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MODELLING THE EFFECTS OF CLIMATE VARIABILITY ON GROUNDWATER RECHARGE AND WATER RESOURCE SUSTAINABILITY

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Abstract

Groundwater recharge processes and long-term water resource sustainability are largely affected by climate variability, especially in areas that are becoming more arid and water stressed. The present study evaluated the temporal changes of precipitation, temperature, drought index, and aridity index in the region of the Maamora aquifer in Morocco using secondary hydroclimatic data from 1970 to 2100. Historical and projected hydroclimatic changes were assessed using descriptive statistics, temporal trend analysis, Pearson correlation and climatic classification methods. Results showed decrease in annual precipitation at the rate of 1.19 mm/year and increase in temperature at the rate of 0.017°C/year. The number of drought episodic years rose from 2 to 16 for 1970-2000 and 2051-2100, respectively, and the De Martonne aridity values decreased. The Pearson correlation analysis revealed a negative relationship between precipitation and temperature ($r = -0.519$), suggesting that higher temperatures were correlated with lower precipitation. This indicates a worsening climate for groundwater recharge and possible problems with water availability over the long term. However, the data available did not contain enough hydrogeological parameters or recharge observations to quantify direct groundwater recharge changes. The study emphasizes the need to combine climate variability assessment, groundwater monitoring with validated groundwater recharge modelling for sustainable water resource management and enhance the resilience of the region in the future climatic conditions.

Keywords: Climate Variability; Groundwater Recharge; Hydroclimatic Modelling; Aridity Index; Water Resource Sustainability

1. Introduction

Groundwater is a valuable freshwater resource crucial for agriculture, domestic water supply, industrial development and ecosystem operations. However, with the rising climate variability, concerns have been raised on the sustainability and availability of groundwater resources. Precipitation, temperature and evapotranspiration variations affect hydrological processes and the natural recharge of aquifer systems. Groundwater resources can be influenced by changes in rainfall intensity and distribution, as well as by shifts in atmospheric water demand, especially in water-scarce areas, by climate change (Davamani et al., 2024). In arid and semi-arid regions, groundwater resources are particularly sensitive due to low precipitation and high evaporation rates (Deshmukh et al., 2022). Therefore, it is crucial to understand how changes in climate variability affect groundwater recharge when planning water resource management strategies (Minea et al., 2025).

Groundwater recharge is a complex process that depends upon precipitation, temperature, evapotranspiration, and soil moisture, with all these factors subject to climate variability. Groundwater recharge is influenced by increased rainfall, which can provide a significant recharge source, and increased temperatures which can increase the demand for water in the atmosphere and decrease recharge. Groundwater recharge's sensitivity to shifts in long-term aridity underscores the need to account for climatic conditions in assessing groundwater aquifer responses (Berghuijs et al., 2024). Groundwater recharge processes are also different in different climatic zones due to differences in the seasonality of precipitation, soil properties, and hydrological thresholds (Dubois et al., 2022). Evapotranspiration changes also alter the recharge as it affects the infiltration process in soil and the availability of soil water (Eltarabily et al., 2023). The relationships show that groundwater recharge is not only dependent on precipitation, but also on the variations of several environmental variables.

Changes in precipitation and temperature over time also affect water availability and groundwater sustainability in the region. The distribution of blue and green water resources are influenced by climate variability and land-use changes, which poses challenges for sustainable water management (Liu et al., 2022). Likewise, the variation of water resources in river basins in space and time is shaped by the interaction between climatic conditions and human activities Jin et al., 2024). Land use and climatic changes may alter the infiltration behavior and the recharge of the groundwater, especially in watersheds under environmental stress (Warku et al., 2022). Integrated management approaches for climate-related hydrological cycle disturbances, therefore, should consider both the changing water availability and future water resource needs (Wang & Liu, 2023). Groundwater responses to climatic changes and estimates of potential future recharge are important in understanding the hydrological models. Various recharge estimation techniques have been developed to account for the climatic influence, but the reliability of these methods varies depending on the availability of data, assumptions made by the model and the hydrogeological conditions (Adhikari et al., 2022). Future recharge assessments under various climate scenarios have also been shown to be relevant in water-stressed areas using spatiotemporal modelling approaches (Andaryani et al., 2022). In recent multi-model investigations, the uncertainty in projections of groundwater recharge in warmer climate has also been highlighted (Kumar et al., 2025). Moreover, machine learning methods provide further potential for assessing nonlinear relationships between climatic variables and groundwater behaviour (Bamal et al., 2024).

However, the incorporation of long-term climate variability, drought indicators, groundwater recharge modelling and sustainability assessment pose challenges. Variations in climatic scenarios, recharge estimation techniques, and environmental conditions can make it difficult to interpret and compare results among studies. Thus, the aim of the present study is to evaluate the groundwater recharge sensitivity of the Maamora Aquifer, and to assess historical and future precipitation, temperature and aridity conditions to support an integrated assessment.

Research Objectives

- To assess long-term variations and trends in precipitation, temperature, and aridity under historical and projected climatic conditions.
- To investigate the relationships between climate variability indicators and groundwater recharge using statistical analysis and hydrological modelling.
- To evaluate the potential implications of changing climatic conditions and groundwater recharge patterns for long-term water resource sustainability.

2. Materials and Methods

2.1 Study Design and Data Source

This study employed a quantitative research design using secondary hydroclimatic data to investigate the effects of climate variability on groundwater recharge and water resource sustainability (Ghazzar, 2025). The data were collected from a Mendeley Data repository, Hydroclimatic Projections and Computational Framework for the Maamora Aquifer. Two Excel workbooks were uploaded with precipitation, temperature, drought and aridity data, as well as calculation scripts for groundwater recharge and climate variability modelling. The records available spanned the years 1970-2100, with both historical and future climate information. The statistical analysis was aimed at investigating temporal climatic trends, associations between hydrological variables and possible implications for groundwater replenishment.

2.2 Study Area and Hydroclimatic Characteristics

The study was conducted in the region of Maamora Aquifer in Morocco, where groundwater is a significant source of water for agriculture, domestic, and environmental needs. The area has influences from Mediterranean climate with seasonal rainfall, warm summers, and relatively dry areas throughout parts of the year. The recharge of the groundwater is influenced by the infiltration of the rainwater, evapotranspiration, and local hydrogeologic conditions. Changes in precipitation and temperature could impact the amount of water available to recharge groundwater. It was therefore decided that the Maamora Aquifer would be a suitable study area in which to explore associations between long-term hydroclimatic shifts and stress on potential groundwater resources.

2.3 Data Collection and Variable Selection

The SPI.xlsx file and the De Martonne aridity index.xlsx file were used to obtain the hydroclimatic variables. Records for each month were provided for precipitation, minimum temperature, and maximum temperature, and records for each year were provided for total precipitation, average temperature, Standardized Precipitation Index (SPI), De Martonne aridity index and associated

climatic classification. The study period included 1970 to 2100 (131 annual records and 1,572 monthly observations). Precipitation and temperature were chosen as the key climate variables, and SPI and the aridity index were chosen to describe droughts and long-term climatic dryness, respectively. Groundwater recharge was not measured and instead modelled as a modelling outcome in the workbooks uploaded.

2.4 Data Preparation and Processing

The hydroclimatic records were arranged by year and month for consistency between the two workbooks. Prior to statistical analysis, variable names, observation periods, numerical formats, and possible missing values were checked. The monthly precipitation values were added up to annual values and monthly temperatures were summarized to get climatic characteristics for the year. Records from the two workbooks were matched for year and duplicate observations were eliminated for preparation of the combined analytical table. To avoid any misunderstanding of the future climate projections as observations, the historical and future periods were separated. The current drought and aridity classification were kept for the categorical analysis, and the numerical variables were ready for descriptive statistics, correlation analysis and regression modelling.

2.5 Climate Variability Assessment

Climate variability was evaluated through temporal changes in annual precipitation, average temperature, SPI, and aridity index. Annual trends were examined to identify increasing or decreasing climatic patterns across the study period. The Standardized Precipitation Index was used to characterize precipitation-related drought and wet conditions, while the De Martonne aridity index was used to assess variations in climatic dryness. The aridity index was expressed as:

$$I_{DM} = \frac{P}{T + 10}$$

where (I_{DM}) represents the De Martonne aridity index, (P) represents annual precipitation in millimetres, and (T) represents mean annual temperature in degrees Celsius. Temporal distributions and climatic classifications were examined to identify changes in hydroclimatic conditions relevant to groundwater replenishment.

2.6 Groundwater Recharge Modelling

Groundwater recharge modelling was based on the precipitation-dependent computational framework supplied with the Mendeley materials. The framework incorporates annual precipitation, infiltration coefficients, and contributing areas to estimate potential recharge volumes. The general calculation can be represented as:

$$R_t = \sum_{i=1}^n P_{i,t} \times A_i \times C_i$$

where (R_t) represents annual groundwater recharge volume, $(P_{i,t})$ represents annual precipitation for area (i) expressed in metres, (A_i) represents the contributing area in square metres, and (C_i) represents the dimensionless infiltration coefficient. The framework enables the assessment of recharge responses to changes in precipitation when the necessary hydrogeological parameters are available. Because infiltration coefficients and contributing-area

inputs were not included in the uploaded workbooks, direct recharge volumes could not be calculated from the available climatic records alone. Recharge modelling was therefore treated as a conditional component requiring supplementary input parameters and, where possible, validation against independent groundwater observations.

2.7 Water Resource Sustainability Assessment

Conceptual assessments of water resource sustainability were made based on the implications of long-term precipitation variability, rising temperatures, drought frequency, and changing aridity on potential groundwater recharge. Potential pressures on groundwater recharge were interpreted as climatic conditions showing decreased precipitation, extended drought or increased atmospheric water demand. However, due to the lack of groundwater abstraction, aquifer storage and water demand records, the assessment focused on recharge related vulnerabilities. If recharge could be estimated with the use of the supplementary inputs, relative changes between the climatic periods could be considered to determine potential long-term groundwater sustainability risks.

2.8 Statistical Analysis

Hydroclimatic variables and drought classifications were summarized using descriptive statistics, such as mean, standard deviation, minimum, maximum, frequencies, and percentages. A correlation between precipitation, temperature, SPI and aridity index was performed using Pearson correlation analysis. Simple linear regression was used to assess temporal relationships and trends of climatic variables. When interpreting the statistical relationships, regression coefficients and coefficients of determination (R^2) and the significance values were considered. A significance level of $p < 0.05$ was used as appropriate and temporal autocorrelation was considered when assessing the significance of the trends. Graphical representations included time series plot, trend graphs, drought classification distributions and correlation heatmaps. Only variables provided in the records supplied for statistical interpretation were used, and relationships between climate indicators were not considered direct measurements of groundwater recharge.

3. Results

A total of 131 annual hydroclimatic records from 1970 to 2100 and 1,572 monthly observations in the Maamora Aquifer study area were analysed. The variables available were precipitation, temperature, Standardized Precipitation Index (SPI) and De Martonne aridity index. The selected variables had 100% complete records. These results are presented using descriptive statistics, temporal trends, drought classifications, climatic-period comparisons and correlation analysis.

3.1 Descriptive Characteristics of Hydroclimatic Variables

The Descriptive Characteristics of the Hydroclimatic variables are shown in Table 1. Mean annual precipitation was 520.75 mm, range 310.37 to 821.47 mm, and standard deviation 98.42 mm while mean annual temperature was 19.53°C and De Martonne aridity index (AMDI) averaged 17.69. The mean of the SPI was close to zero, and the standard deviation was 1.00, showing that there were fluctuations between relatively wet and dry years over the period of study. These results show that there is significant spatial variation both in precipitation and in climatic moisture conditions.

Table 1. Descriptive Statistics of Hydroclimatic Variables (1970–2100)

Variable	Mean	SD	Minimum	Maximum
Annual precipitation (mm)	520.75	98.42	310.37	821.47
Annual temperature (°C)	19.53	0.69	18.19	21.07
De Martonne aridity index	17.69	3.58	10.12	28.77
Standardized Precipitation Index	0.00	1.00	−2.14	3.06

The annual precipitation series showed substantial interannual fluctuations, with relatively high precipitation during some earlier years and lower precipitation becoming more prominent toward the end of the projection period. The overall declining precipitation pattern is illustrated in Figure 1.

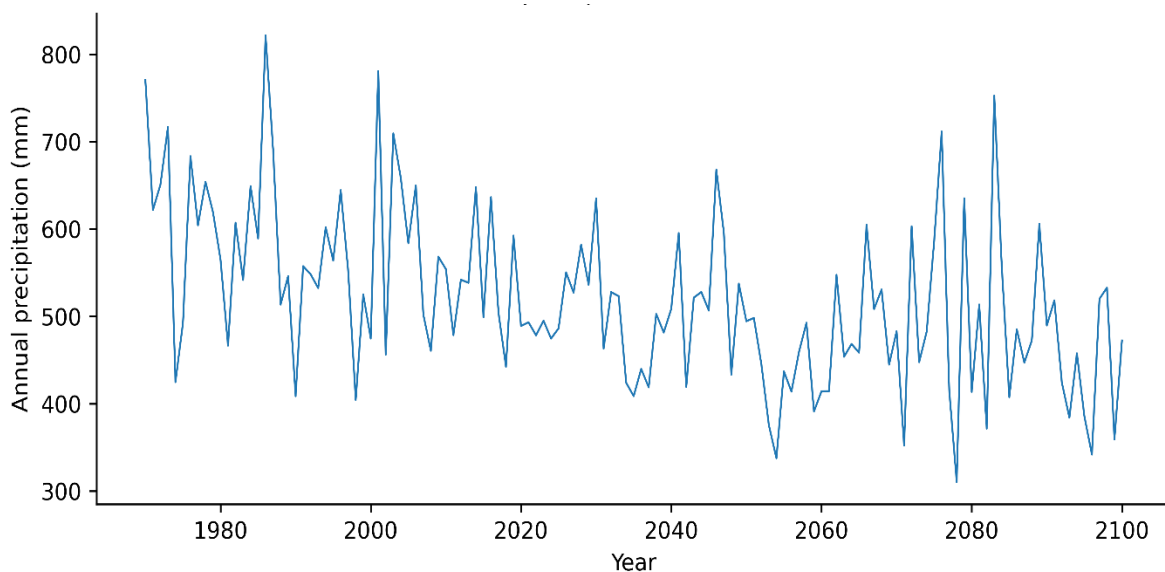


Figure 1. Annual Precipitation Variability (1970–2100)

3.2 Long-Term Climate Variability and Trends

Long-term trend analysis showed that the rainfall decreased and temperature rose over the period of study. The estimated rate of decrease in annual precipitation was 1.19 mm/year and the rate of increase in average temperature was about 0.017°C/year. The evolution of the De Martonne aridity index was negative, that is, the climate became drier. The SPI also decreased over time. Table 2 shows the trend estimates and coefficients of determination and Figure 2 shows the increasing annual temperature gradually.

Table 2. Linear Trends in Hydroclimatic Variables (1970–2100)

Variable	Annual slope	R ²	Direction
Annual precipitation	−1.1894 mm/year	0.210	Decreasing
Annual temperature	+0.0168 °C/year	0.853	Increasing
De Martonne aridity index	−0.0507/year	0.289	Decreasing
SPI	−0.0121/year	0.210	Decreasing

Trends were estimated using simple linear regression against year. R² indicates the proportion of variation explained by the linear time trend. These are descriptive trends across a record containing future projections.

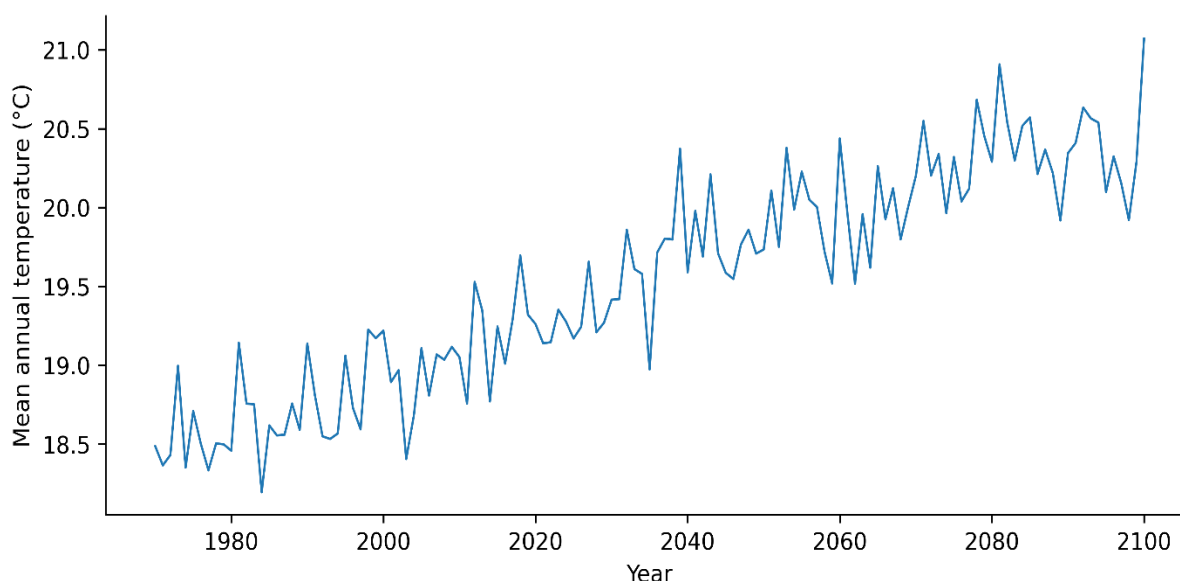


Figure 2. Long-Term Temperature Variability

Figure 2. Annual mean temperature variation between 1970 and 2100, illustrating sustained warming throughout the hydroclimatic record. The estimated annual linear increase was approximately 0.017°C, corresponding to an increasing temperature tendency across the study period.

3.3 Comparison of Hydroclimatic Conditions Across Time Periods

The study period was split into three parts: 1970–2000, 2001–2050 and 2051–2100, in order to investigate the long-term difference of the climate conditions. The mean annual precipitations in the first period and the final period were 581.92mm and 472.62mm, respectively. In the same time intervals, the average temperature rose from 18.68°C to 20.21°C. There was a shift towards drier climatic conditions with the decline in the De Martonne aridity index from 20.31 to 15.65. The average SPI also changed from positive to negative, which means that below-average precipitation

was more common during the latter period. These time differences are summarized in Table 3.

Table 3. Hydroclimatic Conditions Across Three Time Periods

Variable	1970–2000	2001–2050	2051–2100
Precipitation (mm)	581.92 ± 98.65	530.95 ± 80.17	472.62 ± 92.06
Temperature (°C)	18.68 ± 0.29	19.38 ± 0.40	20.21 ± 0.33
Aridity index	20.31 ± 3.53	18.09 ± 2.86	15.65 ± 3.08
SPI	0.62 ± 1.00	0.10 ± 0.81	−0.49 ± 0.94

3.4 Drought Patterns and Aridity Conditions

Precipitation conditions were classified and the number of normal years were most numerous (88 of 131 annual record). There were 15 years of moderate drought, 5 of severe drought and 1 of extreme drought. The number of years in droughts was higher in the latter period, with 16 years of droughts in 2051 to 2100 compared to 2 years of droughts in 1970-2000. According to the De Martonne classification, 100 years of the semi-arid and 31 years of semi-humid type were identified. The later decades saw an increase in the prevalence of semi-arid conditions which were in keeping with the observed reduced rainfall and aridity-index values. In Table 4, drought categories distribution is shown, and temporal variation of SPI is shown in Figure 3.

Table 4. Distribution of SPI Drought and Wetness Categories

SPI classification	1970–2000	2001–2050	2051–2100	Total
Extreme drought	0	0	1	1
Severe drought	0	0	5	5
Moderate drought	2	3	10	15
Normal	18	39	31	88
Moderately wet	6	6	1	13
Severely wet	3	1	1	5
Extremely wet	2	1	1	4
Total	31	50	50	131

Classification frequencies were obtained from the supplied SPI workbook. Drought-classified years include moderate, severe, and extreme drought conditions. Classifications are retained as supplied in the original source.

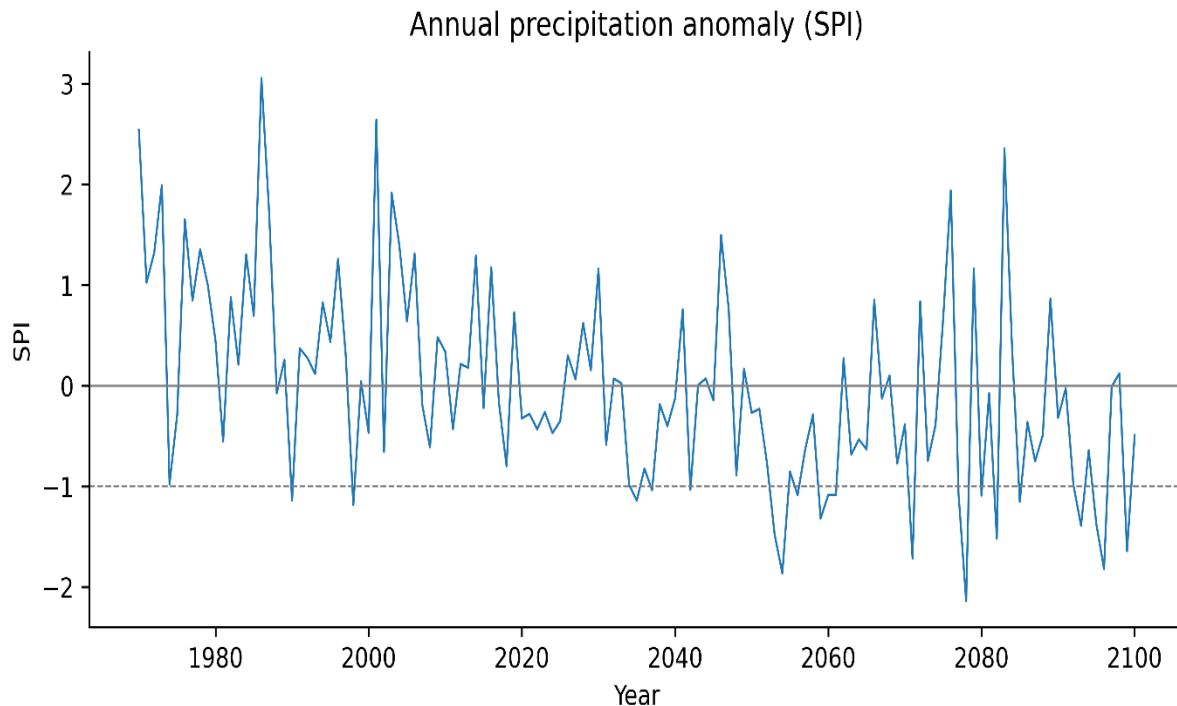


Figure 3. Temporal Variation in Standardized Precipitation Index

Figure 3. Annual variation in the Standardized Precipitation Index between 1970 and 2100. Positive values indicate wetter conditions relative to the supplied reference distribution, while negative values indicate drier conditions, with increasingly negative values appearing in later projected years.

The aridity results further demonstrated increasing climatic dryness. Semi-arid years increased from 16 during 1970–2000 to 45 during 2051–2100, whereas semi-humid years decreased from 15 to five. The annual aridity-index series in Figure 4 shows a generally declining pattern, consistent with increasing temperature and decreasing precipitation.

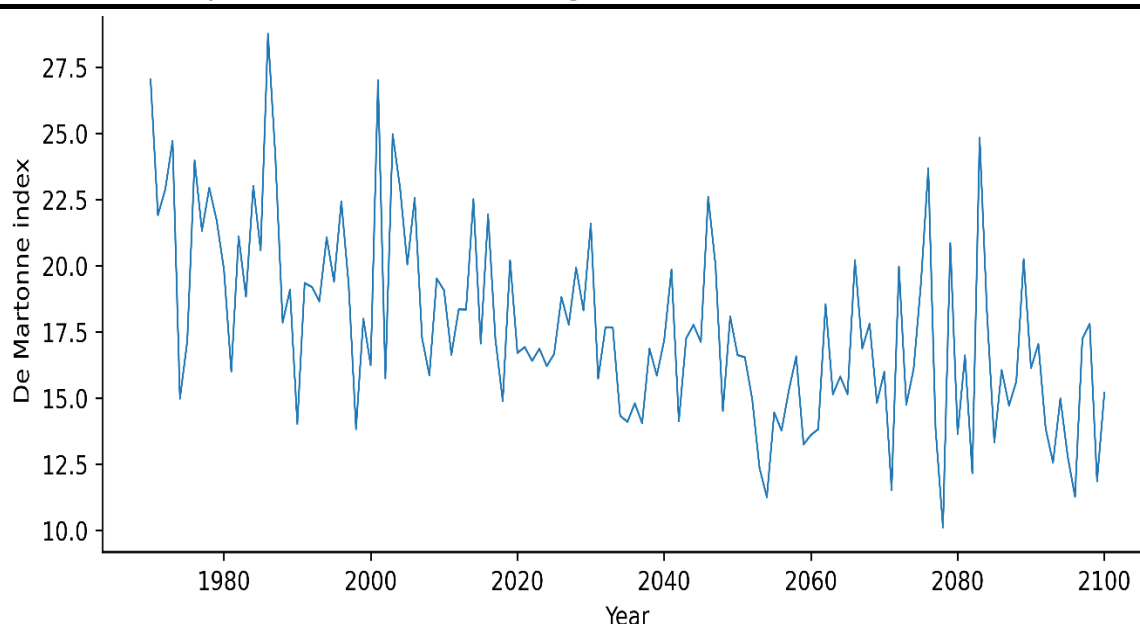


Figure 4. Long-Term Variation in De Martonne Aridity Index

Figure 4. Annual variation in the De Martonne aridity index across the study period. The declining index indicates an increasing tendency toward dry climatic conditions and a greater frequency of semi-arid classifications during the later projection period.

3.5 Relationships Among Hydroclimatic Variables

Pearson correlation analysis revealed good correlation between precipitation, SPI and De Martonne aridity index. The aridity index had a very good positive relationship with precipitation ($r = 0.995$), while SPI had close to perfect correlation with precipitation ($r = 1.000$). Precipitation ($r = -0.519$), SPI ($r = -0.519$) and the aridity index ($r = -0.602$) had negative correlation with temperature. These results suggest that warmer years generally coincided with less precipitation, and increased climatic dryness, in the climate series provided. The correlation coefficient values are shown in Table 5 and plotted in Figure 5.

Table 5. Pearson Correlation Matrix of Hydroclimatic Variables

Variable	Precipitation	Temperature	Aridity index	SPI
Precipitation	1.000	-0.519	0.995	1.000
Temperature	-0.519	1.000	-0.602	-0.519
Aridity index	0.995	-0.602	1.000	0.995
SPI	1.000	-0.519	0.995	1.000

Correlation coefficients represent Pearson's r calculated from 131 annual records. SPI is

mathematically standardized from precipitation, and the De Martonne index is calculated from precipitation and temperature. Their high correlations are therefore expected and should not be interpreted as independent validation.

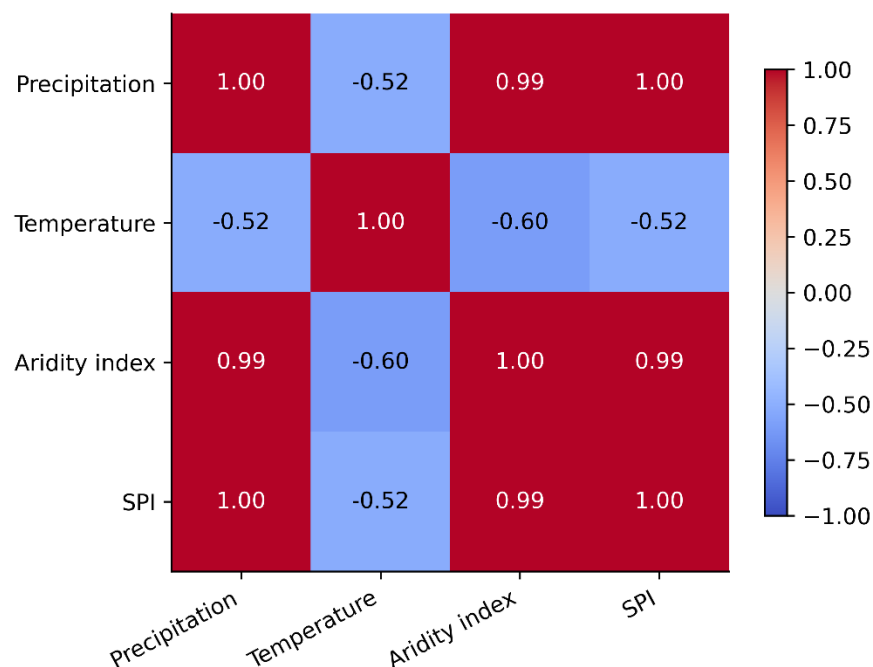


Figure 5. Correlation Heatmap of Hydroclimatic Variables

Figure 5. Pearson correlation heatmap showing relationships among precipitation, mean temperature, De Martonne aridity index, and SPI. Positive correlations are strongest among precipitation-derived indicators, whereas temperature demonstrates moderate negative associations with moisture-related variables.

3.6 Implications for Groundwater Recharge and Water Resource Sustainability

The overall hydroclimatic outcomes suggest that the hydroclimatic conditions are getting drier through the study period in the Maamora Aquifer. In the year 2051-2100, the mean annual precipitation was about 18.8% less than during the baseline period of 1970-2000, and the mean temperature was about 1.53°C warmer. There is a higher number of drought class years and a lower number of the De Martonne aridity index, indicating perhaps less favourable conditions for groundwater recharge. These changes can put additional stress on groundwater, particularly if the aquifer recharge relies heavily on seasonal precipitation.

The results thus can be used to pinpoint potential recharge risks due to climate change rather than actual groundwater depletion. Additional recharge, abstraction or aquifer storage data would be needed for a quantitative sustainability assessment.

4. Discussion

The present study focuses on the hydroclimatic variability in the Maamora Aquifer region during the period 1970–2100, which showed a decrease in precipitation, increase in temperature, and

increase in aridity. Precipitation reduced around 1.19 mm/year, and temperature raised around 0.017°C/year. The mean precipitation reduced from 581.92 mm in 1970-2000 to 472.62 mm in 2051-2100 indicating a decreasing trend in precipitation, which can impact the replenishment of groundwater. Groundwater recharge changes with future climate scenarios have also been observed in arid and semi-arid areas (Cheng et al., 2024). Further, a hydrological model has also illustrated the sensitivity of groundwater recharge to climate change (Ngo et al., 2024).

The declining precipitation and increasing temperature indicate potentially unfavourable conditions for groundwater recharge. The lack of precipitation can result in less infiltration while warmer temperatures can cause an increase in evapotranspiration and a decrease in the availability of soil moisture. The impact of climate change and land-use on water availability in semi-arid watersheds has been previously shown (Ait M'Barek et al., 2024). Climate-sensitive variations in groundwater recharge have also been identified with rainfall-based forecasting models (Banerjee et al., 2024). The negative correlation between precipitation and temperature ($r = -0.519$) also suggests that higher temperatures were associated with lower rainfall. AI models have shown promise in the evaluation of relationships between ground water resources and climatic conditions, particularly in the context of complex relationships (Secci et al., 2023). Integrated surface-water and groundwater models also are valuable for providing insights into hydrological responses across changing environmental conditions (Sheikha-BagemGhaleh et al., 2023).

Climate analysis showed an increase in drought conditions, with years classified as droughts increasing from 2 in the period of 1970 to 2000 to 16 in the period of 2051 to 2100. The decreasing De Martonne aridity index also revealed a shift to more frequent semi-arid conditions. The impact of these changes can be to put more pressure on groundwater recharge and future water supply. The impacts of urbanization and climate change have been modelled together for groundwater level changes (Asadollahi et al., 2024). Groundwater quality could also be impacted by climate variability, raising further environmental issues (Chowdhury et al., 2025). Groundwater vulnerability increases challenges for sustainable resource management (Hirata et al., 2025). The same concerns about climate related groundwater sustainability have been raised by regional groundwater modelling (Khadim et al., 2023).

The results stress the need for climate friendly groundwater management. The decreased precipitation and rising aridity indicate a need for better groundwater stewardship and innovative planning of groundwater resources. Adaptive management strategies are needed to ensure the availability of resources in the face of groundwater instability under future climate conditions (Ashofteh et al., 2024). Under favourable environmental conditions, water harvesting and managed aquifer recharge can contribute to groundwater recharge (Gebreslassie et al., 2025). Land-use change and adaptation strategies must be considered as well for sustainable groundwater exploitation (Hanifehlou et al., 2022). Integrated water management is even more relevant when considering the interaction between climatic pressures and the water requirements of agriculture (Lyra et al., 2025).

This study lacked direct measurements of groundwater recharge, abstraction records and aquifer storage information. Hence, the results represent climate change related risks to groundwater recharge without any actual reduction in recharge. The addition of future projections also adds uncertainty to long-term interpretations. The same methodological issues have been found in groundwater modelling in data lacking areas (Borzi, 2025). Future studies should integrate

measured groundwater levels, estimated recharge, aquifer properties, and water extraction history to better validate the model and assess the sustainability.

5. Conclusion

The present study evaluated the impacts of long-term climate variability on groundwater recharge conditions and water resource sustainability in the Maamora Aquifer region based on hydroclimatic data from 1970–2100. Results showed a decrease in the precipitation and an increase in temperature, indicative of increasingly dry climatic conditions. Annual precipitation decreased by approximately 1.19 mm/year, while temperature increased by 0.017°C/year. The mean annual precipitation for 1970-2000 was 581.92 mm and for 2051-2100 was 472.62 mm, indicating significant changes in climatic conditions in the region. Drought analysis showed that dry conditions are becoming more frequent, and that the De Martonne aridity index is decreasing. A moderate negative correlation between precipitation and temperature was found by correlation analysis indicating that temperature generally decreased as precipitation increased. These shifts can affect groundwater recharge through reduced recharge opportunities and higher water demand by the atmosphere. But no direct measurement of groundwater recharge and aquifer storage records made it impossible to quantify recharge changes and groundwater depletion. The findings highlight the need to account for long-term climate variability in planning and managing groundwater resources. Future water scarcity risks may be reduced through climate-adaptive solutions such as water conservation, better monitoring of recharge and sustainable groundwater extraction. To enhance groundwater sustainability assessments and to facilitate effective regional water resource management under the changed climatic conditions, further study is needed to incorporate hydrogeological observations, groundwater abstraction data and validated recharge models.

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