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Statistical analysis of rainfall trends, hydrological variability, and land cover dynamics in the Bouregreg watershed, Morocco

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ABSTRACT

Understanding hydroclimatic variations and land cover changes is crucial for effective watershed management, as they directly impact water availability, soil stability, and ecosystem health. However, management is often hindered by limited long-term data availability, rapid land-use changes, and increasing climate variability, making continuous monitoring essential. This study evaluates hydroclimatic trends and land cover dynamics in the Bouregreg watershed (Morocco), using observed rainfall and streamflow data (1977–2020) and remote sensing techniques (2018–2022). Results show significant land cover changes, including declines in forest cover and irrigated farmland due to urban expansion, deforestation, and land degradation. In contrast, grazing lands expanded, likely driven by agricultural decline and economic pressures. Prolonged droughts and increasing aridity further contributed to these transformations. The reduction in bare soil and continued urbanization reflect shifting land use patterns. Statistical analyses, including Pettitt, Buishand, and Lee and Heghinian tests, were applied to detect trends and ruptures in rainfall time series. The results indicate no significant long-term trend in rainfall. However, fluctuations in precipitation and streamflow, analyzed using the Deviation from the Mean and the Standardized Precipitation Index, reveal a clear shift toward aridity. Flow variations confirm the predominance of deficit years, frequently exceeding 60% of observed years. A strong correlation between rainfall and streamflow highlights the interconnected influence between rainfall and hydrological response, influenced by topography, land cover, and human activities. These findings emphasize the need for integrated and adaptive watershed management strategies to mitigate climate impacts and balance competing land uses. Effective management requires data-driven planning to regulate urban expansion, optimize water resource allocation, and enhance climate risk adaptation. Addressing challenges such as deforestation, overexploitation of water resources, and increasing climate variability demands integrated and long-term sustainable land and water management approaches.

Keywords: Bouregreg watershed, deficit indices, land cover changes, rainfall, statistical tests, streamflow dynamics.

INTRODUCTION

Rainfall is a vital natural resource influencing streamflow variability, flood risk, ecosystem health, and water availability within watersheds (Abera et al., 2017; Zhao et al., 2015; Kliment et al., 2011). Variations in precipitation patterns significantly impact agricultural and industrial sectors by disrupting irrigation, affecting crop yields, and increasing water costs. Understanding rainfall trends is crucial for optimizing water resource management and sustainability (Chauluka et al., 2020; Orke and Li, 2021).

Hydroclimatic studies have shown that climate change influences precipitation and streamflow through increasing temperatures, shifting rainfall regimes, and altering extreme weather patterns (Abungba et al., 2020; Arrieta-Castro et al., 2020; Charifi Bellabas et al., 2021; Chauluka et al., 2020; Zhong et al., 2020). Some studies highlight declining streamflow trends linked to reduced precipitation (Sönmez and Kale, 2018 and; Ferreira et al.,2021), while others report an inconsistent response to rainfall variability (Hannaford, 2015; Wang et al., 2009). These findings emphasize the need for regional-scale analyses to assess the impacts of hydroclimatic variability on water resources.

Beyond hydroclimatic factors, land cover dynamics play a fundamental role in shaping watershed hydrology and ecosystem stability. Land cover change, driven by natural processes and human activities, significantly affects soil infiltration, surface runoff, and water availability (Foley et al., 2005; Lambin et al., 2003). Rapid urbanization, agricultural intensification, and grazing land expansion in Morocco have led to profound transformations in watershed landscapes. The Bouregreg watershed, in particular, has been experiencing increasing pressure due to both human activities and climate variability, impacting vegetation cover and water resources (Khattabi, 2008).

The Bouregreg watershed is crucial in maintaining environmental integrity and socio-economic activities, making it one of Morocco's most important basins. As a major water source for urban and rural communities, the Bouregreg rivers support essential needs such as drinking water and agriculture. However, due to changing climatic conditions and growing water demand, the Bouregreg basin is experiencing an increasing degradation of its water resources (Khattabi, 2008).

Despite its importance, streamflow and rainfall variability in the Bouregreg basin remain understudied. Previous research has highlighted significant seasonal and annual fluctuations. For instance, Khomsi et al. (2016) analyzed precipitation and runoff trends (1977–2003), revealing seasonal variability across different watershed regions. Autumn and winter rainfall showed mixed trends, with declining patterns in most areas except for parts of the south. Spring and summer rainfall exhibited consistent decreases. On an annual scale, Tramblay et al. (2013) reported a significant long-term decline in precipitation. Regarding streamflow, findings suggest modest variations without clear long-term trends. El Aoula et al. (2021) examined precipitation-runoff dynamics (1977–2013) and found that streamflow regimes varied significantly across sub-basins. The decline in rainfall since the late 1970s drought mainly affected winter flows, reducing discharge at most stations. The Tsalat sub-basin (humid Middle Atlas) showed a persistent decline in precipitation, whereas the Ain Loudah sub-basin (semi-arid Center-West) exhibited more variable trends. The year 1996 marked an anomaly with exceptionally high rainfall across all sub-basins.

This study is particularly crucial given the Bouregreg watershed's significant role in regional water management and its vulnerability to climate variability and land cover change. The watershed supports key agricultural activities, directly influencing local livelihoods and national food security. It also plays a vital role in regional hydrology, affecting water availability and quality in major urban centers. The Sidi Mohamed Ben Abdellah Dam, a key infrastructure for regulating river runoff and providing potable water, underscores the need for a comprehensive understanding of the watershed's hydroclimatic and land cover dynamics.

However, despite its strategic importance, few studies have comprehensively analyzed hydroclimatic variability and land cover changes together in the Bouregreg watershed. While studies on climate variability exist for other Moroccan basins, research on how rainfall trends, land use transformations, and hydrological dynamics interact in this specific region remains limited.

This study provides a valuable contribution to the understanding of environmental changes in the Bouregreg watershed. By integrating land cover change assessment, statistical rainfall trend detection, and hydroclimatic variability analysis, our research fills a critical knowledge gap. Understanding these interactions is essential for sustainable water resource management, especially in the context of increasing climatic and anthropogenic pressures.

Moreover, this study serves as an essential baseline for future research and projections. Before modeling future climate and land-use scenarios, it is crucial to first establish a detailed understanding of current trends and changes. Our research provides an updated, data-driven assessment of recent environmental transformations, offering valuable insights for both researchers and decision-makers working on climate adaptation strategies in Morocco.

To better understand hydroclimatic variability in the Bouregreg watershed, this study first applied statistical tests to detect potential shifts in precipitation time series before analyzing rainfall fluctuations. Identifying these breakpoints is crucial, as sudden shifts in precipitation regimes can significantly alter streamflow patterns, soil moisture availability, and long-term land use trends.

Among the various statistical methods available, the Pettitt, Buishand, and Lee & Heghinian tests were selected because they are widely used in climate studies to identify abrupt changes in time series data. These tests help distinguish whether observed fluctuations are part of a natural cycle or represent a structural shift in the climate system. Detecting such change points allows for a more accurate assessment of rainfall variability, helping determine whether recent climatic trends deviate significantly from historical norms.

Once the statistical tests confirmed the presence (or absence) of significant shifts, the analysis proceeded with an in-depth examination of precipitation fluctuations over the past 44 years. This approach ensured that observed trends were not misinterpreted as random variations but rather linked to long-term hydroclimatic dynamics. The results were then correlated with streamflow variations and land cover changes to assess how shifts in precipitation patterns influence watershed hydrology and ecosystem stability.

By incorporating these statistical methods, this study provides a more robust and data-driven understanding of rainfall variability, supporting efforts to develop sustainable water resource management strategies in the face of climate change and anthropogenic pressures.

MATERIALS AND METHODS

Study area

The Bouregreg watershed, the subject of our study (Fig. 1), is situated northwest of Morocco. The Sebou watershed borders it to the northeast, the Oum Er Rbiaa basin to the south, and the coastal Oueds basins (Oued Cherrat, Oued N'fifikh, Oued Mellah) to the southwest, and opens westward to the Atlantic Ocean. The basin's hydrographic network comprises four principal streams: Oued Bouregreg (264 km), which drains the northeastern part of the basin; Oued Grou (249 km), Oued Korifla (139 km), and Oued Mechra (132 km), which drain the southwestern part. These rivers originate from the western flank of the Middle Atlas (Eddefli et al., 2023), traverse central Morocco, and ultimately flow into the Sidi Mohamed Ben Abdellah dam reservoir (SMBA), which is situated not far upstream from the watershed's point of discharge (Bounouira, 2012).

The region's coastline between Rabat-Salé and Casablanca receives drinking water from the reservoir, which has a usual capacity of 975 hm^3. Additionally, pastoral and agricultural activities constitute the majority of the watershed's socio-economic activity, which is contingent upon the availability of water (Nafii et al., 2023).

The Bouregreg watershed region has a Mediterranean climate, with 86–92% of the yearly precipitation occurring during the moist period from October to April and only 8–14% during the arid period from May to September. On average, the region receives around 400 mm of rainfall each year. The temperature ranges from 35 to 45 °C in summer and 5 to 15 °C in winter (Tra Bi, 2013).

Hydroclimatic data

The Bouregreg watershed has eight hydro-rainfall stations (Table 1, Fig. 1) strategically positioned along its main rivers. These stations are Aguibet Ezziar, Lalla Chafia, Tsalat, Ras Fathia, Sidi Jabeur, Ouljat Haboub, Sidi Mohamed Cherif, and Ain Loudah. Hydro-rainfall data collected

Table 1. Hydro-rainfall stations used in the study

Hydro-rainfall stations	Latitude	Longitude	River
Aguibet Ezziar	33.91	-6.54	Bouregreg
Lalla Chafia	33.7	-6.39	Bouregreg
Tsalat	33.33	-6.03	Guennour
Ras Fathia	33.76	-6.54	Grou
Sidi Jabeur	33.58	-6.43	Grou
Ouljat Haboub	33.1	-6.26	Grou
S.M. Cherif	33.54	-6.63	Mechra
Ain Loudah	33.55	-6.76	Korifla

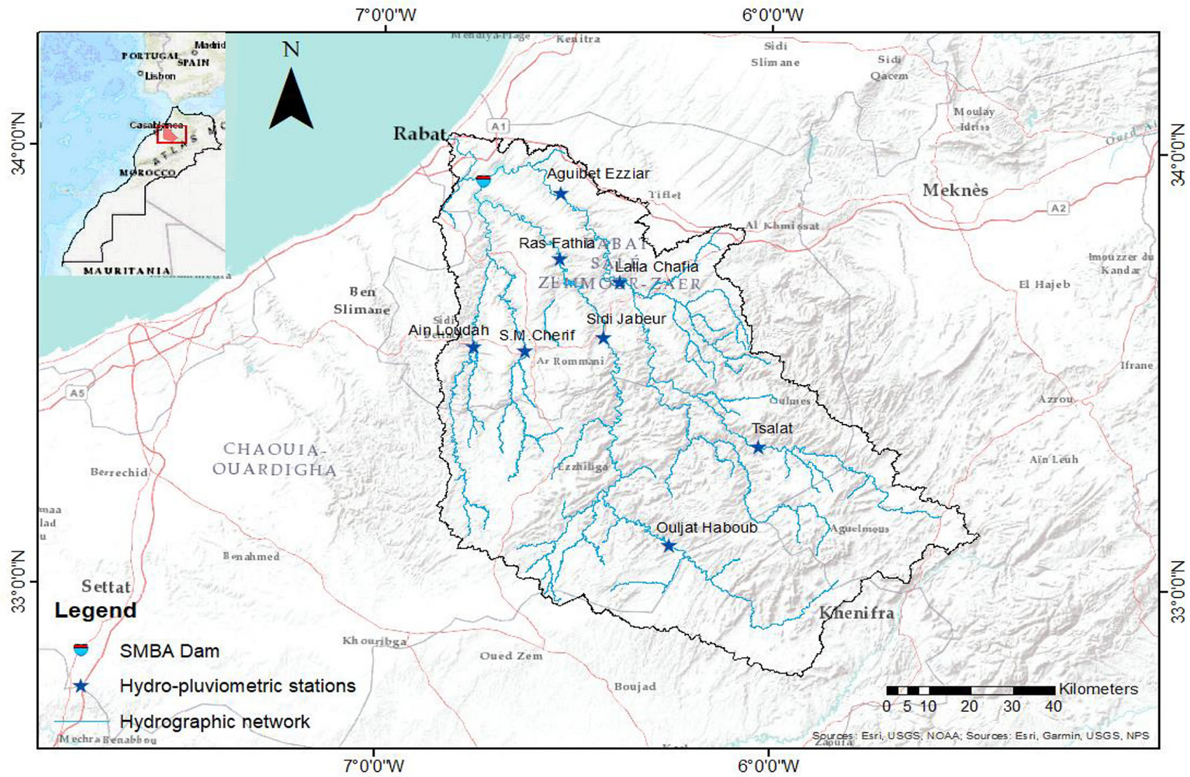

Figure 1. The spatial distribution of hydro-rainfall stations in the Bouregreg catchment

from the Bouregreg and the Chaouia Hydraulic Agency (ABHBC) covers the period from 1977 to 2020.

METHOD

Land cover dynamics

The study of land cover in the Bouregreg watershed relied on spatial remote sensing to assess spatio-temporal vegetation changes. This approach helps determine whether vegetation has expanded or declined over time. Landsat images, widely used for land use analysis, are valued for their free availability, high quality, efficiency, and reliability, making them essential for regional and global studies. Landsat satellite images from 2018 and 2022 were used to identify changes in land cover classes. With a spatial resolution of 30 meters, they provide sufficient detail to distinguish crops, watercourses, and vegetation. The Landsat satellite is equipped with the Operational Land Imager (OLI) and the Thermal InfraRed Sensor (TIRS), which capture multi-wavelength data, including surface temperature.

The watershed is covered by two distinct scenes, requiring two satellite images per year to be merged using the mosaicking tool in ArcGIS. The final image is then clipped to the watershed boundary. The normalized difference vegetation index (NDVI) quantifies vegetation density based on the difference between the red (R) and near-infrared (NIR) spectral bands:

$$NDVI = \frac{PIR-R}{PIR+R} \in [-1; 1] \quad (1)$$

Computed in ArcGIS via the Raster Calculator, NDVI values range from -1 to 1:

- Close to 1: High vegetation density (forests).
- Around 0: Sparse or no vegetation (bare soil, urban areas, croplands, pastures).
- Negative values: Water, snow, or clouds.

The methodology (Fig. 2) aimed to map land cover dynamics in the Bouregreg watershed accurately.

Detection of changes in historical rainfall series

A rupture in rainfall data occurs when significant, sudden, or abnormal changes are detected within a historical time series. To identify such abrupt change points in precipitation trends from 1977 to 2020, this study applied three widely used statistical tests: the Pettitt

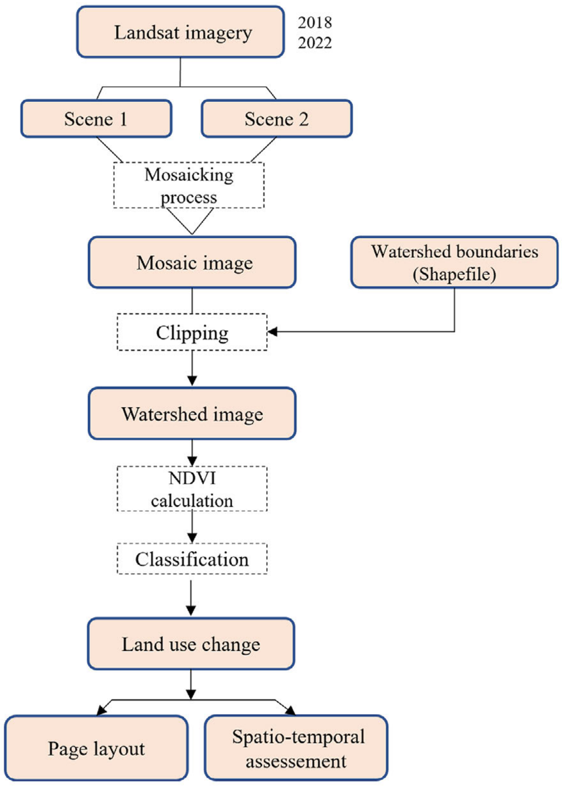

Figure 2. Diagram of the methodology adopted to analyze land cover dynamics

test, the Buishand test, and Lee and Heghinian's Bayesian approach. These methods were selected for their effectiveness in detecting structural breaks in climatic time series, distinguishing between natural variability and significant shifts that could indicate long-term climate changes. Before identifying breakpoints, it was necessary to assess whether the rainfall data series exhibited random variations or followed an underlying trend. For this purpose, the rank correlation test was employed (Lubes et al., 1994) to determine whether the observed fluctuations were purely stochastic or showed signs of non-random changes. Once randomness was evaluated, the Pettitt, Buishand, and Lee & Heghinian tests were applied to pinpoint the moments of significant changes in rainfall patterns.

All methods were applied to the previously homogenized (reconstructed) rainfall series from eight stations within the watershed. Verifying randomness and detecting breaks were performed using Khronostat software (IRD, 2000), which integrates all these tests. The Pettitt test (Pettitt, 1979) identifies breakpoints with precise dates. It is defined as:

$$K_t = max \mid U_t \mid$$

where:

$$U_t = \sum_{i=1}^{t} \sum_{j=t+1}^{n} sign(x_j - x_i) \tag{2}$$

where: x_j and x_i are observations in the time series, n is the total number of observations, and t is the potential change point.

The *p-value* is estimated using the following approximation:

$$p \approx 2\, e^{\frac{-6K_t^2}{n^3+n^2}} \tag{3}$$

If the p-value < 0.05, the null hypothesis (no rupture) is rejected, indicating a statistically significant change point in the time series.

The Buishand test (Buishand, 1984, 1982) evaluates whether a significant shift has occurred by analyzing cumulative deviations from the mean. It is computed as:

$$R = max \mid S_k \mid$$

where:

$$S_k = \sum_{i=1}^{k} (x_i - \bar{x}), \quad k = 1, 2, \ldots n \tag{4}$$

where: x_i is observations in the time series and $\bar{x}$ is the mean of the entire series. The point K, where S_k reaches its maximum absolute value, is considered the candidate change point. A significant structural break is detected if the test statistic exceeds a critical threshold.

The Lee and Heghinian method (Lee and Heghinian, 1977) method estimates the most probable change point by comparing the mean values before and after a potential shift. The model assumes that a time series $x_1, x_2, \ldots, x_n$ follows a normal distribution before and after the change point *t*:

$$x_i \sim N(\mu_1, \sigma^2)\ for\ i \le t\ and$$

$$x_i \sim N(\mu_2, \sigma^2)\ for\ i > t \tag{5}$$

where: $N(\mu_2, \sigma^2)$ represents a normal distribution with mean μ and variance σ^2, μ_1 and μ_2 are the mean values before and after the detected change, σ^2 is the variance assumed constant throughout the series.

This method estimates the probability of a change occurring at each time step and identifies the most likely breakpoint based on the highest probability.

Rainfall deficit indices calculation

These indices will characterize the interannual rainfall pattern in the Bouregreg watershed and dry and wet periods from 1977 to 2020.

The deviation from the mean index (E_m) is useful for assessing yearly rainfall deficits, identifying significant trends, estimating the length of dry spells, and measuring their intensity. It is computed by deducting the average interannual precipitation (P_m) from the annual rainfall (P_i) and then expressing the result as a percentage. This is the formula:

$$E_m = 100 \times \frac{P_i - P_m}{P_m} \quad (6)$$

where: $E_m < 0$ denotes a year with insufficient precipitation or dryness. Conversely, $E_m > 0$ indicates a year with excess precipitation (wet year).

The identical formula is applied to mean annual and interannual streamflow to emphasize the notable fluctuations in the hydrological patterns of the rivers examined within the Bouregreg catchment area.

The standardized precipitation index (SPI) calculates rainfall deficits over a chronic period (Mckee et al., 1993). It is computed using the following relationship:

$$SPI = \frac{P_i - P_m}{Standard\ deviation} \quad (7)$$

where: P_m is the series' average annual precipitation (mm), and P_i is the yearly precipitation (mm).

Table 2 shows the intervals of SPI values used to identify anomalies in rainfall.

Spatialization of annual rainfall

Examining the spatial distribution of rainfall is a crucial step that complements the analysis of rainfall fluctuations at each selected station. This spatial analysis aims to map the rainfall distribution across the catchment area, identifying regions with higher and lower average rainfall. In this study, the spatial average rainfall over the watershed is estimated using the Thiessen polygon method by the following formula:

$$P_{moy} = \frac{1}{A} \times \sum_{i=1}^{n} A_i P_i \quad (8)$$

where: P_{moy} – average precipitation at the watershed scale (mm). A_i – surface area of the polygon associated with station i (km²), A – total watershed area (km²).

Table 2. SPI ranges and their corresponding characters

SPI ranges	Character
Above 2	Extreme humidity
1 to 2	High humidity
0 to 1	Moderate Humidity
0 to -1	Moderate dryness
-1 to -2	High dryness
Below -2	Extreme dryness

Rainfall-Streamflow relationship

The correlation method investigated the relation between the streamflow and rainfall regimes at the catchment scale. Many earlier studies (Bodian et al., 2012; Elbouqdaoui et al., 2006; Haida et al., 1999) have successfully employed this methodology. The relationship was identified by comparing the average annual rainfall at each rainfall-hydrometric station with the average yearly streamflow of the rivers. Excel's "Analysis Tool" was used to perform this analysis, precisely the "Correlation" function within this toolkit. This function calculates the Pearson correlation coefficient, which measures the strength and direction of the linear relationship between two variables. By using this method, the study was able to quantify the extent to which precipitation variations are associated with streamflow changes.

RESULTS

Changes in land cover

Figure 3 illustrates the evolution of land cover between 2018 and 2022. During this period, the forest category declined by 3%, resulting in a total loss of 29 431 hectares. Likewise, agricultural land decreased by 9%, corresponding to 88714 hectares. In contrast, grazing lands expanded by approximately 25%, adding 119 303 hectares. Landsat images used for land cover analysis indicated an urban growth of only 0.3%, which likely underestimates the actual extent of this expansion. The coastal area remains the most urbanized zone within the basin.

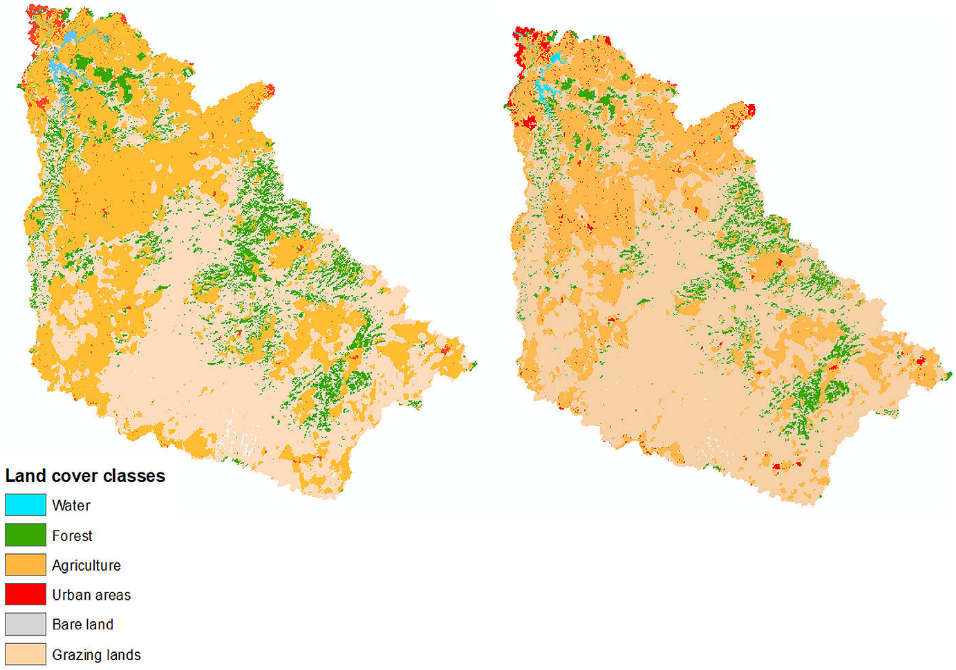

Figure 3. Evolution of land cover in the Bouregreg basin between 2018 (left) and 2022 (right)

Analysis of rainfall series tests

Rank correlation tests indicate no significant trend in the rainfall series, with the null hypothesis (random time series) accepted at 99%, 95%, and 90% confidence levels. The Pettitt test (Fig. 4) and Buishand test (Fig. 5) confirm the absence of significant ruptures, with the null hypothesis (no ruptures) also accepted at these confidence levels. However, the Lee and Heghinian test identified ruptures in the rainfall data at the Aguibet Ezziar, Tsalat, and Ouljat Haboub stations

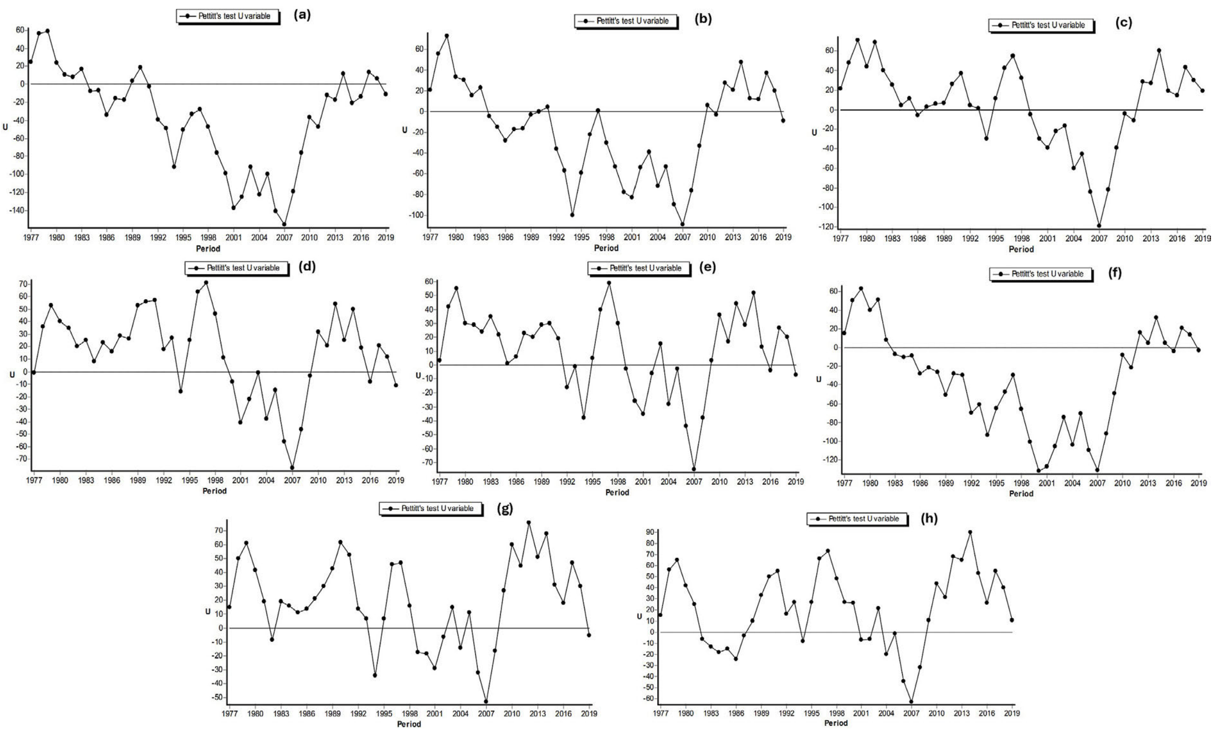

Figure 4. Pettitt test results for annual rainfall in the Bouregreg watershed: (a) Aguibet Ezziar, (b) Lalla Chafia, (c) Tsalat, (d) Ras Fathia, (e) Sidi Jabeur, (f) Ouljat Haboub, (g) S.M. Cherif, (h) Ain Loudah

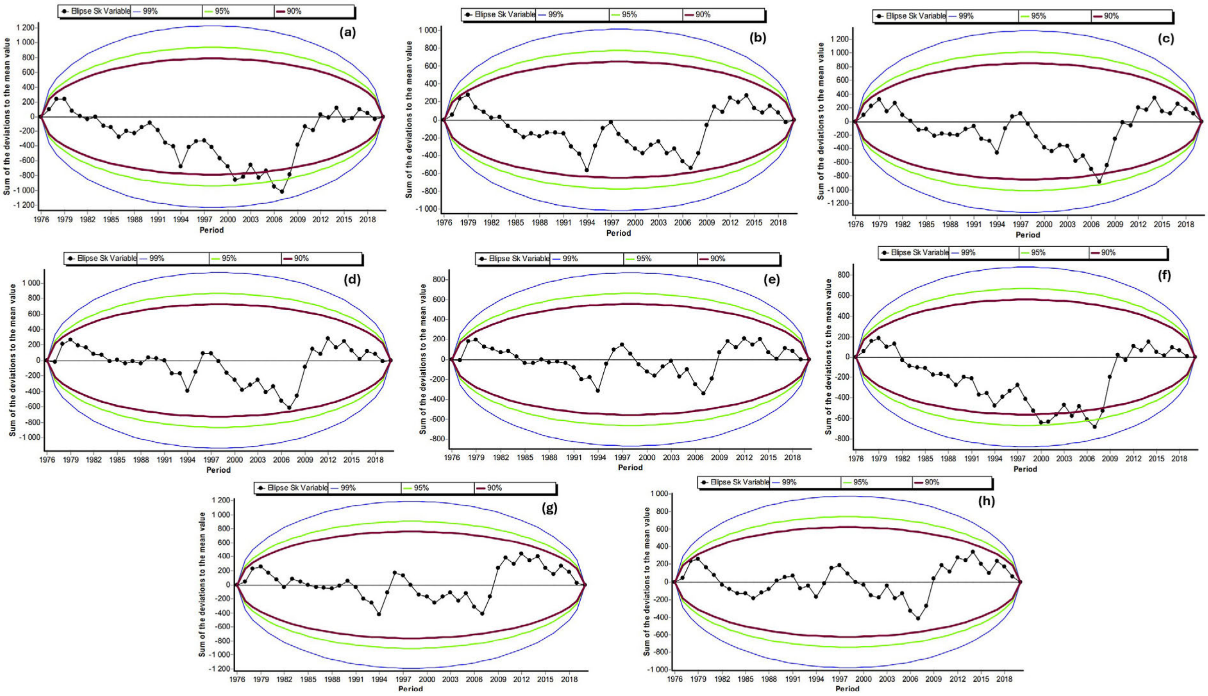

Figure 5. Buishand test results for annual rainfall at stations in the Bouregreg watershed: (a) Aguibet Ezziar, (b) Lalla Chafia, (c) Tsalat, (d) Ras Fathia, (e) Sidi Jabeur, (f) Ouljat Haboub, (g) S.M. Cherif, (h) Ain Loudah

around early 2007, with maximum probabilities of 15.54%, 7.86%, and 11.42%, respectively. This discrepancy arises because the Pettitt and Buishand tests detect sharp, statistically significant ruptures. In contrast, the Lee and Heghinian test identifies variations that, while present, do not meet the threshold for true ruptures in the rainfall series.

Interannual rainfall variability

Annual precipitation graphs for the eight stations within the watershed (Fig. 6) illustrate pronounced inter-annual variability between 1977 and 2020. Significant fluctuations are evident at each station, with notable precipitation peaks occurring in 1995 and 2009 and periods of severe drought. Local variations are also observed across stations, reflecting site-specific geographical or climatic characteristics. The graphs further emphasize the alternation between wet and dry years, sometimes occurring abruptly without transitional periods.

Climatic indices have been calculated to better analyze this interannual variability and characterize dry and wet periods. These include the deviation from the mean index (E_m) and the standardized precipitation index (SPI). These indices provide valuable insights into rainfall deficits and climatic anomalies, offering a clearer understanding of the hydrological dynamics within the watershed.

Deviation from the mean index

The graphs (Fig. 7) present the percentage deviations from the mean of the rainfall series for the eight stations under study, highlighting a succession of dry and wet periods. The longest rainfall deficit in the basin extended from 1980 to 2007, interrupted by several wet years (ranging from 6 to 8, depending on the station). The wettest years were recorded in 1995, 2012, and between 2008 and 2010. The deviation index reveals that 2009 was particularly wet for the stations of Aguibet Ezziar, Lalla Chafia, Tsalat, Ras Fathia, Ouljat Haboub, S.M. Cherif, and Ain Loudah, with deviations ranging from 79.7% to 108%, depending on the station. For the Sidi Jabeur station, in addition to 2009 (with a deviation of 80%), another notably wet year was 1995, with a deviation of 83.5% from the average. Conversely, the driest years varied across stations: 1982 and 1992 for Ouljat Haboub, 1994 for Aguibet Ezziar, Lalla Chafia, Tsalat, and Ras Fathia, 2004 for Sidi Jabeur, and 2006

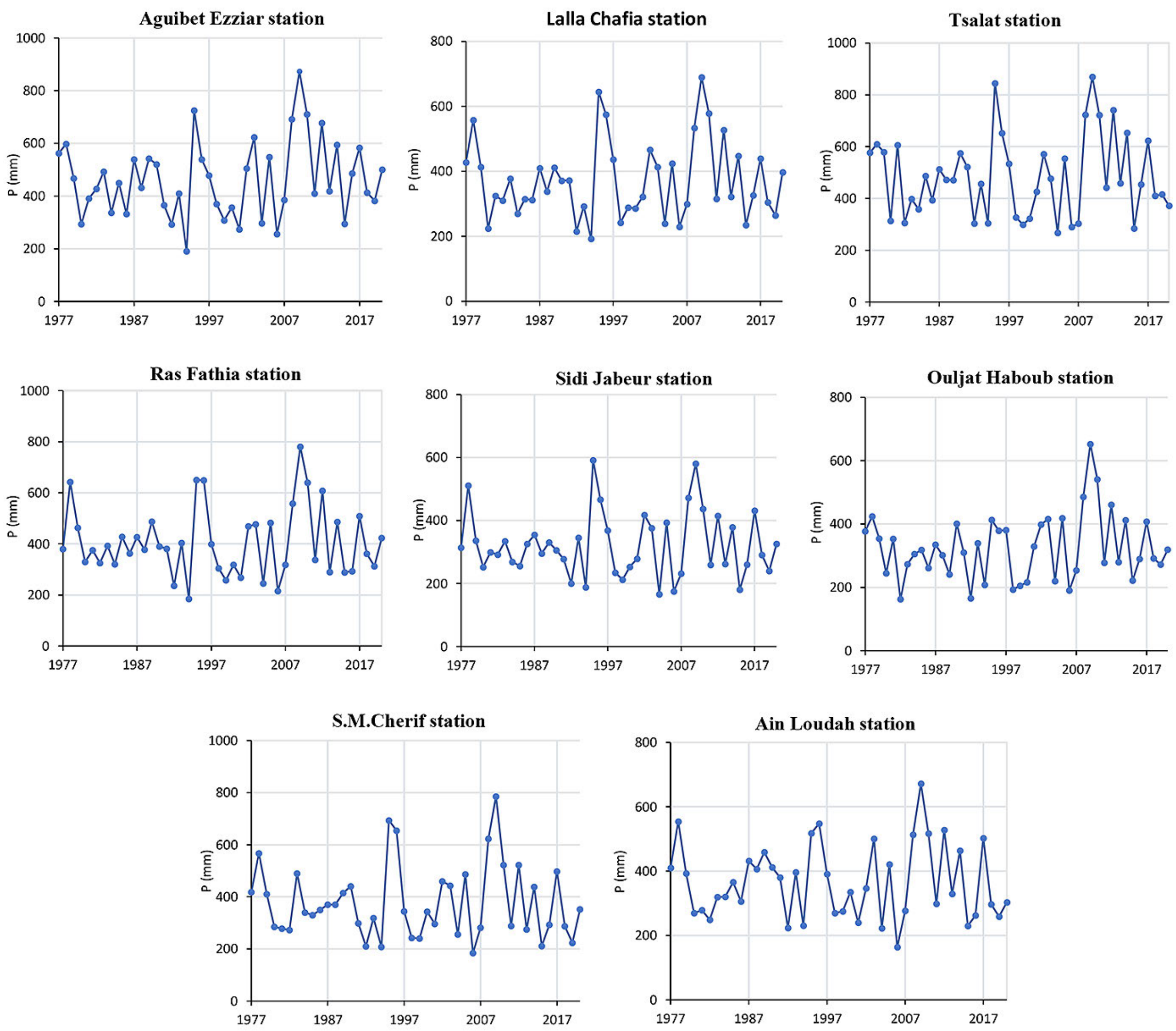

Figure 6. Interannual variability of rainfall at eight stations in the Bouregreg basin

for S.M.Cherif and Ain Loudah. The summary of observed rainfall sequences is:

- 1977 to 1994: a general trend of rainfall deficit was observed across all stations, with occasional surpluses. Notable deficits were recorded in 1982 and 1992 at Ouljat Haboub and in 1992 and 1994 at other stations.
- 1995 to 1997: this was a generally wet period, with 1996 being the wettest year for Ain Loudah and 1995 for the other stations.
- 1998 to 2007: a prolonged period of widespread drought affected all rainfall stations.
- 2008 to 2020: a relatively wet period for all stations, characterized by significant surpluses in 2009. However, this period was also interrupted by several drought years.

Tables 3 and 4 provide information on the number of dry and wet sequences and the years with precipitation deficits or surpluses based on the deviation from the mean index (E_m). These tables also show the average intensity of these events and the cumulative deficits and surpluses over the corresponding periods. Comparing the two tables, dry periods exhibit a longer average duration (25 years) compared to wet periods (19 years), even though wet periods are slightly more frequent (12 sequences vs. 11 sequences). The cumulative deficit during dry periods and the cumulative surplus during wet periods are relatively similar, averaging around 2200 mm, suggesting a degree of compensation in the long-term water balance. However, the average intensity of wet periods (117 mm) significantly exceeds that of dry periods (89 mm). These findings indicate that rainfall across the watershed is experiencing a critical phase characterized by prolonged dry periods.

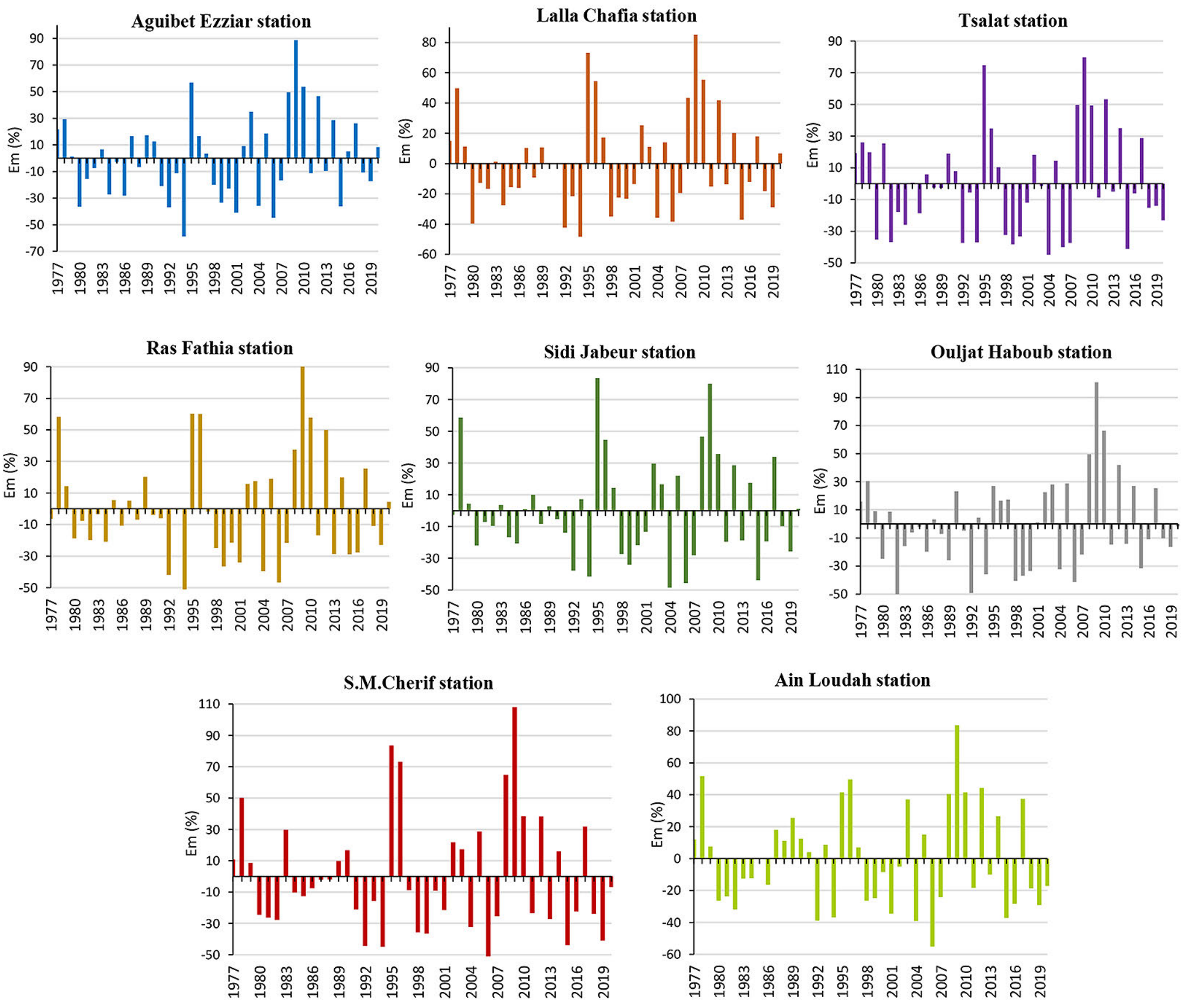

Figure 7. The deviation from the mean index (E_m) for the annual average precipitation at the eight Bouregreg stations

Table 3. Characteristics of dry years over the period (1977–2020) for the eight stations

Stations	Number of sequences*	Duration (year)	Cumulative deficit (mm)	Average intensity (mm)**
Aguibet Ezziar	11	23	2549.8	110.9
Lalla Chafia	11	25	2099.2	84.0
Tsalat	11	25	2765.8	110.6
Ras Fathia	12	27	2283.8	84.6
Sidi Jabeur	13	24	1746.7	72.8
Ouljat Haboub	12	24	1778.4	74.1
S.M. Cherif	10	27	2444.9	90.6
Ain Loudah	10	24	2103.6	87.7
Mean	11	25	2222	89

Note: *interval of successive dry years, **the ratio of the cumulative deficit to the dry period's duration determines its average intensity.

Nonetheless, the slightly higher frequency of wet periods and their capacity to offset water deficits suggest that the system retains a certain level of resilience.

Standardized precipitation index

The SPI proves particularly useful in identifying years with precipitation deficits or surpluses

Table 4. Characteristics of wet years over the period (1977–2020) for the eight stations

Stations	Number of sequences*	Duration (year)	Cumulative surplus (mm)	Average intensity (mm)**
Aguibet Ezziar	12	21	2549.8	121.4
Lalla Chafia	12	19	2099.2	110.5
Tsalat	12	19	2765.8	145.6
Ras Fathia	12	17	2283.8	134.3
Sidi Jabeur	13	20	1746.7	87.3
Ouljat Haboub	12	20	1778.4	88.9
S.M. Cherif	10	17	2444.9	143.8
Ain Loudah	10	20	2103.6	105.2
Mean	12	19	2222	117

Note: *interval of successive dry years, **The ratio of the cumulative surplus to the wet period's duration determines its average intensity.

(Fig. 8) and classifying wet and dry periods by distinguishing their intensity levels, ranging from moderate to extreme (Table 5). The analysis of SPI graphs reveals significant fluctuations in precipitation across all stations. At Aguibet Ezziar, Lalla Chafia, and Tsalat, notable wet periods were recorded in 1995 and 2009, while droughts were observed in 1994 for Aguibet Ezziar and

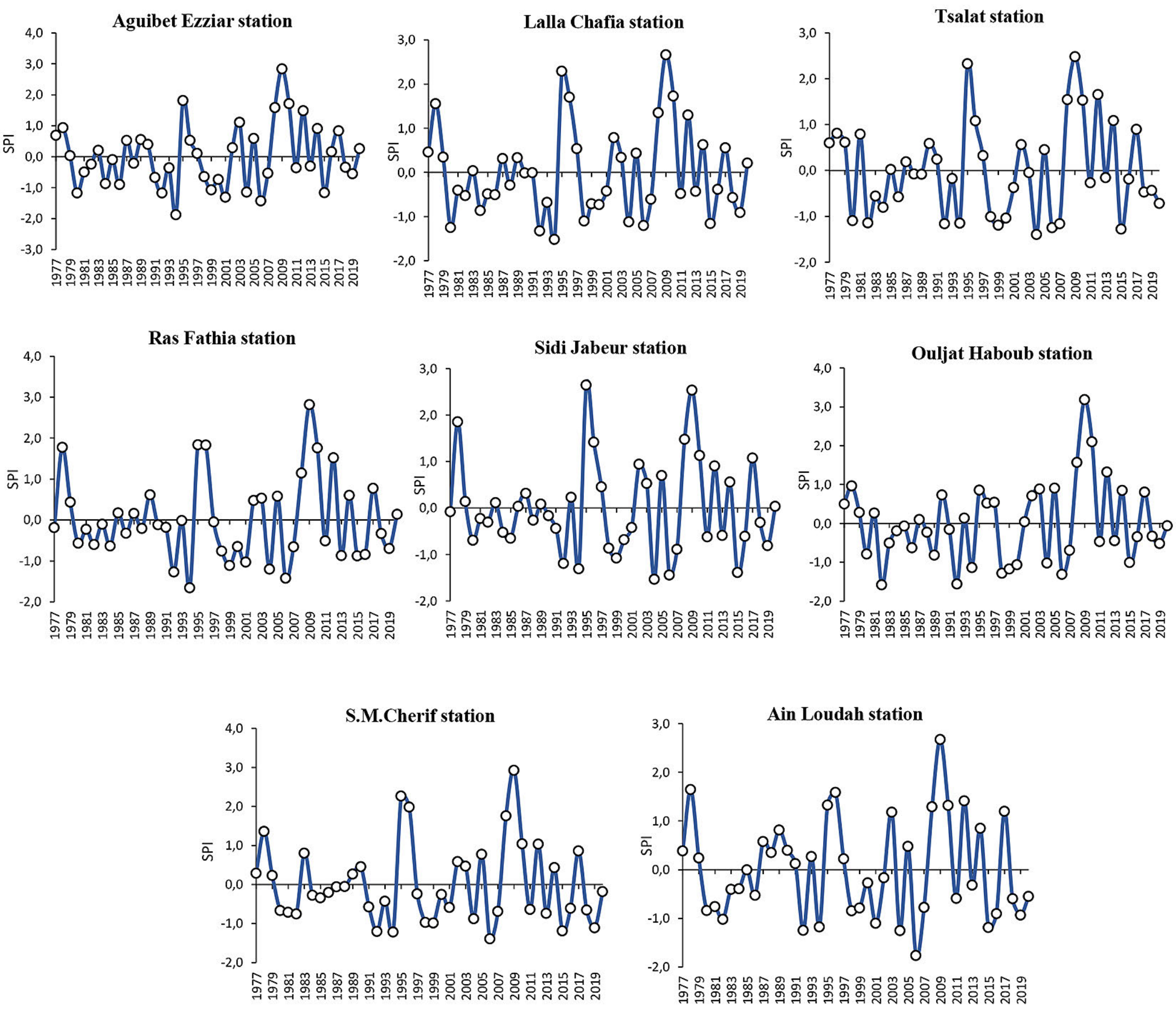

Figure 8. Classification of mean annual rainfall for the eight stations based on the SPI index

Table 5. Frequency of SPI index in all selected stations

Station	Extreme humidity	High humidity	Moderate humidity	Moderate dryness	High dryness	Extreme dryness
Aguibet Ezziar	2%	9%	32%	36%	18%	0%
Lalla Chafia	5%	11%	25%	43%	16%	0%
Tsalat	5%	11%	25%	36%	20%	0%
Ras Fathia	2%	14%	23%	50%	14%	0%
Sidi Jabeur	5%	11%	25%	43%	14%	0%
Ouljat Haboub	5%	5%	34%	39%	16%	0%
S.M.Cherif	5%	7%	27%	48%	11%	0%
Ain Loudah	2%	18%	25%	41%	14%	0%
Mean	4%	11%	27%	42%	15%	0%

Lalla Chafia, and in 2004 for Tsalat. At Ras Fathia and Sidi Jabeur, a rapid alternation between drought and wet periods is evident after 2001, with peaks of wetness in 1995 and 2009 and recurring droughts in the early 1980s and 2015. At Ouljat Haboub, 2009 stands out with a peak in wetness, whereas 1982 and 1992 correspond to drought peaks. Similarly, the S.M.Cherif and Ain Loudah stations confirm this alternation, with particularly wet years in 1995 and 2009 and significant droughts in 1994 and 2006.

The frequency table indicates that moderate droughts are the most common across all stations, with an average occurrence of 42%. Severe droughts represent 15% of cases, while extreme droughts are absent, reassuring in the current context. However, this absence should not dismiss the potential risk of such events in the future, especially given the growing impacts of climate change. Moderate humidity accounts for 27% on average, while high or extreme humidity periods remain relatively rare. Among the stations, Ras Fathia and S.M. Cherif exhibit the highest proportions of moderate drought (50% and 48%, respectively), making them particularly susceptible to water deficits. In contrast, stations like Ain Loudah (18%) show a slightly higher proportion of high humidity, reflecting the unique climatic characteristics of different regions. These variations underscore the need for localized adaptation strategies that consider the specific climatic variability of each area. Both the E_m and SPI indices point to a noticeable shift toward an increasingly dry climate regime, highlighting the need for proactive measures to anticipate and mitigate drought impacts in these regions.

Spatialization of annual rains

The graph (Fig. 9) shows a significant alternation between wet and dry years in the Bouregreg watershed. The highest average annual rainfall was recorded in 2009, while the lowest was in 2006. A rainfall map (Fig. 10) was drawn

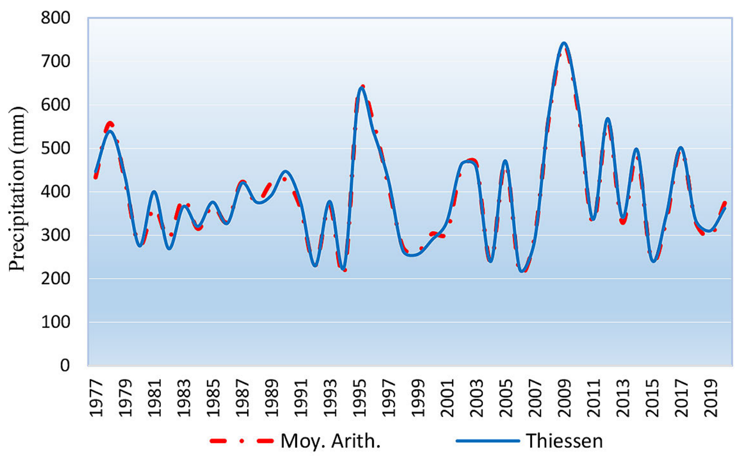

Figure 9. Variation of spatial rainfall averages in the watershed using the Thiessen method

using the Thiessen polygon method to better understand the spatial distribution of rainfall within the watershed. This map highlights the rainfall distribution within the watershed, showing that the northern part of the lower plateau and the mountainous Haut Bouregreg region are the wettest areas, receiving over 400 mm of rainfall annually. These regions likely benefit from the orographic effect, which amplifies precipitation in higher altitudes, particularly in elevated areas. In contrast, the intermediate plateau and parts of the southwestern watershed experience lower rainfall, often below 325 mm per year. These areas lack significant exposure to factors that enhance precipitation, such as altitude or proximity to moisture sources.

Most of the watershed receives between 325 and 400 mm of rainfall annually, forming a transition zone between wetter and drier regions. This precipitation is crucial for recharging rivers and groundwater and sustaining the region's hydrological systems. The entire basin's average annual rainfall is approximately 392 mm. The wettest areas contribute substantially to runoff, which is vital for replenishing dams and water reservoirs. Conversely, the drier areas, particularly in the southwestern part of the watershed, are more vulnerable to drought-related risks.

Interannual variations in streamflow

After analyzing rainfall patterns and identifying dry and wet periods, the hydrological aspects of the Bouregreg basin were studied. Indeed, streamflow is quantitatively influenced by various climatic parameters, particularly precipitation, while other physical factors such as lithology, morphometry, and biogeography affect its characteristics (Sirtou, 1995).

The streamflow data series from the hydrometric stations on the various streams, Bouregreg, Guennour, Grou, Mechra, and Korifla, were analyzed to determine the hydrological pattern of the Bouregreg watershed. The study period spans from 1977/1978 to 2020/2021.

Figure 11 illustrates the marked inter-annual variability in flow across the eight stations, categorized into three intensity levels. The highest flows were recorded at Aguibet Ezziar, Lalla Chafia, and Ras Fathia, with respective peaks of 39.6 m³/s, 28.7 m³/s, and 24.5 m³/s during 2009-2010. Moderate flows were observed at Tsalat, Sidi Jabeur, and Ouljat Haboub, with maximum values ranging between 10 and 17 m³/s. At Ouljat Haboub, the peak flow occurred in 1995–1996, while at Sidi Jabeur, it was observed in 2008–2009. Low flows were recorded at Ain Loudah

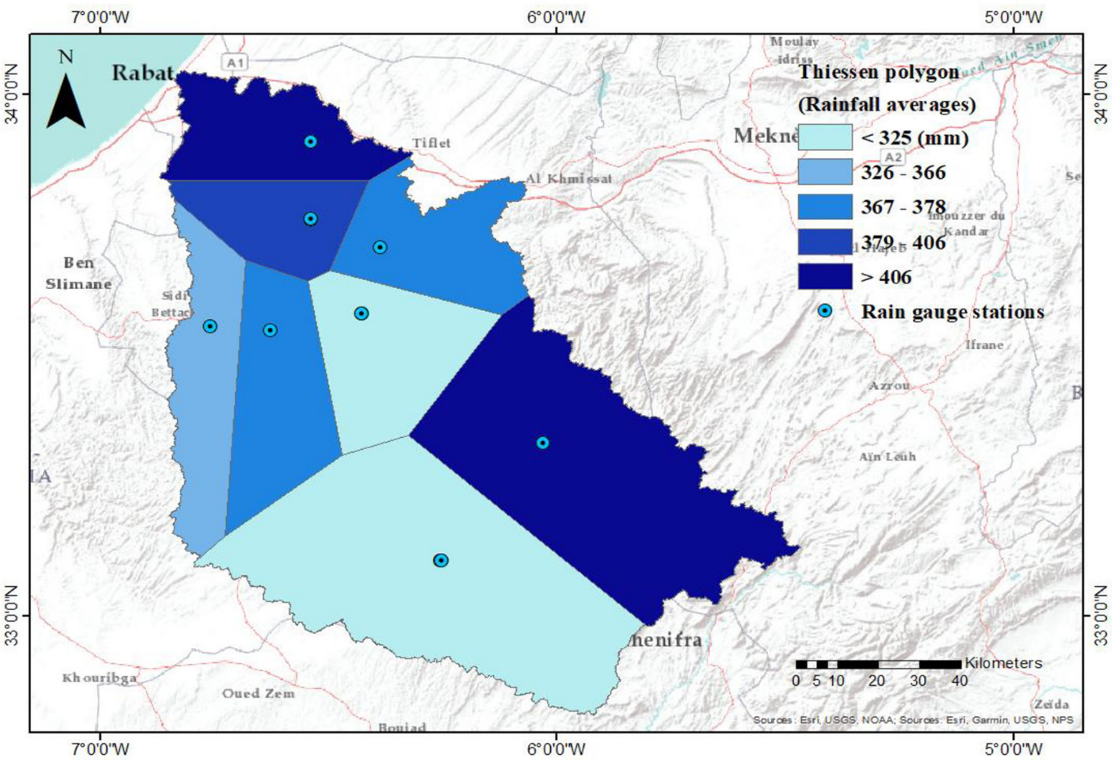

Figure 10. Spatialization of mean annual precipitation using the Thiessen polygon method

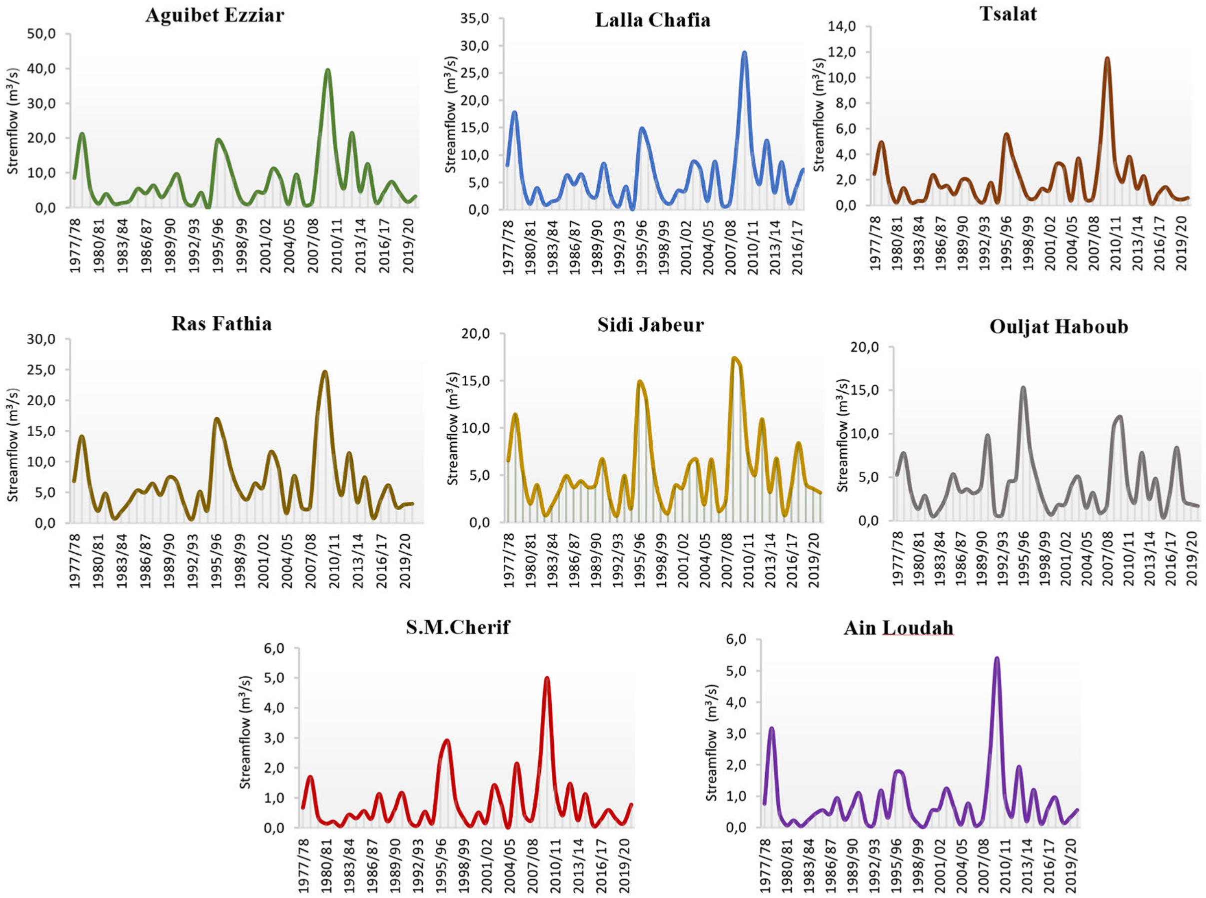

Figure 11. Annual streamflow variation at hydrometric stations (1977/78–2020/21)

and S.M. Cherif, with peak values limited to approximately 5 m³/s in 2009-2010.

Since 2010, a gradual decline in flow has been observed across nearly all stations. This trend indicates a transition to drier conditions, which may be a potential signal of the impacts of climate change on the region's hydrological systems.

Monthly hydrological regime

The graph (Fig. 12) illustrates seasonal variations in river flows from September to August. Flows generally increase between November and March, reaching their peak in February. The highest flow is recorded at Aguibet Ezziar, with approximately 23.2 m³/s. Moderate peaks, ranging from 12 to 20 m³/s, are observed at stations such as Lalla Chafia, Ras Fathia, and Sidi Jabeur. Meanwhile, Tsalat, Ouljat Haboub, S.M. Cherif, and Ain Loudah exhibit lower flows, with 2 and 10 m³/s peaks. A flow decline occurs from April onwards, leading to very low flow levels during the summer months (May to August).

Characterization of flow fluctuations

Deficit years (combining very deficient and deficient years) dominate across all rivers studied, often accounting for over 60% of observed years. For instance, at the Tsalat station (Oued Guennour), very deficient years represent 39% of the total. This proportion reaches 41% at the Ain Loudah station (Oued Korifla) and 43% at the S.M. Cherif station (Oued Mechra). Similarly, data from the Aguitet Ezziar and Lalla Chafia stations (Oued Bouregreg) and the Ouljat Haboub station (Oued Grou) confirm the prevalence of water deficits, with very deficient years making up 34% to 36% of observations. The Ras Fathia and Sidi Jabeur stations (Oued Grou) exhibit a slightly more balanced distribution, though deficit years still predominate. Surplus and very surplus years are less frequent, generally between 9% and 25% depending on the station (Table 6). These findings highlight a significant hydrological instability characterized by a high frequency of water deficit years, likely driven by the effects of climate change.

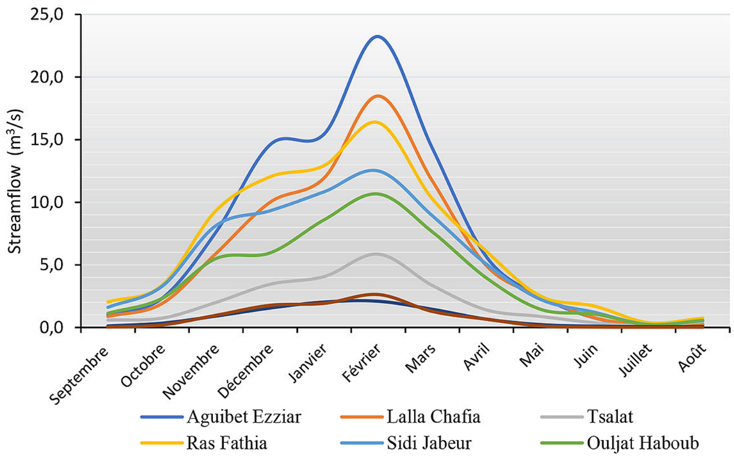

Figure 12 Monthly variation in streamflows at all hydrometric stations (1977/78–2020/21)

Rainfall-streamflow relationship

The correlation method was employed to analyze the relationship between the rainfall and hydrometric regime at the watershed scale. Numerous previous studies have validated this method (Bodian et al., 2012; Elbouqdaoui et al., 2006; Haida et al., 1999), which is based on comparing precipitation and average annual flows observed at each station (Fig. 13).

The analysis revealed significant correlation coefficients at most stations, indicating a strong relationship between rainfall and streamflow. The coefficients were as follows: $R^2 = 0.66$ for Tsalat, $R^2 = 0.74$ for Aguibet Ezziar, $R^2 = 0.76$ for Ras Fathia, $R^2 = 0.77$ for S.M. Cherif, $R^2 = 0.78$ for Lalla Chafia, and $R^2 = 0.79$ for Sidi Jabeur. These results confirm that increases in precipitation generally correspond to increases in streamflow and vice versa.

However, lower correlation coefficients were observed at the Ouljat Haboub ($R^2 = 0.53$) and Ain Loudah ($R^2 = 0.63$) stations. This discrepancy could be attributed to missing values in the original rainfall data, which required imputation. The data-filling process may have affected the strength of the correlation between precipitation and flow at these two stations.

Table 6. Frequency of deficit and surplus years in the hydrometric regime of rivers (1977/78-2020/21)

Description	Oued Bouregreg							
	Aguibet Ezziar				Lalla Chafia			
	V.Def.	Def.	Excd.	V. Excd.	V. Def.	Def.	Excd.	V. Excd.
Number of years	15	14	8	7	16	12	10	6
Frequency %	34%	32%	18%	16%	36%	27%	23%	14%

Description	Oued Guennour				Oued Mechra				Oued Korifla			
	Tsalat				S.M.Cherif				Ain Loudah			
	V.Def.	Déf.	Excd.	V.Excd.	V.Def.	Def.	Excd.	V.Excd.	V.Def.	Def.	Excd.	V.Excd.
Number of years	17	12	11	4	19	12	8	5	18	13	9	4
Frequency %	39%	27%	25%	9%	43%	27%	18%	11%	41%	30%	20%	9%

Description	Oued Grou											
	Ras Fathia				Sidi Jabeur				Ouljat Haboub			
	V.Def.	Def.	Excd.	V.Excd.	V.Def.	Def.	Excd.	V.Excd.	V.Def.	Def.	Excd.	V.Excd.
Number of years	15	12	9	8	12	16	10	6	16	12	8	8
Frequency %	34%	27%	20%	18%	27%	36%	23%	14%	36%	27%	18%	18%

Note: V. Def – very deficient; Def: deficient. Excd. – surplus. V. Excd – very surplus.

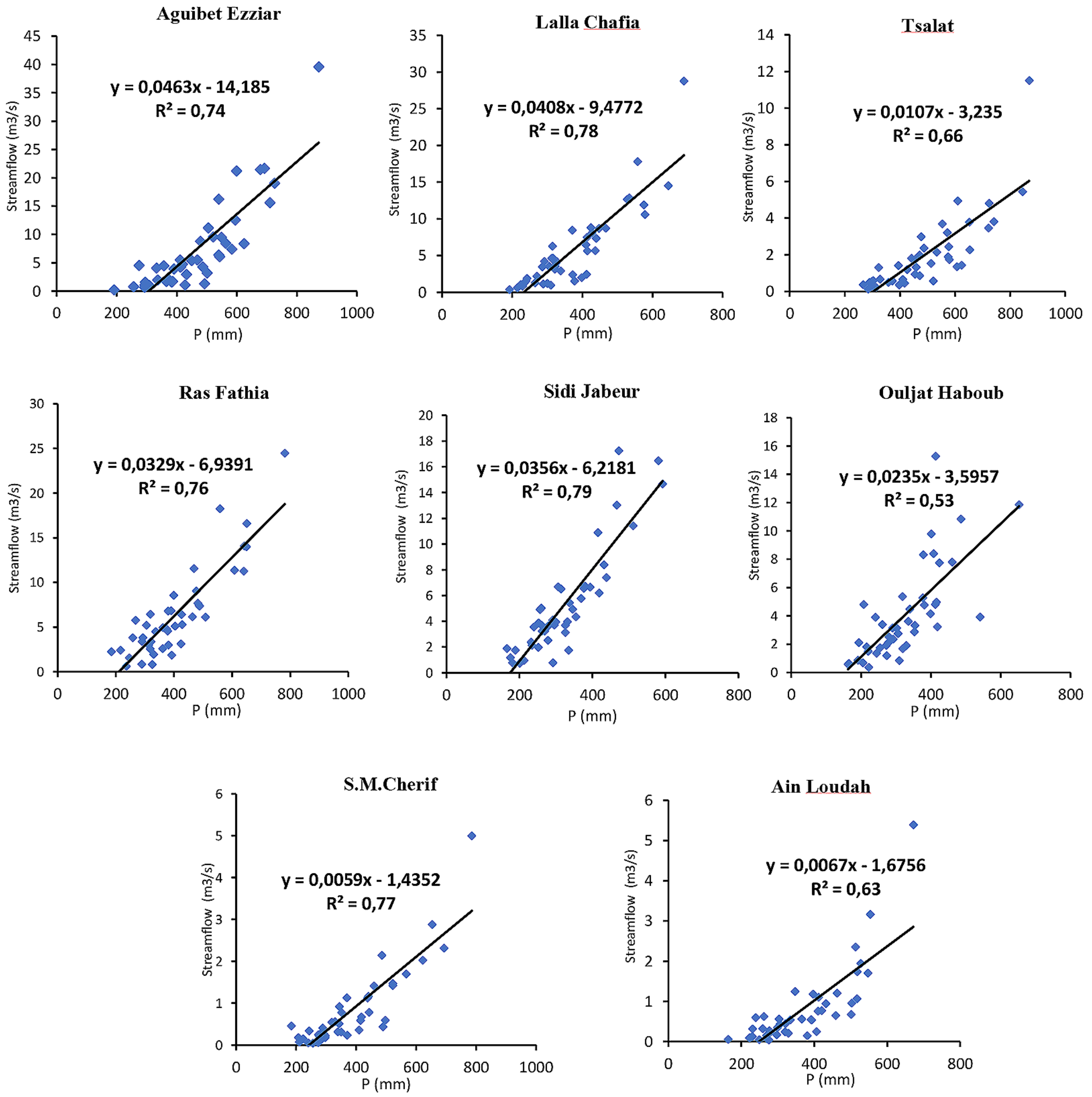

Figure 13. Correlation between rainfall and average annual flow at rainfall-hydrometric stations (1977/78–2020/21)

Overall, the findings underscore the strong linkage between precipitation and hydrometric regimes across the watershed and highlight the influence of data quality on correlation analyses.

DISCUSSION

The analysis of land cover dynamics reveals significant transformations in the Bouregreg watershed, including a decrease in forest cover, a decline in irrigated agricultural land, an increase in grazing land areas, a reduction in bare soil extent, and a significant expansion of urbanization. These changes are primarily driven by urban expansion, demographic pressure, and unsustainable logging for firewood and construction. Climate change, marked by prolonged droughts and increased forest fire occurrences, exacerbates this degradation, along with water, air, and soil pollution. The absence of effective preservation strategies further accelerates vegetation loss. Cereal farming remains dominant in the region, but lower-altitude municipalities cultivate a wider range of crops, including legumes, vegetables, fruit plantations, and forage crops. In contrast, parts of the Upper and Southwestern areas are left fallow, although cereals continue growing. Despite the presence of the SMBA dam, irrigated agriculture remains limited, as its water is mainly allocated for drinking supplies to coastal cities (Laouina, 2013). As shown by land cover maps, the decline in agricultural land results from interrelated factors. Urban expansion reduces available farmland, converting it into urban or industrial zones. Market demand and shifts in dietary preferences influence farmers' decisions to adapt their practices or reduce production. Environmental degradation, including soil and water pollution and prolonged droughts, further diminishes land fertility and agricultural productivity.

Livestock farming is a key economic activity in the watershed, with part of the cultivated land used for forage production. However, overgrazing is a major issue, particularly in hilly middle and upper regions. While cattle are predominant in the northern basin, goats are more common in the Upper and Southwestern arid zones. The Zaër and Zemmour tribes in the lower and middle basin engage in agriculture and livestock farming, whereas the Zaïan in the Upper region follow an agro-silvopastoral system (Laouina, 2013). Overgrazing significantly contributes to vegetation loss and agricultural land degradation.

The expansion of grazing lands can also be linked to rapid population growth, which increases the demand for pasture. Consequently, degraded croplands are often converted into grazing areas, especially when affected by unsustainable farming practices or excessive chemical use. Climate change, particularly more frequent droughts, makes agriculture less viable, while economic pressures and weak regulatory frameworks further accelerate this transition.

Changes in land cover are closely linked to climatic variations, particularly rainfall patterns, which play a crucial role in vegetation dynamics and water resource availability. Understanding these variations is essential for assessing their impact on land cover changes in the Bouregreg Basin.

The analysis revealed a general trend of rainfall deficit from 1977 to 1994 across all stations despite sporadic surpluses. Particularly pronounced precipitation deficits occurred in 1982 and 1992 at the Ouljat Haboub station, while other stations experienced significant rainfall deficits in 1992 and 1994. Additionally, recorded flows were consistently below the annual average. Between 1995 and 1997, a period of generally increased rainfall was observed. Specifically, 1996 was the wettest year at the Ain Loudah station, whereas 1995 recorded the highest precipitation levels for other stations during the same timeframe. From 1998 to 2007, a widespread drought characterized all rainfall stations. The period spanning from 2008 to 2020 saw relatively wetter conditions, with the most significant surpluses recorded in 2009/10 for most stations, except for the Sidi Jabeur station, where the peak surplus occurred in 2008/09. Nevertheless, drought years were also noted during this period.

El Aoula et al. (2021) corroborated these findings. Their study, titled "Evolution of the hydrological regime in relation to climate change: Case of the Bouregreg River basin, Morocco", highlights significant fluctuations in monthly flows and rainfall across different sub-regions of the Bouregreg catchment. The reduction in precipitation since the late 1970s has notably impacted precipitation levels in January and February, leading to decreased streamflows, particularly since 1979. Across all sub-basins, excessive precipitation amounts were recorded in 1996, marking a distinct period amidst varying rainfall time series trends across different regions within the basin. Specifically, the Southeast's Tsalat sub-basin, characterized by a hilly and moist environment (Middle Atlas), saw a steady reduction in precipitation in the Center-West semi-arid plateau region compared to the Ain Loudah sub-basin. Similar patterns were noted by Khomsi et al. (2016) in the Tensift basin, situated within the High Atlas region, close to Marrakech, Morocco.

A peak in precipitation was observed in 1996, a year marked by heavy rains and the longest flood period across all stations, in agreement with (Khomsi et al., 2012). This significant rainfall was attributed to a strong North Atlantic Oscillation (NAO) anomaly, which led to increased precipitation in Morocco. The variation in monthly rainfall and streamflow between stations could be explained by local conditions such as topography and proximity to the coast. These findings align with the research by Sebbar et al. (2017), which shows that Morocco's northwest region experiences significant climatic variability influenced by oceanic effects and watershed altitude.

The significant decline in precipitation over the years, and consequently in streamflow rates, indicates a potential trend related to ongoing climate variability. While this observation pertains explicitly to the study region, it is crucial to consider that local factors, such as land-use changes or other environmental modifications, might influence these patterns (Malede et al., 2022). Thus, while the trend indicates a climate-related impact, regional and local factors must be considered when interpreting changes in precipitation and streamflow. Climate change influences precipitation patterns, including rising temperatures, altered atmospheric circulation, and extreme weather events. Higher temperatures increase evaporation rates, reducing water availability for river runoff. Data filling may have affected the correlation values found for the Ain Loudah and Ouljat Haboub stations, emphasizing the importance of rigorous data management in climate studies.

The land cover analysis in the Bouregreg watershed was conducted up to 2022, based on the most recent and available data at the time of the study. This period was carefully selected to provide a reliable and validated assessment of recent land cover dynamics. However, given current trends, urban expansion, hydroclimatic variability, and human activities are expected to continue reshaping land cover in the coming decades.

Urban expansion and demographic pressure will likely accelerate land cover changes, with increasing demand for residential, commercial, and industrial zones further reducing agricultural land and impacting food security and ecosystem stability. Climate models suggest rising temperatures and declining annual precipitation, leading to more frequent and prolonged droughts, which will exacerbate vegetation loss and land degradation (Mahdaoui et al., 2024). Additionally, overgrazing and agricultural decline may intensify due to economic and climatic pressures, driving pastureland expansion and soil fertility loss.

Although this study does not include future land cover projections, the identified trends highlight the need for further research integrating predictive modeling approaches. Developing spatial modeling techniques combined with territorial development scenarios could provide valuable insights into the long-term evolution of land use patterns in the Bouregreg watershed. Without intervention, these factors could lead to severe water scarcity, heightened erosion risks, and biodiversity loss by 2030. Future research should focus on integrating climate change projections, socioeconomic trends, and land use models to support adaptive watershed management strategies that ensure long-term environmental and socio-economic resilience.

In addition to land cover transformations, this research also addresses the critical issue of water resource management by analyzing the interplay between climate variability and hydrological dynamics. The study focuses on a growing concern: the variability of precipitation and its direct impact on streamflow. Understanding this relationship is vital, especially in regions like northwestern Morocco, where water resources are already under pressure from both natural and anthropogenic factors. This work builds on earlier studies but fills a significant gap in the literature by providing an integrated analysis of precipitation and streamflow patterns over time.

To detect shifts in rainfall patterns and their influence on streamflow, statistical tests, including Pettitt and Buishand tests, were applied. The study ensures greater data reliability by using the regional vector method (MVR) to fill precipitation data gaps. Additionally, indices such as the Deviation from the Mean (E_m) and the standardized precipitation index (SPI) provide a refined understanding of drought and surplus periods, underscoring the need for careful climate risk assessments in this region.

CONCLUSIONS

The analysis of land cover dynamics in the Bouregreg Basin between 2018 and 2022 highlights significant transformations driven by anthropogenic and climatic factors. Urban expansion, deforestation, and land degradation have led to a decline in forest cover and irrigated farmland, while grazing lands have expanded, partly due to agricultural decline and economic pressures. Climatic variations, particularly prolonged droughts, have further contributed to these changes. The reduction in bare soil and continued urbanization reflect shifting land use patterns, emphasizing the need for sustainable management to balance agriculture, livestock, and urban growth while mitigating climate impacts.

Correlation tests on rainfall ranks reveal no clear trend, such as a consistent increase or decrease, and most tests confirm the absence of significant ruptures in the rainfall series. The analysis of hydro-rainfall variations in the Bouregreg watershed highlights an irregular alternation of dry and wet years with distinct seasonal patterns. Marked drought periods typically occur from June to August and often extend into September, while May and October serve as transitional months between dry and wet seasons. November to February emerge as the wettest months.

The indices indicate a clear shift toward an increasingly dry climate. Between 1977 and 2020, dry years accounted for 57% of the total, exceeding wet years (42%). River flow variations confirm the predominance of deficit years, which frequently represent over 60% of observed years.

Significant correlation coefficients highlight a strong relationship between hydrometric variations and rainfall fluctuations, emphasizing the interdependence of precipitation and river flow. This relationship is shaped by the region's continental context and diverse topography, which includes plains, plateaus, mountains, and high mountains at varying distances from the Atlantic and Mediterranean coastlines. Land use changes, land cover variations, watershed characteristics, and upstream water abstraction contribute to hydrological flow alterations.

The findings of this study provide valuable insights for managing hydrological streamflow in the Bouregreg watershed under the impacts of climate change. Incorporating temperature data alongside precipitation analyses could offer a deeper understanding of the factors influencing streamflow. Future research may benefit from integrating indices such as the standardized precipitation-evapotranspiration index (SPEI), which accounts for precipitation and temperature effects. Such approaches would complement this study, adding critical insights for the sustainable management of the Bouregreg watershed under evolving climatic conditions.

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