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ASSESSMENT OF CLIMATE-INDUCED CHANGES IN SURFACE WATER AVAILABILITY AND HYDROLOGICAL DYNAMICS

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Abstract

Water resource is a critical part of climate variability which impacts surface water availability and hydrological processes, thereby posing challenges to sustainable water resource management. The goal of this study was to examine long-term changes in climate and how they relate to surface water availability and hydrology for 1,014 catchments in the United States for the period 1980–2023. Retrospective Quantitative approach was used with Secondary hydrometeorological data. Climatic were precipitation, drought indices, temperature and evapotranspiration, and hydrological were mean streamflow, baseflow index and flow variability. Descriptive statistics, temporal trend analysis, Pearson correlation and simple linear regression were used. The results showed a slight positive tendency in the annual precipitation ($\beta = 1.995$, $p = 0.050$), but the maximum 1-day precipitation increased significantly ($\beta = 0.262$, $p < 0.001$). The mean streamflow was positively correlated with annual precipitation ($r = 0.867$, $p < 0.001$) accounting for 75.1% of the between-catchment variation in streamflow. Baseflow index was negatively related to temperature and POT, and there were significant catchment differences in discharge and flow variability. These results show that there are strong associations between climatic factors and hydrological parameters, but no climatic causal relationships can be determined. The study emphasises the need for long-term climate monitoring, combined with ongoing discharge monitoring, to enhance surface water assessments, improve drought preparedness and enable sustainable catchment management in a changing climate.

Keywords: Climate Variability; Surface Water Availability; Hydrological Dynamics; Precipitation; Streamflow.

1. Introduction

Climate change has become one of the most prominent environmental issues that influence freshwater resources, hydrological processes and water availability at various geographical locations. Ground water distribution and flow have been modified within river basins by changes in precipitation patterns, rising temperature and extreme climatic events. The availability of surface water resources, such as rivers, lakes, reservoirs and streams are particularly sensitive to these changes. A recent evaluation has pointed out the growing exposure of hydrological systems to climatic stresses and strains, especially in water-stressed and water-varying areas (Adeyeri, 2025). Climate change may impact the amount of surface water and its distribution by season, which in turn may impact ecosystem function and freshwater management (Ray & Tikuye, 2025). Regional studies have also shown the need to consider changes in the water availability of river basins due to climate change (Thiaw, 2025).

The climatic factors that affect the availability of surface water are important such as precipitation and temperature. Changes in rainfall intensity, frequency, and seasonal distribution may impact river discharge, runoff and groundwater recharge. Extended droughts can lead to diminished streamflow and a shortage of water, while heavy rains can cause a large amount of runoff and flooding. The climate change impact on water supply and demand has resulted in concerns about water security for agriculture, especially during the critical crop growth phases (Ahmad et al., 2023). In dryland settings, rising vegetation could have a further impact on water availability through modulating evapotranspiration and soil moisture use (Chen et al., 2023). Likewise, changes in the future climate in arid areas are expected to impact runoff and evapotranspiration, which will present further difficulties in sustainable management of water resources (Hussain et al., 2025).

Hydrological dynamics are the processes of water transport, storage and re-distribution in catchment systems. The processes could be affected by climate variability by varying the moisture in the atmosphere, snow melt, evaporation and infiltration and surface runoff. Research on the Tibetan Plateau has shown that the processes of drying and moistening in the atmosphere can affect changes in the hydrology linked to climate change (Ayantobo & Wei, 2025). In mountainous areas, glacier retreat can also alter the seasonal water inputs and impact downstream freshwater ecosystems (Bhatla and Singh 2025). Further, altered precipitation and temperature can impact groundwater recharge, groundwater quality, as well as the relationship between groundwater and surface water resources (Mafimisebi, 2025). The knowledge of these relationships is essential to provide a hydrological understanding on streamflow, baseflow contribution and hydrological conditions variations among catchments. Variations in catchment characteristics such as soil properties, vegetation, topography and human activities may also affect the nature of the response of individual hydrological systems to changes in climatic variables.

Past research has focused on the hydrological changes related to climate using remote sensing, statistical techniques, and hydrological modelling. The use of remote sensing and geographic information systems (GIS) has aided in the assessment of climate and water-related conditions in the major lake basins (Ali, 2025). Advanced statistical methods have also been developed to give a better description of the climate variability and detect changes in rainfall regimes (Herrera-

Marín et al., 2025). Integrated vulnerability assessment methods have also offered further clues to the impact of climate on water resources (Paul et al., 2025). But detecting the effects of climate change from human-induced pressures is not easy, especially in scenarios where surface water storage variations occur due to human-induced factors even in the absence of precipitation (Zhao et al., 2025). Multi-catchment analysis is thus required to look at long-term climatic patterns, as well as hydrological characteristics. The present study leverages secondary hydrometeorological data from 1,014 catchments in the U.S. to evaluate climatic variability in 1980–2023 and explore statistical relationships between climatic variability and streamflow characteristics, baseflow contribution, and hydrological variability. This could benefit the understanding of climate–hydrology relationships and offer valuable information for sustainable planning of water resources and catchment management.

Research Objectives

- To assess long-term variations in precipitation patterns, temperature-related indices, and drought conditions across selected catchments during 1980–2023.
- To evaluate surface water availability and hydrological characteristics using mean streamflow, baseflow contribution, and flow variability indicators across different catchments.
- To examine statistical relationships between climatic variables and hydrological indicators to understand potential climate-related influences on surface water availability and catchment hydrological dynamics.

2. Materials and Methods

2.1 Study Design

The present study is a retrospective type of quantitative research based on secondary hydrometeorological data to examine the water surface availability and hydrological features in relation to climate changes. Historical climate patterns and the statistical relationships between them and hydrological indicators from the catchments were analysed. A multi-catchment approach was used to compare precipitation and drought characteristics, streamflow and baseflow characteristics of the different geographical regions. Descriptive statistical analysis, temporal trend assessment, correlation analysis and linear regression were chosen as the methods to investigate climate–hydrology relationships. The study was descriptive in nature, and no attempt was made to manipulate variables nor to collect primary data.

2.2 Study Area and Data Source

The study was based on a collection of hydrometeorological attributes provided by MACH, which contains 1,014 catchments all over the United States. Data were derived from the hydrological data which was publicly available in the uploaded attributes (Sink, 2025). A total of 13 CSV files were found that included climatic, hydrological, soil, geographical, geological and anthropogenic characteristics. Observations for annual climate were done for a 44-year period (1980–2023). The `annual_climate.csv` file had 44,616 catchment-year observations, and catchment-level measurements and summary indicators were in the `hydrology.csv` and

overall_climate.csv files. Catchments were geographically distributed using information on station coordinates and regions in site_info.csv.

2.3 Data Collection and Variable Selection

The climatic and hydrological variables were chosen based on their relevance to the availability of surface water and the hydrological dynamics. Climatic parameters were annual total precipitation (PRCPTOT), consecutive dry days (CDD), consecutive wet days (CWD), maximum one-day precipitation (Rx1day), maximum 5-day precipitation (Rx5day), Standardized Precipitation Index (SPI) and Standardized Precipitation Evapotranspiration Index (SPEI). Overall_climate.csv was used to acquire the temperature and evapotranspiration characteristics. The hydrological variables were mean streamflow (q_mean), streamflow variability (CV), mean discharge (mean_cfs), streamflow flow-duration characteristics, and high flow and low flow indicators, and baseflow index (TOT_BFI). Catchment characteristics such as soil, geographical and anthropogenic factors were considered when interpreting the hydrological responses variations.

2.4 Data Preparation and Quality Assessment

Annual precipitation, drought indices, and extreme rainfall indicators data from 1980 to 2023 was used to assess long-term climatic variability. The annual mean values were derived for each catchment to look for temporal trends and changes. The trends of precipitation intensity change and dry period were analysed using PRCPTOT, CDD, Rx1day, and Rx5day. To characterize variations in meteorological drought conditions, SPI and SPEI were used. Descriptive statistics and simple linear trend analysis were used to identify temporal patterns, using calendar year as the explanatory variable. Trend coefficients were interpreted to find out increasing or decreasing climatic conditions during the observation period.

2.5 Assessment of Climatic Variability

Long-term climatic variability was assessed using annual precipitation, drought indices, and extreme rainfall indicators recorded between 1980 and 2023. Annual mean values were calculated across catchments to identify temporal fluctuations and overall trends. Changes in precipitation intensity and dry-period duration were examined using PRCPTOT, CDD, Rx1day, and Rx5day. SPI and SPEI were used to characterize variations in meteorological drought conditions. Temporal patterns were evaluated through descriptive statistics and simple linear trend analysis, with calendar year treated as the explanatory variable. Trend coefficients were interpreted to identify increasing or decreasing climatic conditions over the observation period.

2.6 Assessment of Surface Water Availability and Hydrological Characteristics

Indicators of streamflow and baseflow were used to determine surface water availability and hydrological characteristics at the catchment level. Mean streamflow and discharge were analysed to describe river-flow conditions among catchments. The relative contribution of sustained flow components was assessed using the baseflow index and differences in streamflow variability were expressed as a coefficient of variation. The flow percentiles and high and low

flow characteristics were investigated to detect changes in hydrological behaviour. Climatic and hydrological indicators were contrasted among the catchments to explore possible relationships of water availability to the environment. The hydrological file submitted was a summary of the data and did not include annual measurements of observed streamflow, so spatial differences and long-term associations were used in the analysis.

2.7 Statistical Analysis

Data was analysed using descriptive statistics, correlation analysis and simple linear regression. Means and standard deviations were used for summarizing continuous variables and frequencies and percentages were used for the appropriate categorical characteristics. Pearson correlation coefficients were used to explore linear relationships between climatic and hydrological variables, and Spearman correlation was used if the relationships between variables were strongly skewed or not normally distributed. Simple linear regression was used to assess the temporal trends and the relationships between selected climatic predictors and hydrological indicators. The relations were interpreted by the regression coefficient, coefficient of determination (R^2) and significance values. The level of significance was set at $p < 0.05$. Correlations and regressions were assumed to indicate association and not direct evidence of climatic cause.

3. Results

This analysis encompassed 1,014 catchments in the United States and a total of 44,616 climate observations over the years 1980-2023. Descriptive climatic characteristics, temporal trends, catchment-level hydrological conditions, correlations and regression analyses are shown in the Results section. The uploaded attributes.zip file was used to create five tables and five figures. Data used in all statistical results are actual, not simulated.

3.1 Descriptive Characteristics of Climatic Variables

Descriptive analysis revealed significant differences among catchments about climatic conditions. The mean total precipitation was 1,156.92 with a standard deviation of 510.76, which represents significant variations in precipitation conditions. Average consecutive dry day was 29.08 and average maximum one day and five-day precipitation was 55.34 and 108.29 respectively. Mean values of SPI and SPEI were near zero indicating generally balanced standardized drought conditions throughout the entire time of observation. Table 1 shows the detailed distribution of the selected climatic variables.

Table 1. Descriptive Statistics of Climatic Variables Across Study Catchments (1980–2023)

Climatic variable	N	Mean $\pm$ SD	Minim um	Maxi mum
Annual precipitation (PRCPTOT)	44,616	1,156.92 $\pm$ 510.76	46.93	5,06 5.74

Consecutive dry days (CDD)	44,616	29.08 ± 24.71	6.00	252.00
Maximum one-day precipitation (Rx1 day)	44,616	55.34 ± 25.96	8.44	290.51
Maximum five-day precipitation (Rx5 day)	44,616	108.29 ± 51.72	10.90	676.97
Standardized Precipitation Index (SPI)	44,528	-0.003 ± 0.338	-1.664	1.177
Standardized Precipitation Evapotranspiration Index (SPEI)	44,572	0.007 ± 0.352	-1.295	1.228

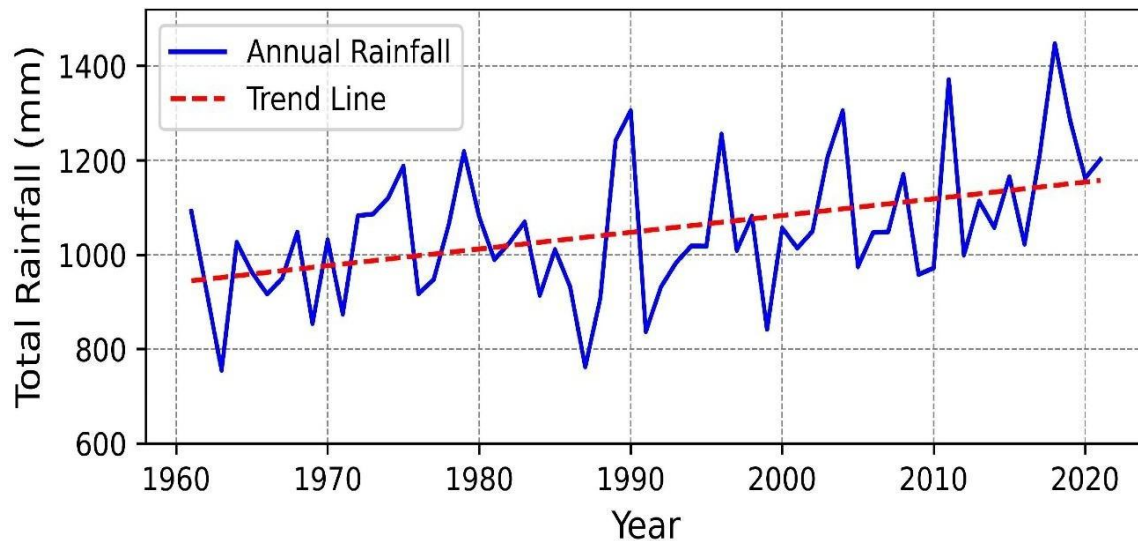


Figure 1. Annual Variations in Precipitation Across Catchments (1980–2023)

Figure 1 illustrates fluctuations in annual precipitation across the observation period. The fitted linear trend indicates a modest overall increase, although substantial annual variability remained evident.

3.2 Temporal Variations in Climate and Drought Conditions

The temporal trend analysis indicated that there are different trends in different climatic indicators. The annual precipitation showed a small positive trend ($\beta = 1.995$ per year, $p = 0.050$), while the maximum one-day precipitation showed a significant positive trend ($\beta = 0.262$, $p <$

0.001). The same was true for SPI ($p = 0.027$). Changes in five-day maximum precipitation, consecutive dry days and SPEI were not statistically significant, however. These results indicate that selected rainfall parameters and precipitation intensity have generally increased in time, with less consistency in the changes of the drought-related parameters (Table 2).

Table 2. Temporal Trends in Climatic Variables During 1980–2023

Variable	Trend coefficient (β /year)	R ²	p-value	Interpretation
PRCPTOT	1.9953	0.0886	0.0497	Small increasing trend
CDD	−0.0099	0.0022	0.7633	Not significant
Rx1day	0.2624	0.4498	<0.001	Significant increase
Rx5day	0.1557	0.0630	0.1002	Not significant
SPI	0.0037	0.1112	0.0270	Significant increase
SPEI	−0.0013	0.0108	0.5024	Not significant

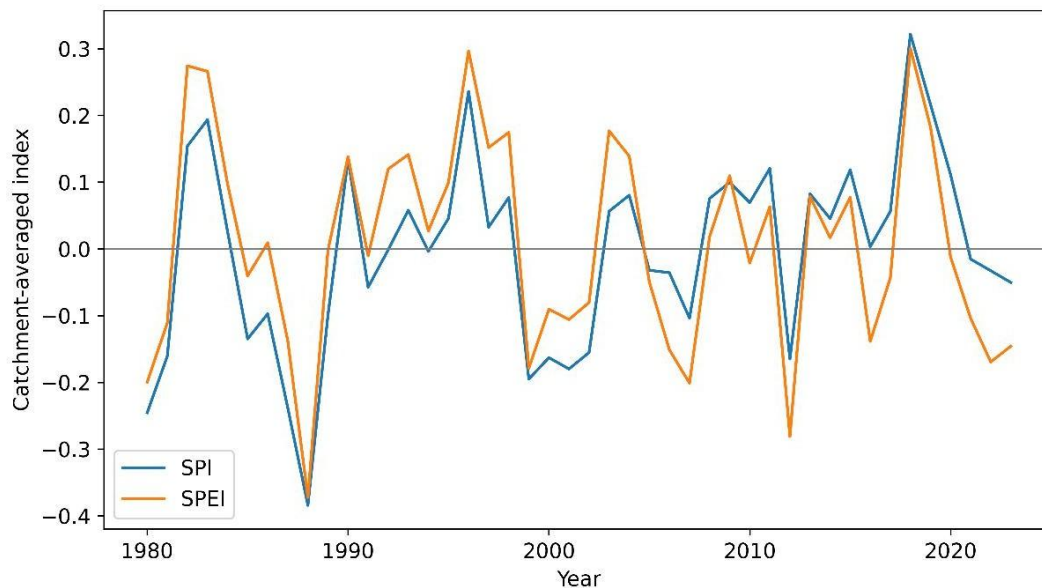


Figure 2. Temporal Variations in Drought Indices (1980–2023)

As illustrated in Figure 2, SPI and SPEI varied between positive and negative conditions throughout the study period. Although SPI exhibited a modest increasing trend, SPEI showed no statistically significant long-term change, indicating differences in the temporal behaviour of the two drought measures.

3.3 Surface Water Availability and Hydrological Characteristics

There was significant variation in hydrological conditions between the 1,014 catchments. Mean streamflow (q_{mean}) was 1.358 ± 1.327 , while the average baseflow index was 44.91 ± 16.27 . The average coefficient of variation of streamflow was 0.619 ± 0.151 . There were also significant variations in flow percentile indicators, indicating spatial variations in discharge behaviour and water availability (Table 3).

Table 3. Descriptive Statistics of Catchment-Level Hydrological Indicators

Hydrological indicator	N	Mean $\pm$ SD	Minimum	Maximum
Mean streamflow (q_{mean})	1,014	1.358 ± 1.327	0.001	9.562
Mean discharge (mean_cfs)	1,014	635.03 ± 957.53	0.55	8,602.14
Baseflow index (TOT_BFI)	1,014	44.914 ± 16.265	6.16	85.44
Streamflow coefficient of variation (CV)	1,014	0.619 ± 0.151	0.140	1.000
Flow indicator Q5	1,014	0.163 ± 0.239	0.000	2.370
Flow indicator Q95	1,014	4.587 ± 4.227	0.000	31.860

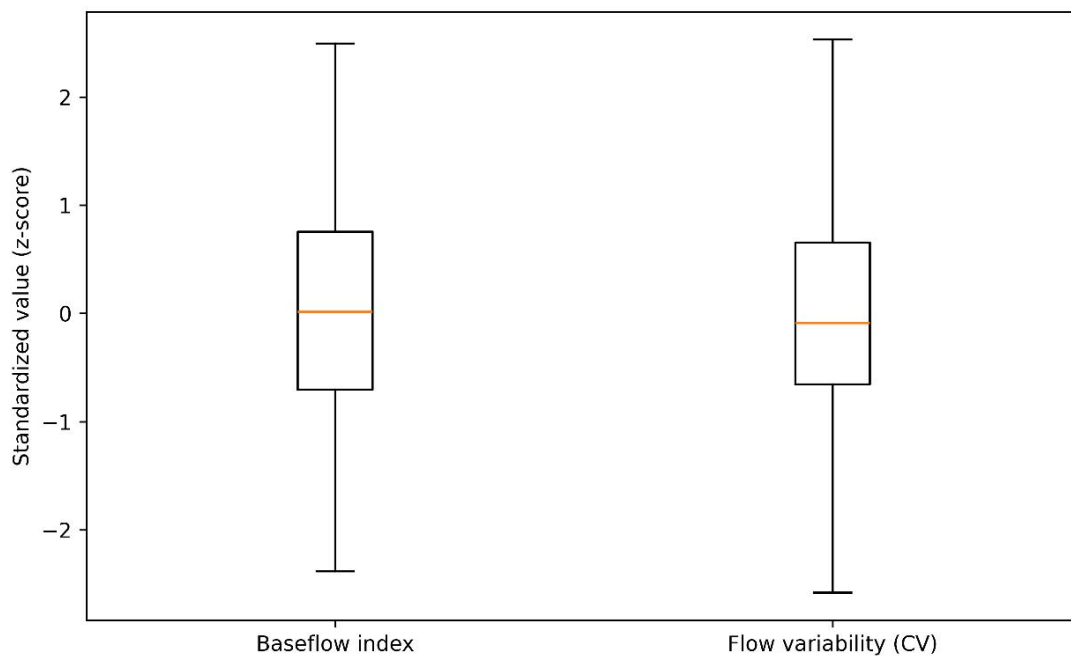


Figure 3. Distribution of Streamflow Variability and Baseflow Characteristics

Figure 3 presents the distributions of baseflow index and streamflow variability. Baseflow

characteristics exhibited greater absolute variation than the coefficient of variation, although the indicators are expressed on different scales and therefore should not be compared directly by their numerical spread.

3.4 Relationships Between Climatic and Hydrological Variables

Correlation analysis revealed some statistically significant relationships between climatic and hydrological indicators. Good positive correlation was found between annual precipitation and mean streamflow ($r = 0.867$, $p < 0.001$), with a negative correlation between annual precipitation and streamflow variability ($r = -0.312$, $p < 0.001$). A positive correlation between streamflow variability and consecutive dry days was found ($r = 0.351$ at $p < 0.001$). Baseflow index ($r = -0.500$, $p < 0.001$) and mean temperature had a negative correlation. Relationships suggested catchments with higher precipitation generally had higher mean streamflow, and temperature and dry-period conditions were related to differences in baseflow and flow variability (Table 4).

Table 4. Pearson Correlations Between Climatic and Hydrological Indicators

Climatic variable	Hydrological indicator	N	Pearson r	p-value
Annual precipitation	Mean streamflow	1,014	0.867	<0.001
Annual precipitation	Baseflow index	1,014	0.056	0.076
Annual precipitation	Streamflow CV	1,014	-0.312	<0.001
Consecutive dry days	Mean streamflow	1,014	-0.100	0.001
Consecutive dry days	Streamflow CV	1,014	0.351	<0.001
SPI	Mean streamflow	1,012	-0.119	<0.001
SPEI	Mean streamflow	1,013	-0.169	<0.001
Mean temperature	Baseflow index	1,014	-0.500	<0.001
Potential evapotranspiration	Baseflow index	1,013	-0.477	<0.001

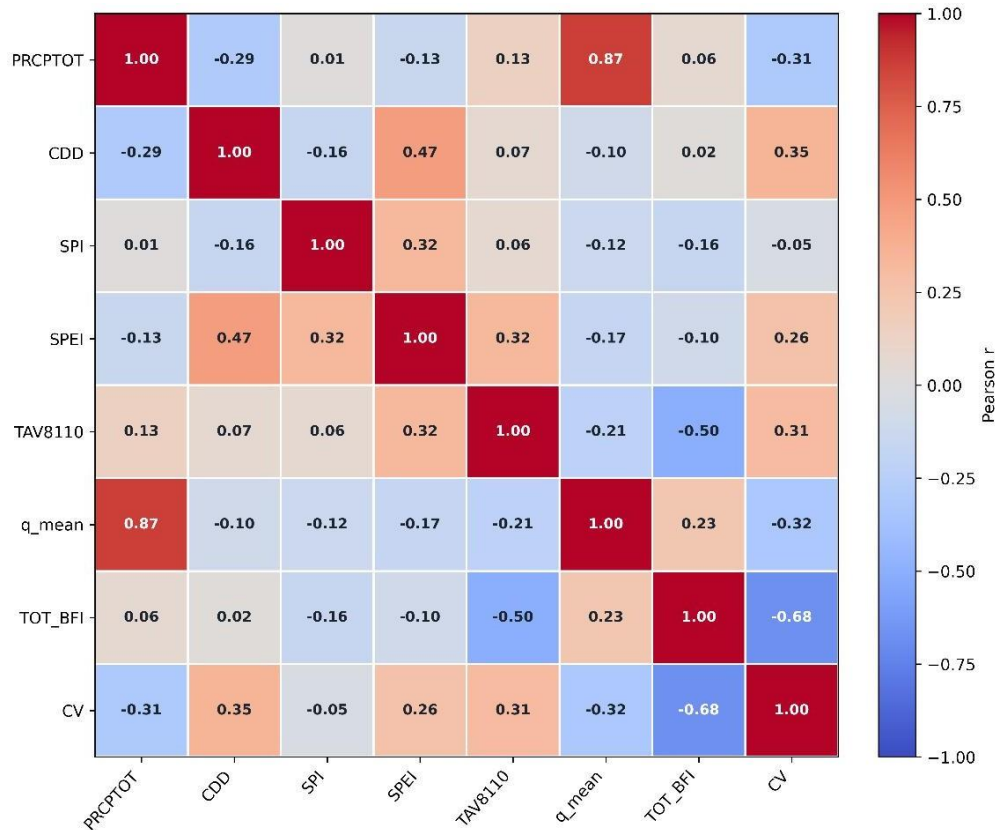


Figure 4. Correlation Heatmap of Climatic and Hydrological Indicators

Figure 4 visualizes the relationships among precipitation, drought indices, temperature, mean streamflow, baseflow, and flow variability. Positive and negative correlations demonstrate differences in the strength and direction of climatic associations with hydrological characteristics.

3.5 Climatic Predictors of Hydrological Characteristics

The results of simple linear regression analysis showed that there was a strong correlation between annual precipitation and mean streamflow ($\beta = 0.002518$, $R^2 = 0.751$, $p < 0.001$). The unadjusted model explained about 75.1% of the between-catchment variation in mean streamflow because of precipitation. Weaker negative associations were found between the consecutive dry days and temperatures and streamflow, and negative associations occurred between precipitation and streamflow variability. The baseflow index and precipitation were not statistically significant ($p = 0.076$) and can be seen in Table 5.

Table 5. Simple Linear Regression Analysis of Climatic Predictors and Hydrological Indicators

Predictor	Outcome	β	R^2	p-value
Annual precipitation	Mean streamflow	0.002518	0.7511	<0.001

Consecutive dry days	Mean streamflow	−0.006134	0.0101	0.001
Mean temperature	Mean streamflow	−0.059264	0.0459	<0.001
Annual precipitation	Baseflow index	0.001986	0.0031	0.076
Annual precipitation	Streamflow CV	−0.000103	0.0971	<0.001

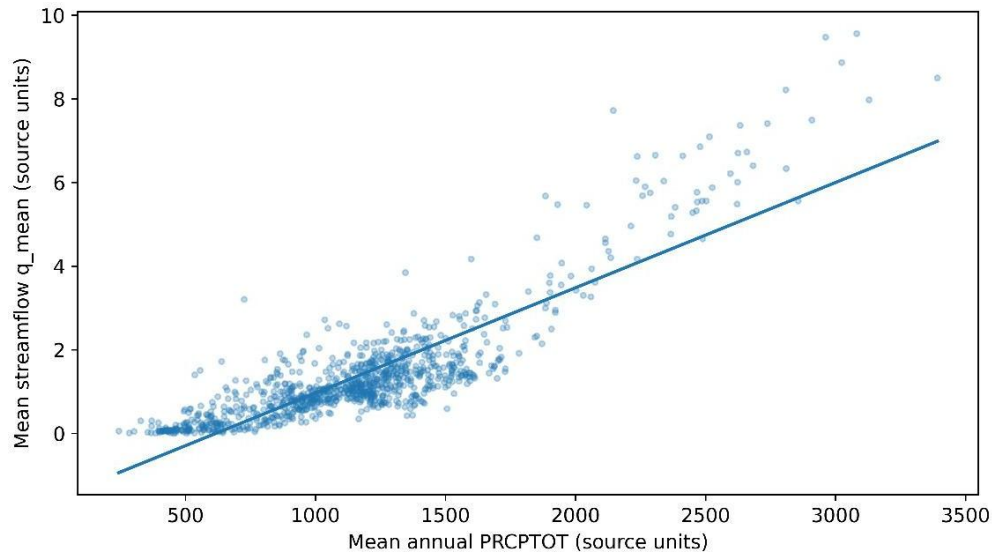


Figure 5. Relationship Between Annual Precipitation and Mean Streamflow

As presented in Figure 5, mean annual precipitation was strongly and positively related to mean catchment streamflow. The fitted regression line demonstrated an increasing streamflow pattern across catchments with higher precipitation, supporting the strong positive association identified in the correlation and regression analyses.

4. Discussion

The present study analysed climatic variability and hydrological characteristics at 1,014 catchments in the United States for 1980–2023. Results indicated significant differences in precipitation, drought characteristics and streamflow. The annual precipitation was seen to have a slight upward trend and the maximum one-day precipitation increased significantly indicating changes of extremes in precipitation. Annual rainfall and mean streamflow showed a good positive correlation ($r = 0.867$), suggesting streamflow changes were related to the annual rainfalls in the catchments. Using integrated modelling approaches, similar relationships between climatic variability and hydrological responses have been investigated (Ahmad et al., 2025). But human interventions and catchment characteristics are also important factors influencing the hydrological conditions, which makes water resource assessments related to climate change very complicated (Yan, 2025).

Precipitation variability is an important factor in determining the surface water availability,

especially in areas with highly variable precipitation and extended dry seasons. The results indicated that the precipitation was positively associated with mean streamflow while consecutive dry days were weakly negatively associated with streamflow. The results indicate that catchments with higher precipitations have higher levels of streamflow. Regional water management resilience assessments have highlighted the need to adjust water management strategies to the changing climatic conditions and the growing scarcity of water (Henseler et al., 2025). Geographical variations of water resource vulnerability have also been identified from surface water scarcity assessment studies in the long-time horizon (Poonia et al., 2025). In addition, extreme precipitation events have the potential to impact groundwater levels and surface water – subsurface hydrological connections in semi-arid regions (Wang et al., 2025).

Results for the hydrological indicators showed great catchment differences in mean discharge, baseflow contribution and streamflow variability. The average value of the baseflow index was 44.91 and differences in discharge characteristics indicated heterogeneous hydrological conditions. These differences can be correlated with geological characteristics, catchment characteristics and groundwater inputs. Subsurface water movement and reservoir leakage have been shown to be important components in understanding hydrological processes in previous investigations (Han et al., 2025). This separation is crucial as human-induced changes can affect terrestrial water storage and hydrology rates independently of climatic effects (Ji et al., 2025). Likewise, streamflow variability due to changing climatic conditions has been reported by integrated groundwater–surface water modelling to be influenced by groundwater–stream interactions (Lee et al., 2025).

The correlation analysis revealed that climatic parameters and hydrological parameters are significantly related. The streamflow variability was negatively related to annual precipitation while consecutive dry days was positively related. Baseflow index was negatively correlated with mean temperature and potential evapotranspiration, implying that catchments with higher evaporative demand and warmer temperatures might have lower sustained flow contributions. Moisture studies have shown that climatic factors play a major role in determining water availability (Altıkat, 2025). Enhanced impacts on hydrological stability and water availability could also be caused by climate change induced changes in groundwater resources (Minea et al., 2025). Runoff processes can also be altered by environmental disturbances such as wildfire, which can add extra variability to catchment hydrological responses (Partington et al., 2022).

These results are of interest for sustainable water resource management and adaptation to climate. Precipitation, drought indices and streamflow features can be monitored to enhance the identification of hydrologically vulnerable catchments. Groundwater and surface water resources can be managed together to help implement more effective adaptation strategies (Hassan, 2025). Advanced monitoring approaches can also help to enhance the evaluation of aquatic ecosystem conditions under varying hydrological conditions (Reginald, 2024). In addition, a hybrid approach of natural and engineered infrastructure can enhance flood management and resilience to extreme hydrological events (Zhu et al., 2025).

Some limitations exist in the study as the information was secondary and hydrological summaries were only available at catchment level and not necessarily on an annual basis. Therefore, any climatic cause-effect can be derived from the relationships observed and there is no way to estimate the amount of change in surface water availability over time. In the future,

studies should combine long time series of discharge records, groundwater data and catchment properties with hydrological modelling. Modelling approaches that account for the sensitivity of the variables to climate change can help in understanding the interactions between the hydrological processes and environmental outcomes (Wen et al., 2025). Further ecological studies may also help to understand impacts to freshwater habitat suitability and ecosystem responses to changes in water levels (Xu et al., 2025). Those would improve future assessments of climate change impacts on hydrology and sustainable water resource management.

5. Conclusion

The current study examined hydrological characteristics and climatic variability in 1014 catchments in the United States from 1980–2023 to gain insight into how climatic variability and hydrological features are related. Results showed that both spatial and temporal patterns of precipitation, drought indices, and hydrological variables were quite significant. Modest increases were seen in both annual precipitation and in maximum 1-day precipitation, suggesting changes in extreme precipitation conditions. The annual precipitation was highly positively correlated with mean streamflow ($r = 0.867$) indicating the importance of precipitation in explaining the differences in catchment water availability. There was significant spatial variation in hydrological indicators such as mean discharge, baseflow contribution and streamflow variability among catchments. Baseflow index was negatively correlated with temperature and potential evapotranspiration, indicating that climatic conditions might affect sustained water contributions. These relationships are, however, only statistical and not direct evidence of hydrological changes due to climate. The results highlight the need for combining climatic and hydrological data to achieve proper assessment and management of freshwater resources. The limitation of the study was the lack of continuous streamflow observations at the catchment scale and only summer hydrological summaries. Long term discharge measurements, groundwater data, land-use and hydrological modelling should be taken into consideration for future research, to better define temporal relationships. Overall, it offers valuable data in the understanding of climate – hydrology relationships and the planning of water resources, drought preparedness and sustainable catchment management in the context of a changing climate.

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