Hydrological regime change and water scarcity in a semi-arid lacustrine ecosystem: a case study of lake Abkhan (Middle Atlas Mountains of Morocco) using remote sensing and drought indices

Bahouar *El-Houssaine*[1,2]*, *Hicham* Bouasria[1,2], *Loubna* Mrabet[1,2], *Abdechahid* Loukili[2]; and *El Hassan* Abba[1]

[1] Laboratory of Biotechnology, Environment, and Georesources, Khenifra Higher School of Technology; Sultane Moulay Slimane University, Morocco.
[2] Laboratory of "Scientific Research and Educational Innovation"; Regional Center for Education and Training Professions, (CRMEF Rabat-Sale-Kenitra), Morocco.

* Corresponding author: el-houssaine.bahouar@usms.ma

Abstract. This study examines the determinants of hydrological degradation of Lake Abkhan, an endorheic wetland in the Middle Atlas Mountains of Morocco, over four decades (1984-2024). The methodological approach combines the analysis of drought indices (SPI, SPEI), remote sensing (Sentinel-2) from 2015 to 2023 to assess lake dynamics and land cover, as well as statistical methods (Pettitt test, correlations).

The results reveal a major hydrological disruption in September 2019, marking the beginning of a chronic structural drought. From 2015 to 2023, the lake's surface area shrank by 94.67%, from 25.91 to 1.38 hectares. Simultaneously, human impact on the watershed accelerated, with irrigated agriculture expanding by 181%. Statistically, temperature is the strongest predictor of this contraction ($r = -0.576$, $p < 0.001$). The increase in evapotranspiration demand, exacerbated by massive agricultural withdrawals, has now exceeded rainfall.

In conclusion, the collapse of Lake Abkhan is the result of a destructive synergy between climate change and human pressures. The long-term viability of this hydrosystem requires an urgent overhaul of water management and strict regulation of irrigation in the face of these new arid conditions.

Keywords: Drought, SPI, SPEI, Sentinel-2, Land cover, Abkhan Lake, Middle Atlas, Morocco.

1 Introduction

The Middle Atlas Mountains of Morocco harbor the highest concentration of wetlands in North Africa, including natural lakes, streams, and freshwater springs **[1,2].** These aquatic ecosystems provide essential services such as drinking water, food production, and recreational activities, while also possessing invaluable economic and spiritual significance **[3,4].** However, the climate changes of recent decades, characterized by an increase in drought episodes followed by intense rainfall events, have had major consequences for water resource availability in this region **[5].** The seasonal and perennial diversity of the Middle Atlas wetlands explains the differentiated dynamics with which the various hydrosystems respond to climatic disturbances **[1].** Water levels in endorheic lakes are particularly sensitive indicators of changes in the water balance induced by variations in temperature and precipitation **[6],** with future projections indicating a potential decrease in these water levels in Africa**.** These climatic impacts are amplified by anthropogenic disturbances, particularly changes in land use **[7].**

Although several studies have been conducted in Morocco on the impact of climate change on the lakes of the Middle Atlas, including Dayet Aoua **[7],** Aguelmam Sidi Ali **[8],** Lake Ifrah **[5],** and Aguelmam Azigza **[1,9,10]**, no scientific investigation has been specifically dedicated to Aguelmam Abkhan. Given the lack of in-situ data, the use of satellite imagery offers considerable opportunities for the systematic monitoring of wetlands **[11].** Sentinel-2 satellite images, recognized for their quality **[12],** allow the quantification of irrigated areas and the mapping of land use.

This study aims to highlight the synergistic effects of climate change and land-use changes on the hydrological dynamics of Lake Abkhan. The methodology adopted is based on the use of open-access hydrological modelling tools based on open-source code **[13]** to calculate widely validated drought indices (SPI, SPEI), combined with the use of Sentinel-2 imagery to map the lake's surface area over the period 2015–2023.

Indeed, a thorough understanding of the hydrological impacts of climate change and land-use changes is essential for ensuring the rational and sustainable management of water resources**,** thus guaranteeing the long-term viability of wetland ecosystems.

2.1

Aguelmam Abekhan **(Figure 1)** forms part of the Middle Atlas wetland complex. This permanent, endorheic mountain lake is of karstic origin and oval. To the west, one can see hillsides covered in holm oaks, whilst to the east, the surrounding flatlands are used for growing apple trees and potatoes **[2].** This lake is classified as a site of biological and ecological interest, granting it Level 3 protection status, considered to be of medium importance **[14].** It receives its water supply mainly from precipitation and runoff, part of which comes from snowmelt. Water losses from the lake are mainly due to evaporation, owing to the endorheic nature of its catchment, as well as to withdrawals for agricultural purposes **[15].**

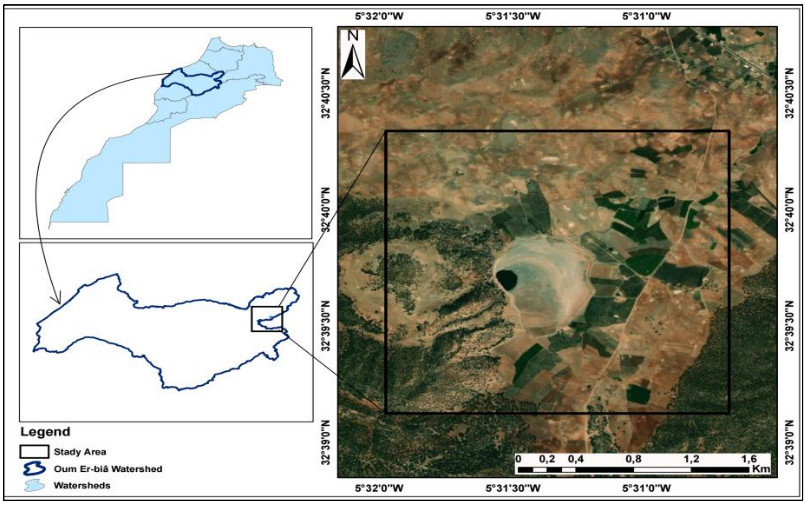

Fig.1. Location of the Abkhan lake, Morocco

2.2 Climate data Processing

Climate data were taken from the Copernicus Climate Change Service (ERA5) and the Climate Hazards group Infrared Precipitation with Stations (CHIRPS) **[16]** in order to monitor temperature and precipitation time series at lake level. Two drought monitoring indices served as the focal point for this study's handling of temperature and precipitation time series:

2.2.1 The Standardized precipitation index (SPI)

The standardized precipitation index (SPI) was developed to describe precipitation deficits over a given period (Equation 1) **[17].** The main advantage of this index is that it can be calculated for different time scales (1, 3, 6, 12, 24, and 48 months), allowing for the monitoring of water supply in both the short and long term **[18].** Drought severity is appropriately determined based on SPI values (Table 1). In this study, we used R Studio software version 4.3.0 to calculate the SPI **[19]** in order to identify hydrological droughts and their impacts on water resources (Lake Abkhan).

Eq. 1: $SPI = (pi - pm) / \sigma$ (1)
Pi: Precipitation of year i
Pm: Average Precipitation
σ : Standard deviation

Table 1 Classification of drought severity according to **[17]**

SPI values	**Classification of Drought**
[0 -0.99]	slight drought
[-1.00 -1.49]	A Moderate drought
[1.5 -1.99]	*I*ntense dry spell
≤ -2.00	Acute drought

2.2.2 The Standardized Precipitation-Evapotranspiration Index

The Standardised Precipitation-Evapotranspiration Index (SPEI) is calculated by combining precipitation measurements with estimates of potential evapotranspiration **[21].** This methodology offers a clear advantage over the Standardised Precipitation Index (SPI), as it accounts for the influence of potential evapotranspiration on the exacerbation of drought conditions**.** Its multiscale nature enables it to cover a wide range of timescales. As such, this index optimises the detection of water deficit events, thereby allowing their impacts to be understood within the context of global climate change.

SPEI is based on the monthly (or weekly) difference between precipitation and potential evapotranspiration (PET) **[21],** thus representing a simple hydrological climate balance **[22]** assessed over different time intervals to derive the SPEI. In this study, we calculated the SPEI using the SPEI v.2.8 framework **[23].** This index is exceptionally effective for detecting, monitoring and examining the impacts of climate change on drought conditions **[21].**

2.3 Satellite Data Processing

This study utilized a dual-sensor approach to analyze spatial dynamics. Long-term water changes were assessed using the Landsat-based WOfS product, which applies a regression tree classification of individual bands and band ratios to accurately identify water areas in 93% of cases **[24].**

To map recent land cover and lake area (2015–2023), Sentinel-2 imagery was selected for its good performance in terms of data quality, encompassing radiometric and geometric accuracy **[12].** The Sentinel-2 data underwent DOS1 radiometric correction via the QGIS SCP plugin to calculate TOA reflectance. Finally, water and land classes were extracted using Support Vector Machine (SVM) classification due to its high accuracy in classification results **[25].**

3.1 Climate data

3.1.1 Annual variation in precipitation

The study of interannual climate variability **(Figure 2)** reveals that annual rainfall experiences strong fluctuations, with humidity peaks recorded in 1996, 2010, and 2018. However, from 2018 onwards, a notable decrease in rainfall is observed, with a trend towards aridity.

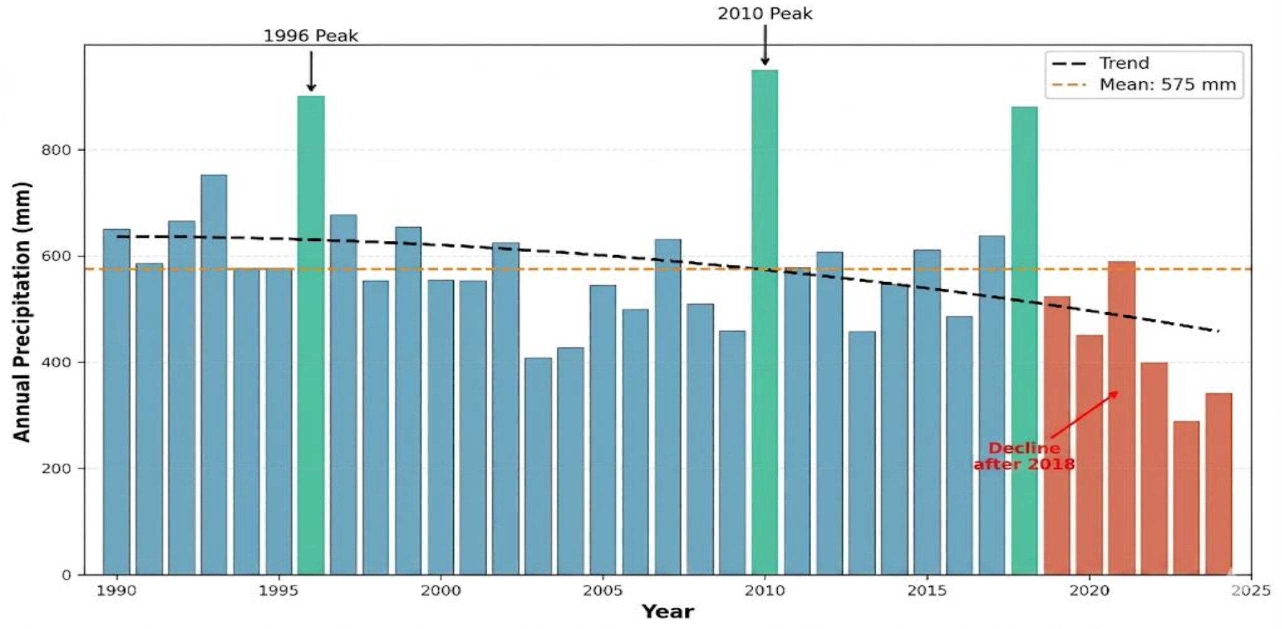

Fig.2. Annual variation in rainfall at Lake Abkhan (1990-2024)

3.1.2 Interannual variation in temperatures

For the average annual temperatures recorded between 1990 and 2024 **(Figure 3),** the values fluctuate around an average of 15°C. It should be noted that from 2018 onwards, an increase in the average annual temperature compared to 15°C has been observed.

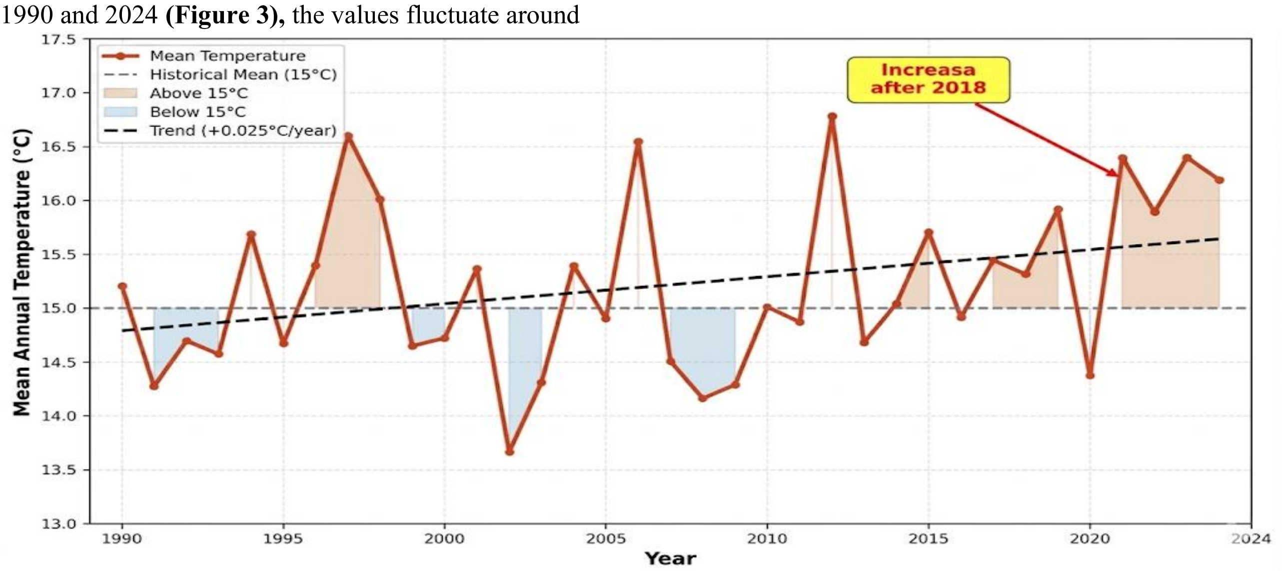

Fig.3. Interannual temperature variation in the Lake Abkhan catchment area (1990-2024)

These precipitation and temperature results are consistent with several studies conducted in the Middle Atlas region, which have indicated that the area is transitioning from temperate to arid conditions, with rising temperatures and decreasing precipitation**.** This climate change is altering bioclimatic stages, leading to the replacement of humid and sub-humid zones with semi-arid and arid conditions **[26].**

3.2 Variation in the surface area of Lake Abkhan

Calculating the lake area over the years, taking into account pixels classified as water (if "the frequency is > 0.20", then the pixel is considered to be regular open water during the year) **[23],** allowed the graphical representation of the variation in the annual area of open water **(Figure 4).**

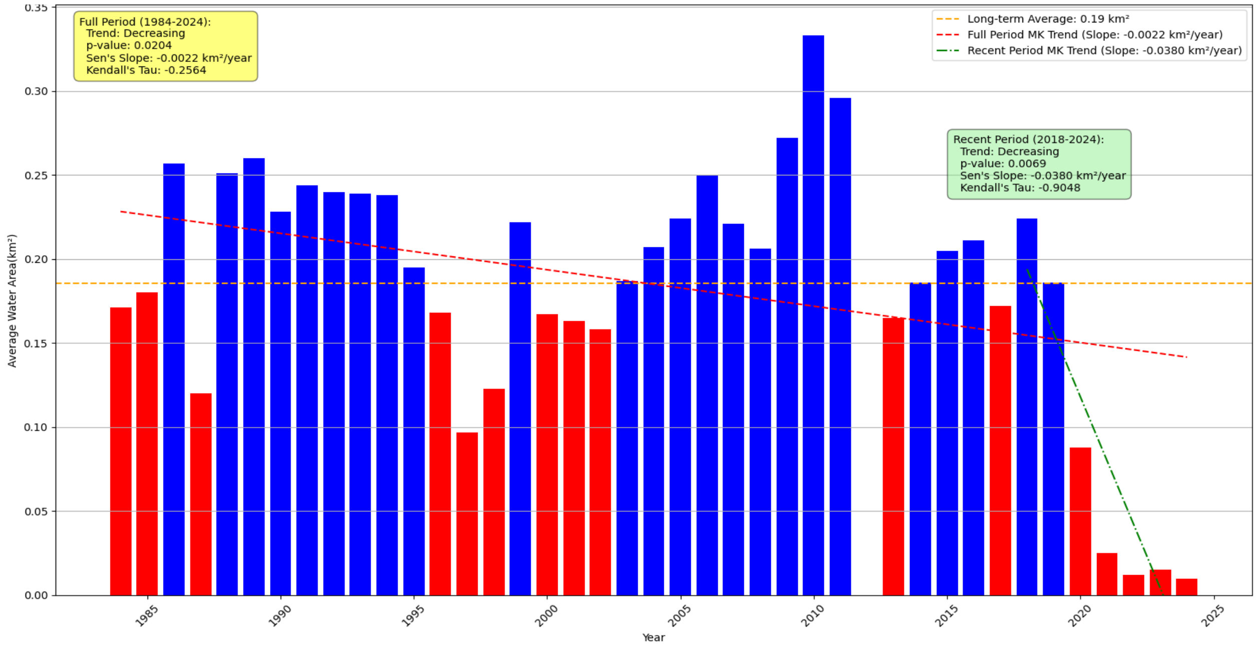

Fig.4. Change in the surface area of Lake Abkhan between 1984 and 2024

The graph highlights the interannual variability of the water resource relative to the long-term average (0.19 km², green line). While the period 1985-2015 is characterized by fluctuations around the average, punctuated by a major peak around 2010 (~0.33 km²), the recent period (2020-2024) shows a dramatic collapse in the water surface area. The observed post-2020 values are consistently and significantly lower than the historical average, reaching absolute minimums close to 0 km² (less than 0.02 km²), indicating a major hydrological crisis in the recent period (2018–2024). The Mann-Kendall test **[27,28]** detects a highly significant downward trend (τ = -0.905, p = 0.0069), with an average decrease of 38 m² per year. This accelerated decline suggests a recent change in the hydrological regime, potentially linked to climatic or anthropogenic factors **[29].**

3.2.1.1 Effect of drought severity and land use on lake surface variation

Like other lakes in the Middle Atlas, which have experienced significant water deficits in recent decades due to recurring droughts and human overexploitation, notably DayetAoua**[30,31]**,Aguelmam Sidi Ali**[32]**,Lake Ifrah**[33]**and Aguelmam Azigza**[9,10],** Lake Abkhane is not immune to this trend of water scarcity in the Middle Atlas. Hence the importance of elucidating the potential impacts of the combination of climate change and human activity on the hydrological behavior of this lake system through drought indices.

3.2.2 Impact of the drought on the lake

3.2.2.1 The Standardized Precipitation Index (SPI)

The SPI was calculated over a variable time scale (1, 3, 6 and 12 months), which made it possible to highlight wet and dry periods and to measure the intensity and severity of drought at the study site **(Figure 5).**

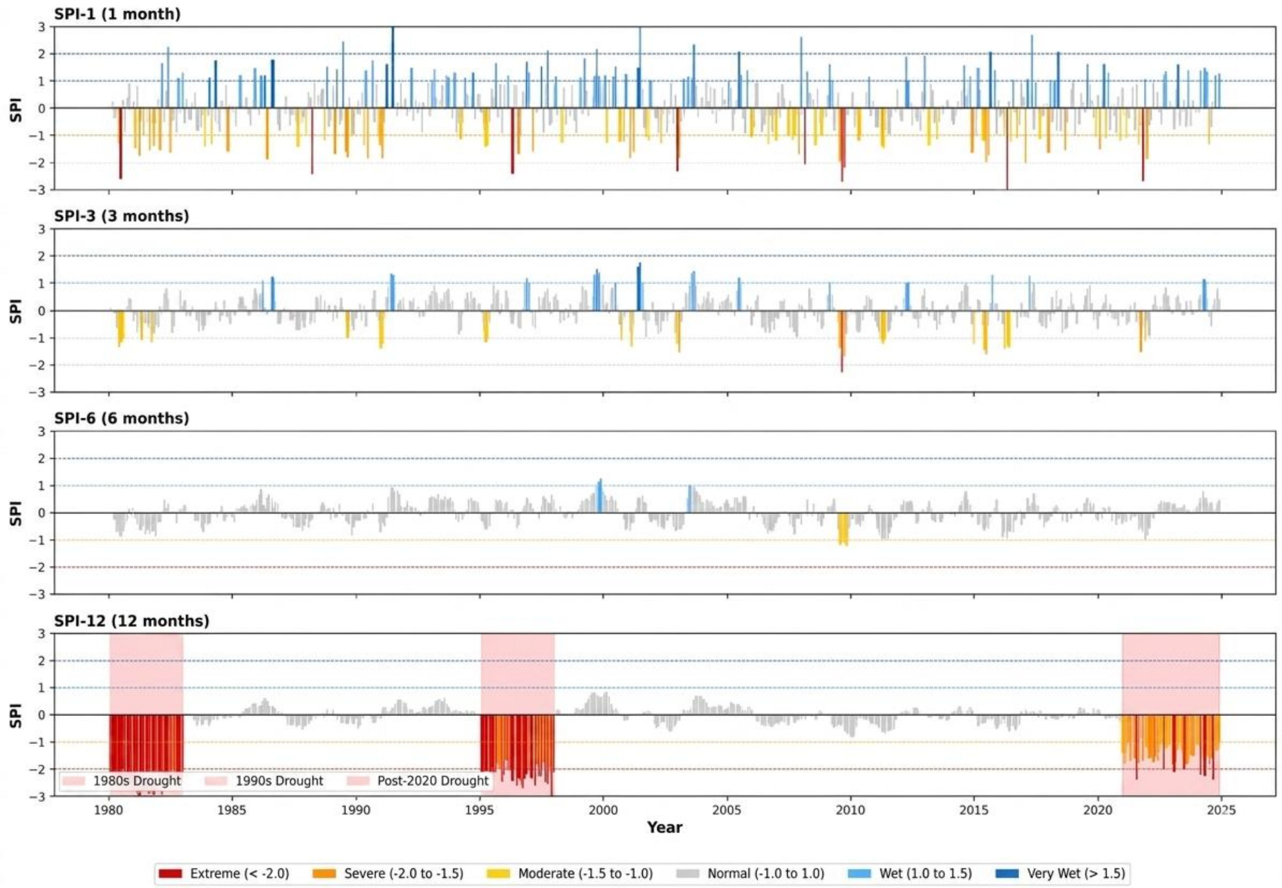

Fig5. Standardized Precipitation Index – Multiscale Analysis

Analysis of time series data has identified several major drought episodes that have affected the region:

- Early 1980s: A period of severe to extreme drought is visible at all scales, culminating in the SPI-12, indicating a critical cumulative deficit that likely impacted the lake waters.
- Mid-1990s: A sudden intensification of the deficit is observed, particularly visible on the SPI-6 and SPI-12 with values plunging below the threshold of -2.0.
- Recent period post 2020: There has been a significant return of moderate to severe drought conditions, confirming a trend towards hydro-climatic instability.

The extracted statistics (approximately 17-18% overall drought frequency across all scales) indicate a recurring risk of deficit **[34].**The decrease in the frequency of severe drought at the 12-month scale (5.7%) compared to the 1-month scale (10.3%) underscores the importance of an inter-seasonal storage strategy to mitigate meteorological drought peaks before they translate into major hydrological crises **[35].**

3.2.2.2 Standardized Precipitation-Evapotranspiration Index (SPEI)

The theoretical framework of this index is closely inspired by that of the SPI, taking into account the thermal variable. This approach makes it possible to quantify the influence of temperature anomalies on drought dynamics through a simplified calculation of the climate water balance. In accordance with the classification proposed by **[21],** the SPEI establishes a standardized scale distinguishing between phases of surplus (positive values) and phases of water deficit (negative values). In this study, the index was calculated on a 12-month time scale **(Figure 6)** in order to decipher underlying hydrological trends and analyze the intensity of cumulative episodes of water stress.

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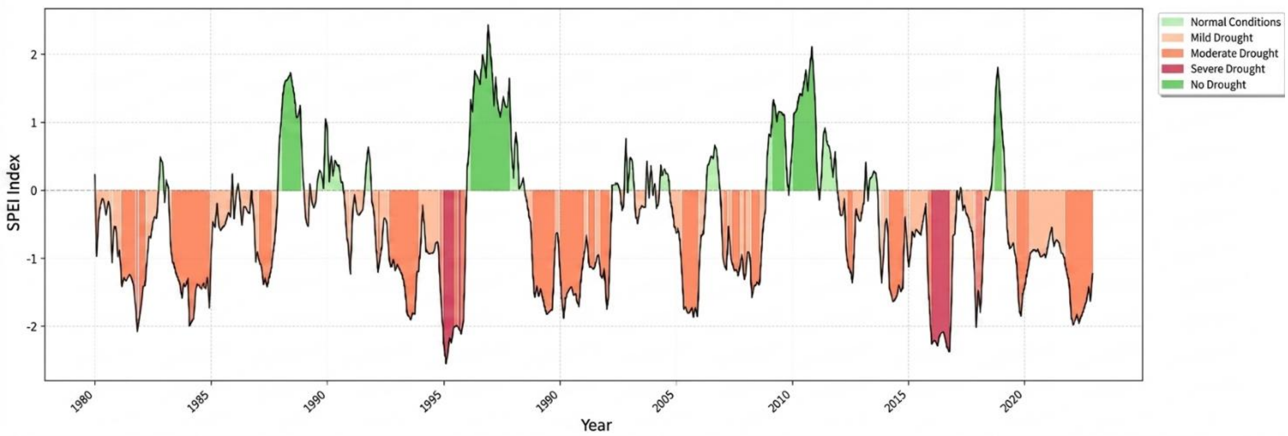

Fig.6. Variation of the SPEI Index at Lake Abkhan

The SPEI index's evolution since 1980 shows a shift from a climate with alternating wet and dry cycles to a time of severe and protracted drought. Although substantial water recharge was still possible in the 1980s and 1990s (positive peaks above +1.5), the system's incapacity to recover from the deficit is evident in the recent post-2020 period, creating a structural drought that is consistent with the decline in the lake's water surface area that has been noted since that time. Since 2019, there has been a shift towards chronic drought, with SPEI values continuously falling between -1.2 and -1.9. This indicates that the lake system cannot recover due to increasing evaporation caused by heat **[36].**

3.2.3 Statistical analysis

3.2.3.1 Pettitt Test

The Pettitt test **[36]** found a big change in the SPI-12 series's water flow in September 2019 (K = 14407.0, p = 0.0001***) **(Figure 7).** This tipping point marks the change from a regime that was changing but still stable to one that is always dry. The probability distributions before and after this date show a big shift toward dry conditions, which greatly lowers the chances of wet years needed to recharge the lake **[38].**

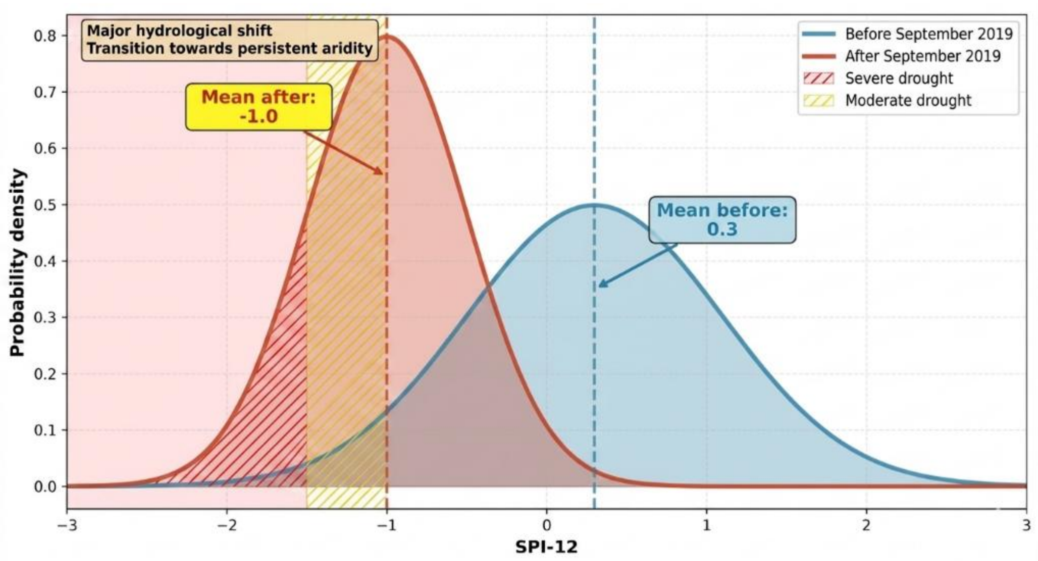

Fig.7. Comparison of the probability densities of the SPI-12 index before and after the break point of September 2019 (identified by the Pettitt test).

- Before September 2019 (Blue curve): The distribution is centered on values close to normal or wet (0 to +1), with a large variance indicating a balanced alternation of cycles.

- After September 2019 (Red curve): A massive concentration of the probability is observed in the moderate to severe drought zone (-1.5 to -0.5). The density peak has shifted to the left, confirming that the system is now trapped in a state of permanent rainfall deficit.

3.2.3.2 Regression and correlation analyses

The correlation analysis between the various parameters studied **(Figure 8)** reveals that the annual mean temperature is the strongest predictor of the reduction in water extent (r = -0.576, p = 0.0001***; Fig. 8.A).

The negative slope of the regression line (y = -0.0459x + 0.70) suggests that a 1°C rise in average temperature is associated with an average loss of approximately 0.046 km² of water surface area, illustrated by a critical divergence after 2015, where temperatures above 12.5°C coincide with a sharp collapse in lake area (Fig. 8.F). The lake shows clear sensitivity to SPI-12 (r = 0.407, p = 0.01; Fig. 8.B), but its weaker association with precipitation (r = 0.377, p < 0.05; Fig. 9.E) indicates that evapotranspiration losses play a larger role in the water balance than direct inflows. In line with this, the mean water deficit emerges as the most informative integrative metric (r = 0.569, p < 0.0002; Fig. 8.D), demonstrating that as the deficit approaches −110 mm per month, the surface area consistently drops below 0.05 km². This metric is thus the most suitable for tracking the lake's condition, as it reflects both declining inflows and the increased evaporative demand associated with warming. In contrast, the SPEI does not reach statistical significance (p = 0.0627 > 0.05; Fig. 8.C) compared with SPI or temperature alone, which may point to a non-linear system response or the influence of human factors such as water withdrawals and local management.

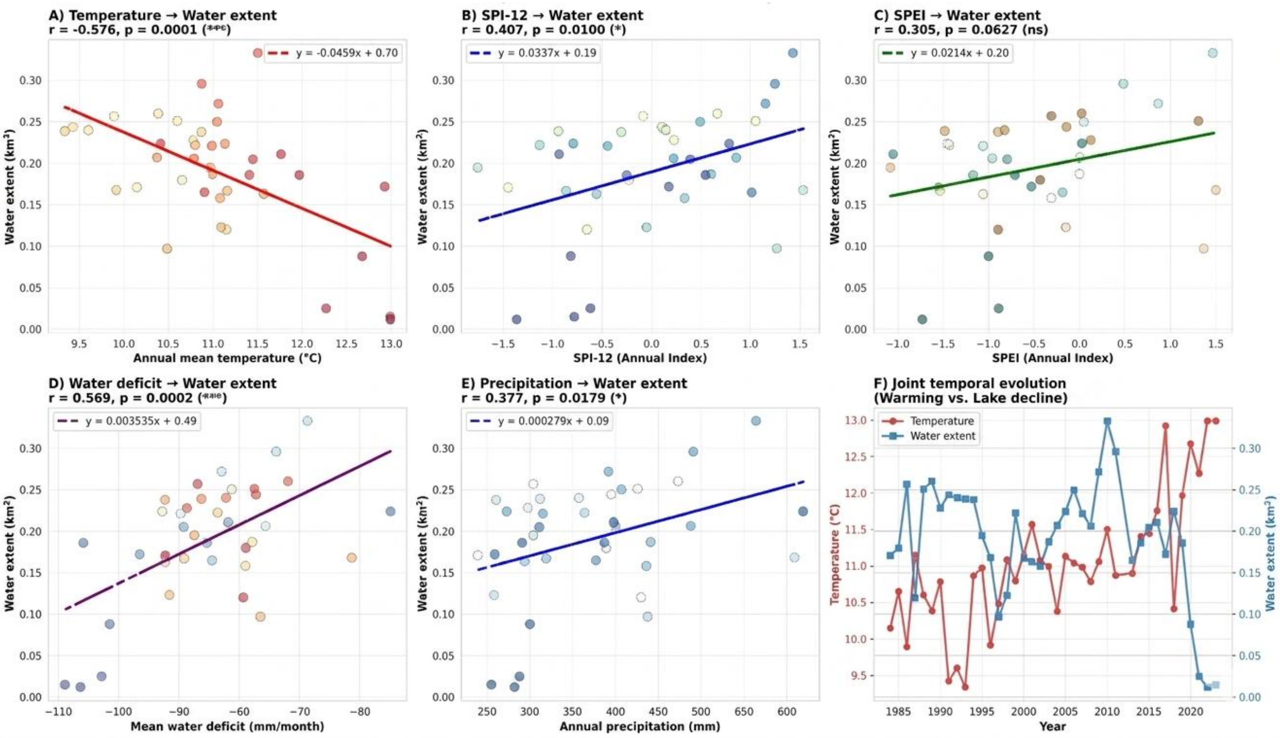

Fig.8. various hydro-climatic interactions and the dynamics of Lake Abkhan

3.2.4 Impacts of Land Use

Over the past few decades, climate change and changes in land use, particularly the growing use of irrigated agricultural practices, have put significant strain on Morocco's Middle Atlas lakes **[2].** The land-use map **(Figure 9),** created from Sentinel-2 images dating from September 2023, clearly shows a remarkable expansion of irrigated areas compared to 2015. This expansion correlated with a significant decrease in the water level of Lake Abkhan. Validation of the dataset's accuracy reveals an overall precision of 99.99%.

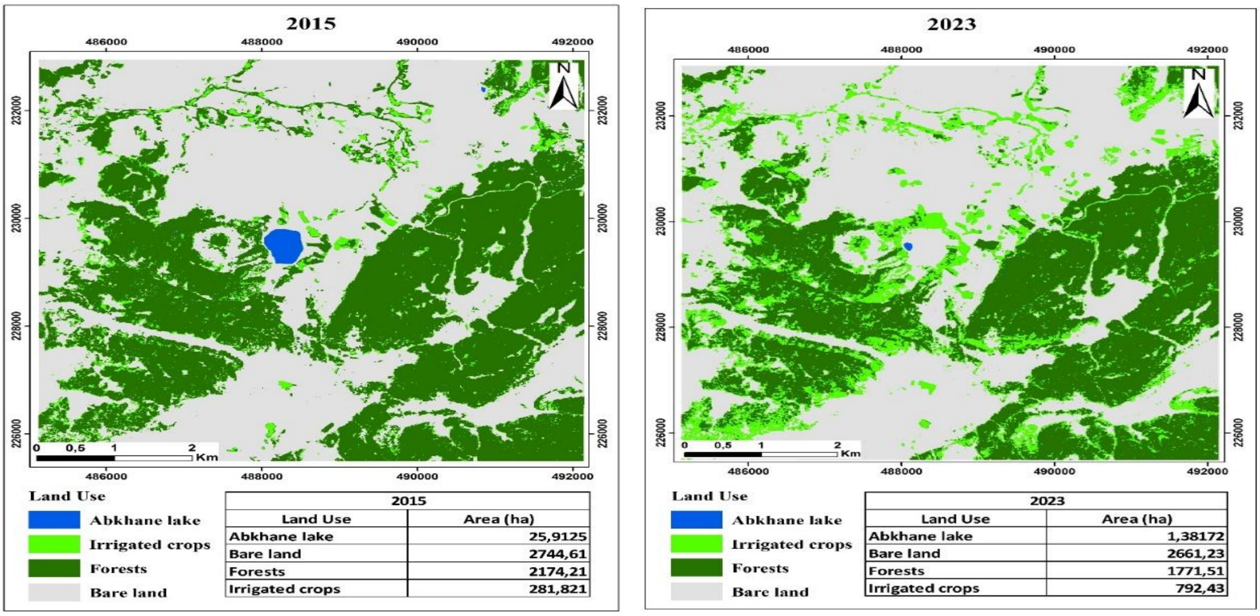

Fig. 9. Maps illustrating the evolution of land use between 2015 and 2023 in the study area

This expansion of agricultural activities is primarily linked to the profits generated by irrigated crops (fruit trees and potatoes) and to subsidies from the "Green Morocco" plan, launched in 2008 (government financial incentives). This shift in the use of mountainous land, traditionally devoted to livestock farming, towards water-intensive fruit tree cultivation has led to a marked reduction in water reserves, a decrease in pastureland, and a decline in forest cover **(Figure 10).**

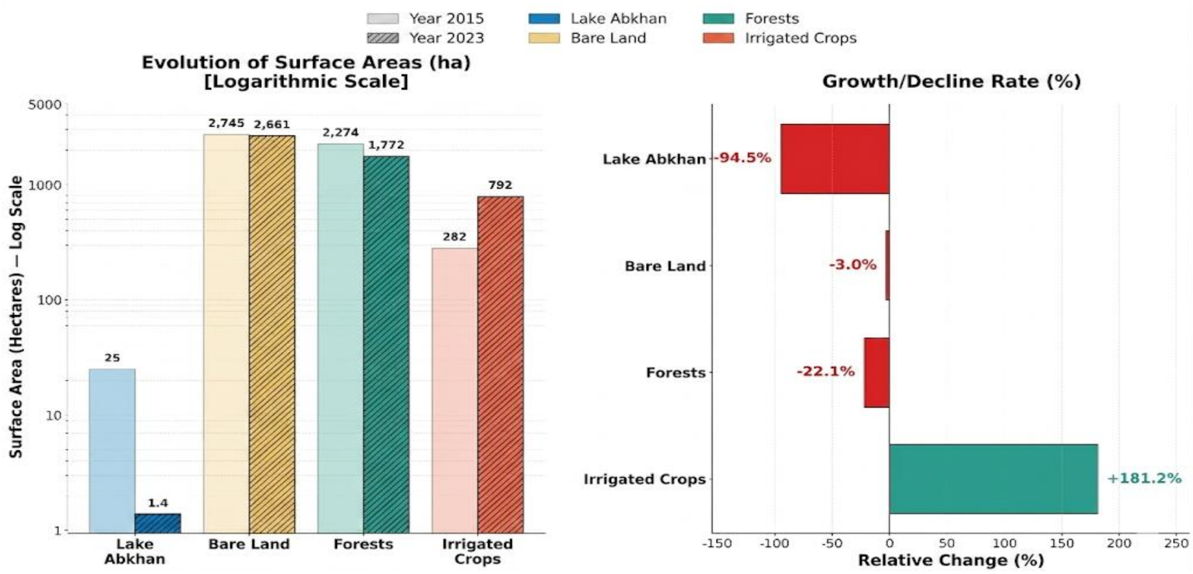

Fig.10. Comparison of land use changes between 2015 and 2023

The area of irrigated crops has jumped by 181.2% (from 281.82 ha to 792.43 ha). Simultaneously, the lake's water surface collapsed by 94.5% (from 25.91 ha to just 1.38 ha). This correlation supports the hypothesis of strong anthropogenic pressure adding to the climatic deficit to explain the drying up of the lake.

4 Conclusion

This study highlighted the extreme vulnerability of Lake Abkhan to climate and human-induced pressures, thanks to a methodological approach combining remote sensing and hydro-climatic indices. The analysis reveals a major hydrological disruption that began in September 2019, precipitating this hydrosystem from a regime of interannual fluctuations to a state of structural drought characterized by near-zero water surface area post-2020.

Rising temperatures (r = -0.576), which raise the demand for evapotranspiration, and increased human impact on the watershed are the two main causes of this ecological collapse. The resilience of the system has weakened, and the water shortage has been greatly worsened by the recent growth of irrigated agriculture.

Adaptive management measures must be put into place immediately since this sentinel wetland is in danger of going extinct. Agricultural development must be balanced with stringent water withdrawal regulations in order to preserve this socio-ecosystem. Lastly, in order to more accurately measure the overall effect of human withdrawals on the depletion of the lake, future research should depend on coupled modeling of surface and groundwater.

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