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Drought Intensification and Hydrological Regime Shifts in Tunisia's Medjerda High Valley

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Abstract

This study examines the influence of drought on hydrological regimes in Tunisia's Medjerda High Valley during 43 years (1980–2023). The methodology involved analyzing homogeneity using the Pettitt, Buishand, and SNHT tests. the use of correlation analysis and standardized indicators, such as the Streamflow Drought Index (SDI) and the Standardized Precipitation Index (SPI), to identify drought. It has been discovered that droughts have become much more frequent and severe, particularly since 2015. A 50% reduction in streamflow during years of severe drought was directly correlated with lower precipitation, according to hydrological data. Flow quantities at the Ghardimaou station were found to have decreased by 45% from pre-2010 values, and similar magnitude reductions were noted across the basin. These findings highlight how urgent it is to put integrated drought adaptation plans into place in order to protect Tunisia's main supply of water..

Keywords: Drought; SPI, SDI; Rainfall variation; Water Resources, Medjerda High Valley; Tunisia

Intensification de la sécheresse et changements du régime hydrologique dans la haute vallée de Medjerda en Tunisie

Résumé

Cette étude examine l'influence de la sécheresse sur les régimes hydrologiques de la haute vallée de la Medjerda en Tunisie sur une période de 43 ans (1980-2023). La méthodologie employée a consisté à analyser l'homogénéité des données à l'aide des tests de Pettitt, Buishand et SNHT, et à utiliser l'analyse de corrélation et des indicateurs standardisés, tels que l'indice de sécheresse des cours d'eau (SDI) et l'indice de précipitations standardisé (SPI), pour identifier les épisodes de sécheresse. Il a été constaté que les sécheresses sont devenues beaucoup plus fréquentes et sévères, en particulier depuis 2015. Une réduction de 50 % du débit des cours d'eau lors des années de sécheresse sévère a été directement corrélée à une baisse des précipitations, selon les données hydrologiques. Les débits à la station de Ghardimaou ont diminué de 45 % par rapport aux valeurs d'avant 2010, et des réductions d'ampleur similaire ont été observées dans l'ensemble du bassin. Ces résultats soulignent l'urgence de mettre en œuvre des plans intégrés d'adaptation à la sécheresse afin de protéger la principale ressource en eau de la Tunisie.

Mots clés : Sécheresse ; SPI, SDI ; Variation des précipitations ; Ressources en eau, Haute vallée de Medjerda ; Tunisie

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1. INTRODUCTION

Mediterranean water resource management presents a major challenge because the region has variable climates and drought occurrences that directly influence water availability. Tunisia, the Upper Medjerda Valley, becomes increasingly susceptible to these occurrences. This study aims to examine the impact of drought on hydrological regimes to direct water management policy towards sustainability.

Droughts are amongst the most devastating natural disasters with far-reaching impacts on water supplies, agriculture, and economic and social development. IPCC (2021) projects that the nations in the Mediterranean region are likely to be drier and experience longer dry periods under climate change projections. The standardized precipitation index (SPI) and standardized drought index (SDI) are strong tools for quantifying the intensity and duration of drought on various spatial scales (McKee et al., 1993; Wilhite & Glantz, 1985). Vicente-Serrano et al. (2012) demonstrated that the two indices are effective in detecting the onset, severity, and spatial extent of drought events in various climatic zones.

In the Mediterranean, drought frequency and severity have been on the rise, as has been shown through recent research. Tramblay et al. (2020) reviewed drought trends across the region in 160 basins, with significant increases in drought severity reported across approximately 70% of the sites being studied. Sousa et al. (2018) also found that drought severity in the southern Mediterranean has risen at approximately twice the rate as that in the north over the past four decades. In Tunisia, Mahdaoui et al. (2018) presented evidence of significant fluctuation in the north watersheds' precipitation, with Kotti et al. (2015) indicating declining trends in annual rainfall in the central regions. Tunisia has been found by Zittis et al. (2021) to be one of the most vulnerable countries in the Mediterranean to deficiency in precipitation, with projections indicating a decrease in annual rainfall by up to 15-20% by the year 2050. The Medjerda Basin, Tunisia's primary source of water, has been the focus of hydrological modeling that indicates significant declines in discharge under various climate projections (Guenouche et al., 2023).

Semi-arid watershed hydrological drought responses have been extensively studied by Lorenzo-Lacruz et al. (2013), who noted that streamflow declines typically exceed the proportional reduction in rainfall due to non-linear watershed processes. Bargaoui et al. (2014) specifically studied these relationships in Tunisia watersheds, with recorded values of streamflow elasticity ranging from 1.5 to 2.3, indicating that a reduction in rainfall by 10% typically leads to a reduction in river discharge by 15-23%. Kingumbi et al. (2016) further demonstrated that repeated drought years impose compounding effects on groundwater-surface water interactions in the aquifer systems in Tunisia, progressively draining base flows and lengthening hydrological recovery periods.

Concerning water management planning, Haddadin (2018) reviewed drought adaptation planning in North Africa, highlighting the need for integrated water resource planning that harmonises agricultural, urban, and environmental water requirements. El Garah et al. (2017) reviewed the efficiency of water-saving technologies in Tunisia, with the water-saving potential recorded at 25-35% through the use of upgraded irrigation systems. Besbes et al. (2019) also reviewed policy mechanisms for water allocation during drought, highlighting the need for robust monitoring systems and tiered response mechanisms.

Besides these notable contributions, the gap in research exists on the effects of structural shifts in climate trends on hydrological regimes, with a focus on the Upper Medjerda Valley.

This work fills the gap by correlating hydrological data with long-term drought indices in a systematic way and applying statistical tests for homogeneity to identify breakpoints in the climatic series. Our specific objectives are to: (1) quantify temporal trends in the frequency and severity of drought using standardized indices; (2) identify structural shifts in the pattern of rainfall; (3) analyze the associated impacts on the regime of the streamflow; and (4) make specific recommendations on sustainable water resource planning.

2. MATERIEL & METHODS

2.1. *Study Area*

The Medjerda High Valley extends over more than 23,700 km², crossing North Tunisia from Ghardimaou to the Sidi Salem dam (Figure 1). The area has a semi-arid climate with dominant winter rains, with an average annual rainfall ranging from 400-600 mm. Its principal tributaries include the Mellegue, Bouhertma, Tessa, and Kasseb

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rivers, which all feed major agricultural production with cereals, olives, and market vegetables. The area also irrigates several urban centers with a combined population of over 1.5 million inhabitants.

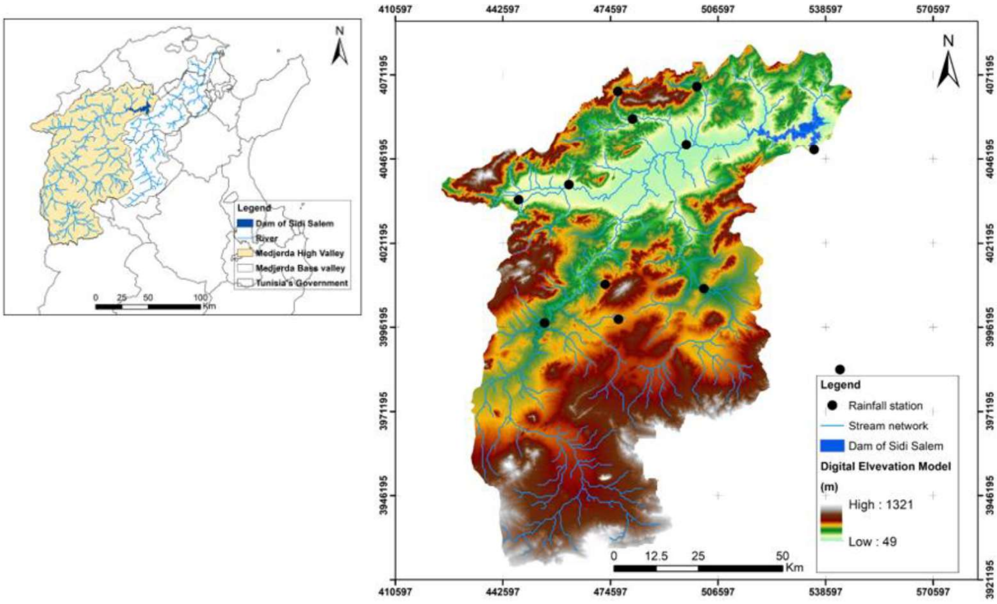

Fig. 1 - Location of the study area in the Medjerda High Valley, Tunisia

2.2. *Methodology*

The meteorological data were acquired with the aid of 12 rainfall stations (1980-2023) and temperature data provided by the National Institute of Meteorology. In order to cover the watershed as thoroughly as possible, the stations were chosen based on the spatial position and data availability (Figure 1). For the years 2015–2022, hydrological data with daily discharge values were obtained from three major hydrometric stations (Ghardimaou, Jendouba, and Bousalem).
Multiple imputation techniques were used to impute missing values in rainfall data, which made up about 7% of the dataset (Teegavarapu & Chandramouli, 2005). In particular, we used k-nearest neighbor algorithms with k=5 for intervals longer than three months and weighted distance averaging for gaps up to three months. When cross-validated against known values, our validation techniques yielded an accuracy of over 85%. Every dataset was checked for consistency and completeness, and outliers were assessed using cross-station comparison and interannual variability.

To find structural changes in the rainfall and outflow time series, three complementary homogeneity tests were used:

- The Pettitt Test is a non-parametric technique that uses the highest rank-sum difference before and after possible breakpoints to identify single change sites (Pettitt, 1979).
- Buishand Range Test: This detects changes in the mean in normally distributed data based on the examination of cumulative deviations from the mean (Buishand, 1982), with the significance being determined with Monte Carlo simulations (10,000 iterations).
- SNHT (Standard Normal Homogeneity Test): A likelihood-ratio test that contrasts the means before and after potential change points, with particular robustness for the identification of shifts at the beginning or ending points of time series (Alexandersson, 1986).

In climatological research, these homogeneity tests are frequently employed to identify non-climatic changes in observational data (Costa & Soares, 2009; Wijngaard et al., 2003).

The Standardized Precipitation Index (SPI) was computed based on all 12 stations' monthly rainfall records. Following McKee et al. (1993), we modeled the rainfall data with gamma distributions and standardized these to normal distributions to compute standardized values. SPI was calculated at the 3-, 6-, and 12-month scales, and the values were classified as: normal (>−1.0), moderately dry (−1.0 to −1.5), severely dry (−1.5 to −2.0), and extremely dry (<−2.0).

The Standardized Drought Index (SDI) was calculated using the three hydrometric stations' discharge data following the methodology of Nalbantis & Tsakiris (2009). Monthly discharge volumes were standardized with the same probabilistic technique as SPI, and the meteorological and hydrological drought conditions could be directly compared. SDI values were categorized using the same thresholds as SPI.

To assess lag correlations between meteorological and hydrological manifestations of drought, the Pearson correlation coefficients for SPI and SDI values on different timelines were also calculated, following established approaches for linking meteorological and hydrological drought dimensions (Zhu et al., 2019).

Using packages 'climatol' (v3.1.2) for homogeneity testing (Guijarro, 2018), 'SPEI' (v1.7) for drought index computation (Beguería & Vicente-Serrano, 2017), and 'trend' (v1.1.4) for temporal trend analysis (Pohlert, 2020), all statistical analyses were carried out using R statistical software version 4.1.2. ArcGIS 10.6 was used for spatial mapping and visualization.

3. RÉSULTATS ET DISCUSSION

The primary findings of the drought index analysis, homogeneity testing, and hydrological responses noted during the study period are compiled in the sections that follow.

3.1. *Homogeneity Testing and Structural Changes*

Several tests for homogeneity revealed significant breakpoints in the rainfall regime in the Upper Medjerda Valley. Nine of the twelve rain stations had breakpoints found by the Pettitt test between 2012 and 2015, with the Sidi Salem, Bou Salem, and Jendouba stations demonstrating statistical significance at $p < 0.05$. These results were corroborated by the Buishand Range test, which found comparable breakpoints at the central watershed stations with exceptionally strong signals ($p < 0.01$). These trends were further supported by SNHT data, which showed that test statistics for stations in the eastern watershed were higher than critical levels at the 95% confidence level.

When comparing periods before and after 2013, the Sidi Salem (Figure 2) and Bou Salem stations showed the biggest reductions, with average annual rainfall declining by 18.7% and 22.4%, respectively.

These results confirm that recent declines in precipitation reflect statistically significant structural shifts, rather than short-term anomalies in the climatic system.

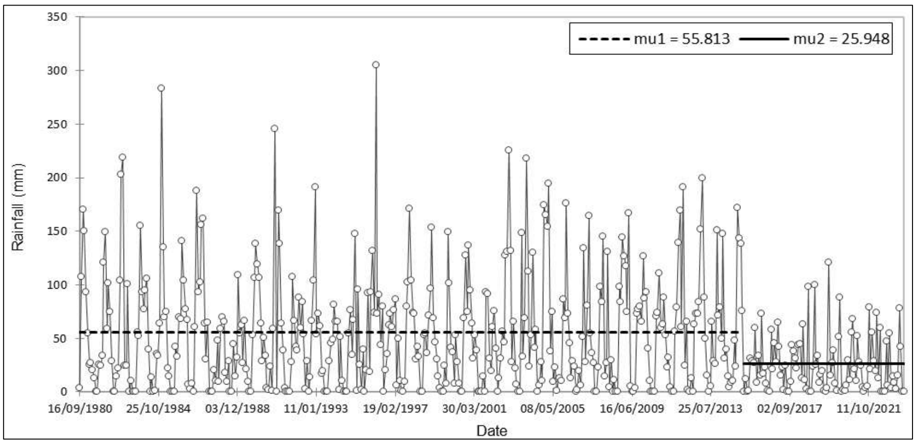

Fig. 2 - Results of the Pettitt homogeneity test for the Sidi Salem rainfall station

3.2. *Temporal Trends in Drought Indices*

SPI values at the 12 weather stations indicated a marked intensification of drought conditions after 2015. All stations had at least one extreme drought event (SPI < -2.0) between 2017 and 2020, according to the 12-month SPI readings, which showed significant severity. The longest drought conditions were observed at the Kef Heliopolis and Barrage Kasseb stations, when SPI values regularly dropped below -1.5 for months in a row (Figure 3). A west-to-east gradient in drought intensity was observed spatially, with slightly milder conditions at western stations than at central and eastern stations. A worsening trend in dry conditions was indicated by the frequency of drought months (SPI < -1.0), which increased from an average of 18% during 1980-2000 to 27% during 2000-2015 and then to 34% during 2015-2023.

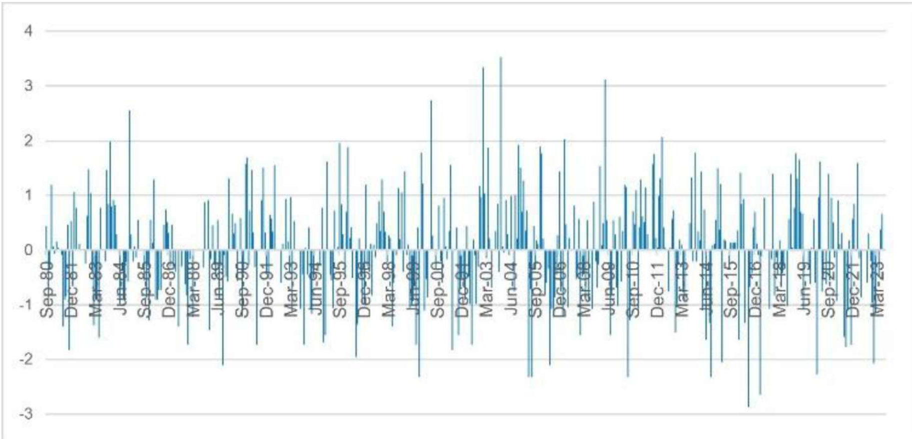

Fig. 3 - Standardized Precipitation Index (SPI) for Kef Heliopolis station throughout time (1980–2023)

3.3. *Hydrological Response to Drought*

Analysis of hydrological data revealed that streamflow has significantly decreased at every monitoring location. Compared to pre-2010 records, flow flows at Ghardimaou decreased by almost 45% between 2015 and 2022. The Jendouba (41.3%) and Bousalem (48.7%) stations showed comparable declines (Figure 4). Strong Pearson correlations between the 6-month SPI values and the SDI values computed for these stations (r = 0.78, 0.81, and 0.76 for Ghardimaou, Jendouba, and Bousalem, respectively) suggested a quick hydrological response to meteorological drought.

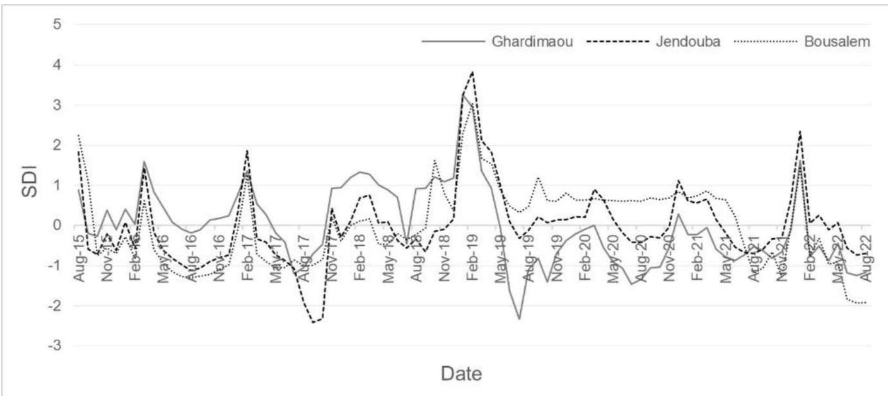

Fig. 4 - Standardized Drought Index (SDI) for the hydrometric stations (2015–2022)

The correlation analysis (Figure 5) demonstrates the strong relationship between SPI and SDI among the three hydrometric stations, hence validating the watershed's limited flow buffering capacity and high susceptibility to precipitation variability. Notable variations were also seen in the monthly flow distribution patterns, with base flows declining by roughly 35% during the summer months (June-September) and peak flows declining by up to 63% during the winter months (December-February). The agricultural water supply faces significant issues as a result of these periodic changes, especially when it comes to satisfying summer irrigation demands.

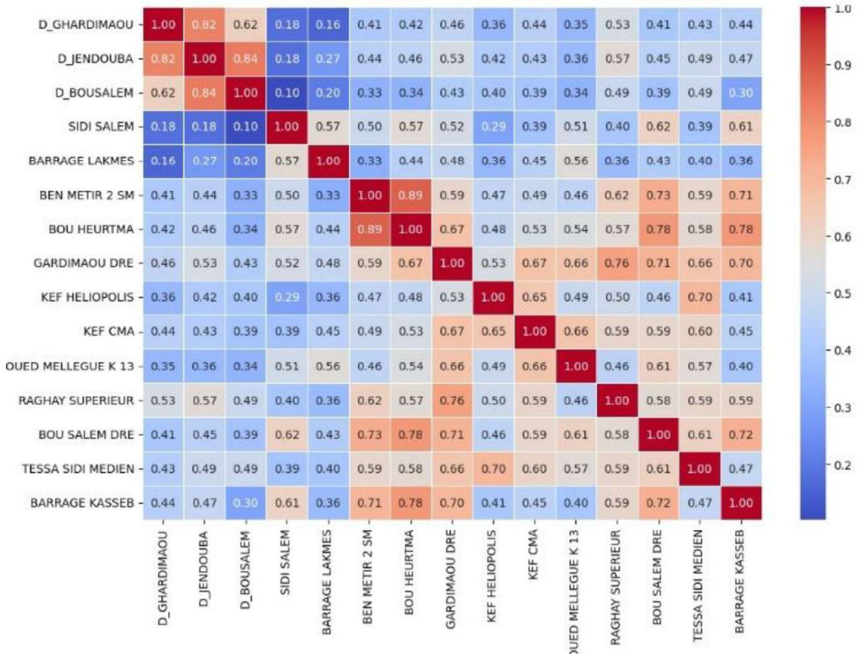

Fig. 5 - Pearson correlation matrix between the Streamflow Drought Index (SDI) and the Standardized Precipitation Index (SPI) across Medjerda watershed stations (2015–2022)

3.4. *Discussion*

The observed structural shifts in rainfall and streamflow have direct implications for sustainable water management and regional planning. The finding of statistically significant breakpoints in precipitation patterns between 2013 and 2015 is consistent with broader regional studies across the Mediterranean basin. Lionello et al. (2018) found similar transition sites in rainfall regimes across southern Europe and North Africa, attributed to shifting atmospheric circulation patterns and sea surface temperature anomalies. The study reveals a considerable association between SPI and SDI values ($r > 0.75$), indicating that this semi-arid watershed is particularly vulnerable to precipitation changes. This sensitivity exceeds that reported by similar investigations in more humid Mediterranean watersheds, where Guenouche et al. (2023) discovered correlations ranging from 0.65 to 0.70. The approximately 45% reduction in streamflow caused by drought intensification constitutes a significant hydrological change, above the 30-35% reductions predicted by earlier modeling studies for the region (Kotti et al., 2015). The integration of homogeneity testing and drought indices provides a comprehensive view of hydrological risk in Tunisia's Upper Medjerda Valley. By demonstrating that recent precipitation declines are statistically significant structural shifts rather than temporary anomalies, our findings imply that water management strategies must adapt to fundamentally altered hydrological regimes rather than simply weathering temporary drought episodes.

The strong correlation between meteorological and hydrological drought indicators aligns with recent trend analyses in the region (Abidi et al., 2025), which identified increasing temperature trends across 100% of analyzed data and spatially heterogeneous precipitation patterns, with 52.4% showing increasing and 47.6% showing decreasing trends at different risk levels.

These findings call into doubt the long-term viability of the region's current water allocation regimes. With agricultural operations accounting for over 80% of water resources in the Upper Medjerda Valley, proven streamflow reductions need a thorough rethinking of irrigation systems, crop choices, and water distribution regulations. The reduced winter peak flows and summer base flows affect reservoir management tactics, potentially necessitating new operational guidelines for important structures such as the Sidi Salem dam.

3.5. *Implications for Sustainable Water Management*

The reported intensification of the drought necessitates broad responses across various sectors. With a 45% reduction in flow in Ghardimaou, drip irrigation could lower agricultural water consumption by 25-30%. 15% of winter runoff might be captured by rainwater collection in western basins, enhancing summer availability. In addition to providing early warning systems connected to drought response protocols, a watershed management authority should coordinate cross-sectoral needs and create allocation mechanisms that retain 15-20% of ecological flows. Since current agricultural rates (0.02-0.04 TND/m³) undervalue this resource and provide no incentives for conservation, reforming the water pricing system is essential. Tunisia's resistance to future climatic variability may be increased by incorporating these findings into national drought management plans.

CONCLUSION

The Upper Medjerda Valley in Tunisia had an extensive deterioration of drought conditions, according to this study, with statistical breakpoints in precipitation patterns occurring between 2013 and 2015, followed by a 45% decrease in discharge at all stations under observation. The strong correlation ($r > 0.75$) between hydrological responses and meteorological drought indicators points to a high degree of climate variability susceptibility, underscoring the urgent need for water conservation measures. Future research should integrate groundwater–surface water dynamics and remote sensing indicators to improve drought forecasting accuracy for Tunisia's critical basins.

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