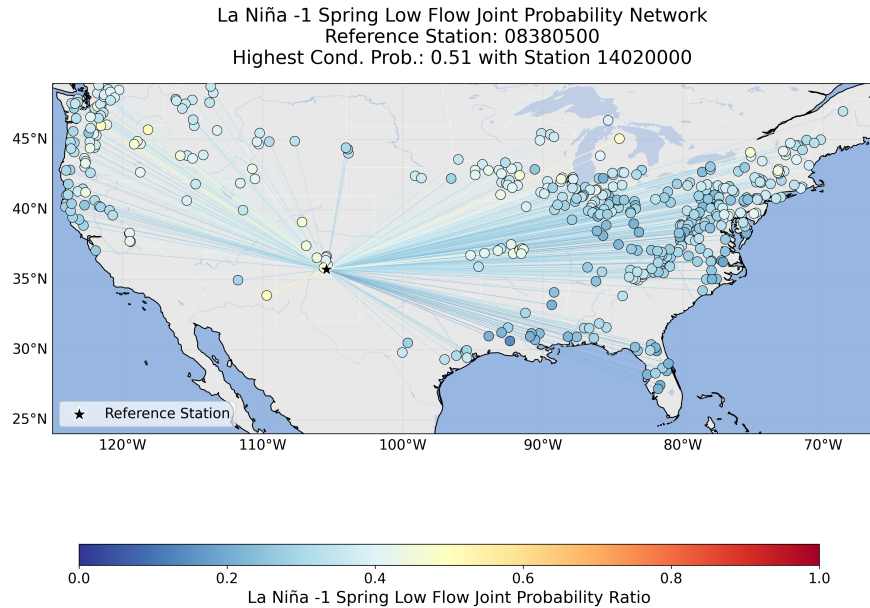


Figure 5: Low Flow Conditional Probability for Station 08380500 for La Niña phase, showing the spatial correlation of low flow events across multiple stations in the study region. Color scale represents the low flow joint probability i.e. probability of low flow events in the reference station when we know another station is in low flow conditions.

Our analysis reveals significant spatial coherence patterns in low streamflow events across the conterminous United States, with notable modulation by ENSO phases.

The comparison between El Niño and La Niña conditions reveals distinct patterns in drought spatial coherence. During El Niño conditions, figure 4, the reference station in New Mexico shows elevated joint probabilities of concurrent low flows with stations across a broad geographic area, particularly in the western United States. The conditional probabilities reach values up to 0.64, indicating a 64% likelihood that the reference station experiences low flow when a correlated station is also experiencing low flow conditions.

In contrast, La Niña conditions, figure 5 demonstrate a different spatial pattern, with slightly higher probability of concurrent low flow events among stations in the Eastern United States. The maximum conditional probability under La Niña conditions appears lower with the maximum joint concurrent probability of 0.51. On the other hand, it also shows a lower likelihood of concurrent low flow event with stations across the western United States compared to El Niño condition.

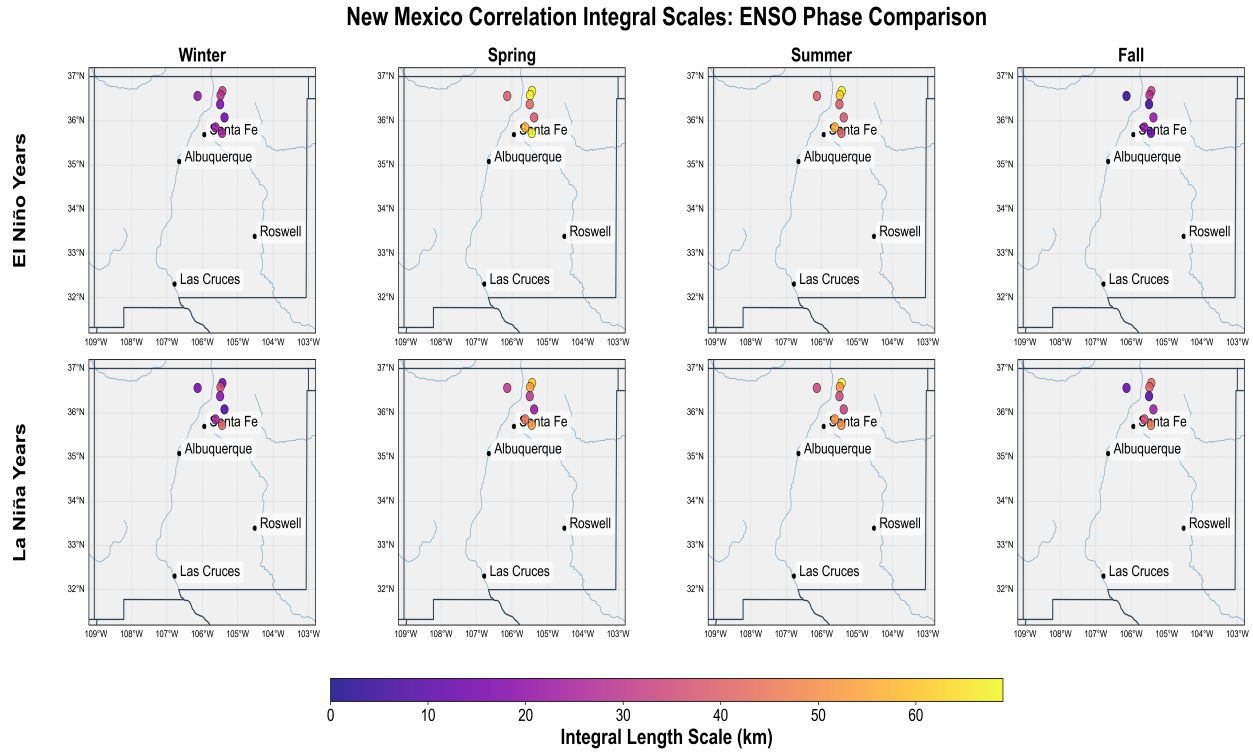


Figure 6: Integral length Scale of streamflow from historical dataset in different seasons for different ENSO phases

The following results are from the observed data i.e. not from the simulated data. Figure 6 represents the integral length scale of streamflow of stations in New Mexico calculated from equation 2. It reflects the synchrony of overall streamflow variability. For El Niño and La Niña both, the synchrony is low in winter and fall and approximately double in spring and summer than that of fall and winter. The most significant deviation occurs during the spring, where the integral length scale during El Niño phase is noticeably higher than that of La Niña phase. The synchrony in summer is similar in both phases.

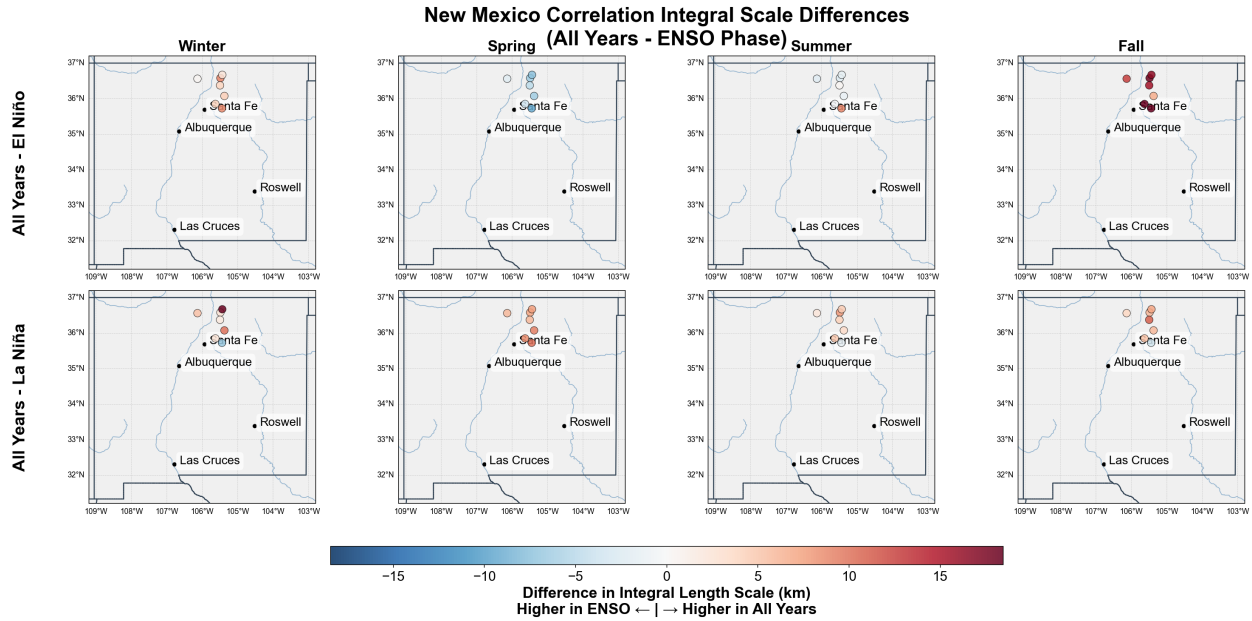


Figure 7: Correlation Integral length Scale Difference of El Niño and La Niña phases from overall dataset

Figure 7 is the difference in integral length scale of streamflow calculated from El Niño and La Niña years from the integral length scale calculated from entire length of time series. This integral length scale was calculated using equation 2. Positive values (red) indicate stations where spatial synchrony of streamflow is lower in El Niño or La Niña years compared to the overall years. On the other hand, the negative values (blue) indicate higher synchrony in El Niño or La Niña years compared to overall years.

During Fall and Winter of El Niño years, the streamflow synchrony decreases compared to integral length scale of overall years as indicated by red dots. During Spring and Summer the streamflow synchrony increases compared to integral length scale of overall years. On the other hand, for La Niña years, there is a decrease in synchrony across all seasons

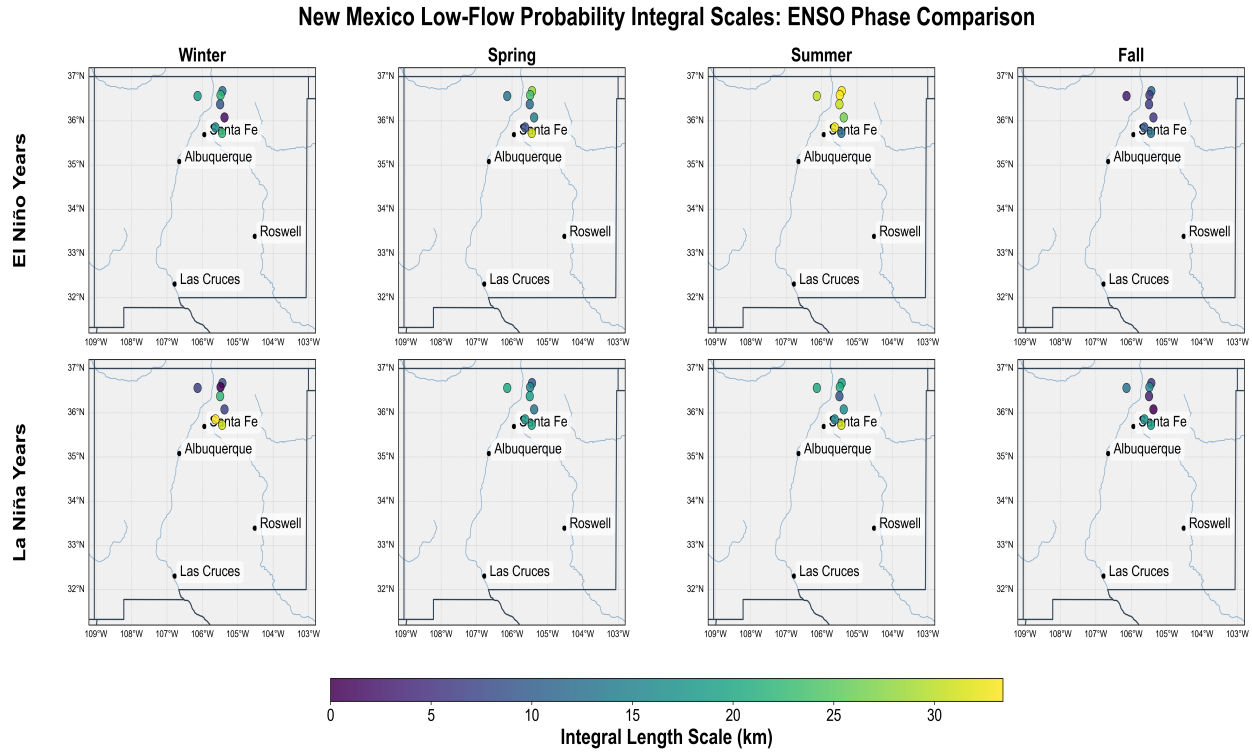


Figure 8: Integral length Scale of Low flow from historical dataset in different seasons for different ENSO phases

Figure 8 represents the integral length scale of low flows of stations in New Mexico calculated from equation 3. The overall synchrony of low flows is lower across seasons and across ENSO phases compared to the overall streamflow as seen in figure 6. The seasonal synchrony is lower in fall in both El Niño and La Niña years, which is the same pattern that was seen in 6. The most noticeable difference is seen in Summer. The synchrony in El Niño season is considerably high in Summer compared to the synchrony in Summer of La Niña years.

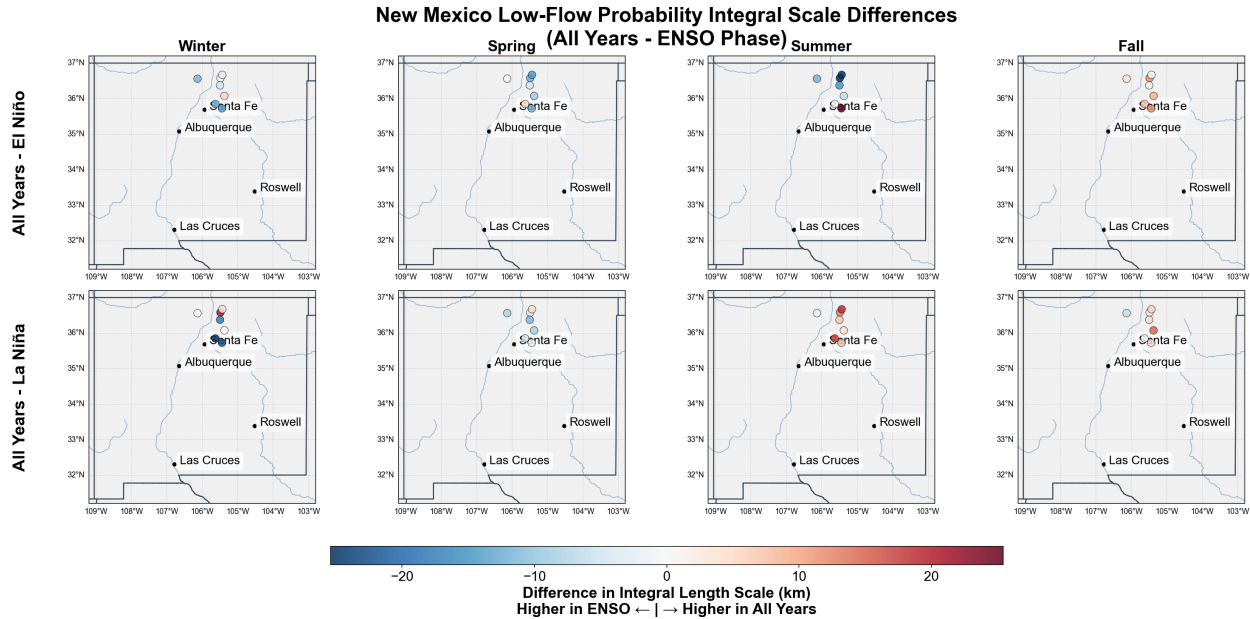


Figure 9: Low Flow Integral length Scale Difference of El Niño and La Niña phases from overall dataset

Figure 9 is the difference in integral length scale of low flows calculated from El Niño and La Niña years from the integral length scale calculated from entire length of time series. This low flow integral length scale was calculated using equation 3. From figure 9 we see a general increase in low flow synchrony across seasons compared to overall streamflow integral length scale difference as seen in figure 7. The exception is summer of La Niña years where we see decrease in low flow synchrony.

6. Conclusions and Recommendations

These spatial coherence patterns suggest that low flow risk in the Southwest is very seasonal. In this study, we found that ENSO modulates this pattern. There are other teleconnections like Pacific Decadal Oscillation (PDO), Atlantic Multi-decadal Oscillation (AMO) etc that are likely to have similar or contrasting modulation behavior. A study incorporating multiple teleconnections quantifying the influence of these large scale climate conditions on extreme streamflow will broaden our understanding of the said patterns.

7. Grant Fund Usage

The NM WRRI grant funds (\$7,496) were allocated as follows:

- **Student Stipend:** \$7,113 provided essential support during the summer 2025 research intensive period, enabling full-time focus on data analysis, methodology development, and manuscript preparation.

- **Fringe Benefits:** \$83 covered mandatory graduate student benefit costs.
- **Conference Travel:** \$300 supported attendance at the 69th Annual NM Water Conference, including poster preparation, lodging, and transportation costs.

All funds were expended within the project period (October 1, 2024 - September 30, 2025) and directly supported the research objectives outlined in the original proposal.

8. Presentations and Publications

8.1 Presentations

- **Poster Presentation:** "Characterizing the spatial coherence of low streamflow events across New Mexico and Colorado" presented at the 69th Annual NM Water Conference, Pojoaque, NM, November 5-6, 2024.
- **Oral Presentation:** "Predicting joint low flow events across the Conterminous United States: An approach based on Stochastic Simulation and Machine Learning prediction" submitted to the New Mexico Geological Society's Spring Meeting, April 2025.

8.2 Publications in Preparation

- **Peer-reviewed Manuscript:** "Characterizing the spatial coherence of low streamflow events over the Conterminous United States and its interannual variability" is in preparation for submission to *Water Resources Research*. Expected submission: November 2025.

9. Degree Completion and Career Plans

Degree Completion: I expect to complete my Master of Science degree in Earth and Environmental Science at New Mexico Institute of Mining and Technology by Spring 2026. This research forms the core of my thesis project, with the extended analysis planned as additional chapters.

Career Plans: Following graduation, I plan to work in the water resources field for several years, with preference for positions either in New Mexico or in my home country of Nepal. This experience will provide practical application opportunities for the research methods developed during this project. After gaining professional experience, I intend to pursue a Ph.D. to further advance my research capabilities in hydrology and water resource management.

Acknowledgments

We gratefully acknowledge funding support from the New Mexico Water Resources Research Institute and the New Mexico State Legislature (Grant NMWRRI-SG-FALL2024). We thank Carolina Mijares for project administration and the USGS for maintaining the comprehensive

streamflow database that made this analysis possible. Additional thanks to the Hantush-Deju Center for Hydrology Innovation at New Mexico Tech for providing computational resources and research infrastructure support. I also thank Dr. Manuela Brunner for her valuable comments.

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