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# Monitoring the impact of drought and land use on the water dynamics of Lake Abkhane in the Middle Atlas of Morocco

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## ABSTRACT

In recent years, Morocco persistent drought and changing land use practices have significantly impacted the nation wetlands, particularly affecting water resource availability. This research aims to elucidate the effects of climate change and human activities Lake Abkhane. Using open-source hydrological modeling tools, the study calculates drought metrics such the Standardized Precipitation Index, Standardized Precipitation-Evapotranspiration Index, and Palmer Drought Severity Index. It also involves cartographic representation of land use and continuous monitoring of Lake Abkhane surface area from 2015 to 2023 using Sentinel-2 Level 1C imagery. Findings reveal significant annual precipitation variability, with peaks in 2006, 2010, and 2018, followed by a notable decline post-2018. The dynamics and regeneration potential of the lake's waters have been significantly impacted by the combination of drought ($p = 0.000639 < 0.05$) and land use change in the surrounding area. This study emphasizes how urgently water management authorities must address how human activity and drought are negatively affecting this vital wetland ecosystem.

**Keywords:** land use, lake, climate change, middle atlas, severe drought.

## INTRODUCTION

Among the North African mountains, the Middle Atlas has the greatest concentration of wetlands, including natural lakes, rivers, and sources of freshwater (Bahouar *et al.* 2024: Id Abdellah *et al*. 2021). These Ecosystems are essential to human survival, by providing a wide range of indispensable life conditions, such as drinking water, food, transport and recreation. Furthermore, they enrich our lives with an aesthetic dimension of inestimable economic and spiritual value (Ramachandra *et al.,* 2024). Climate changes in recent decades, manifested by the exponential increase as well as the recurrence and continuity of droughts followed by abrupt and violent floods, had quite the significant consequences on the availability and abundance of water resources in the central Atlas region (Nourelbait *et al.,* 2015).The seasonal and perennial diversity of wetlands in the Middle Atlas region Morocco explains the dynamics of how the different hydro-systems react to climate changes (Id Abdellah *et al.,* 2021). Naturally, the water level of lakes, especially endorheic lakes, can detect changes in hydrological balance caused by the variations in temperature and precipitation (Zhang *et al.,* 2023). Projections of future evaporation rates on African lakes indicate a potential decrease in water levels in endorheic lakes (Musie *et al.,* 2021). The effects caused by climate change are compounded by the impacts of various additional anthropogenic factors.

Including, the disturbances directly related to land uses (El-Bouhali *et al.,* 2024). The utilization of satellite imagery presented noteworthy opportunities for improvement and enabled the implementation of meticulously monitored wetlands. (Pekel *et al.,* 2016). Landsat archives (1987-present) can be used to study long-term ecosystem dynamics (Pasquarella *et al.,* 2016). Spectral indices extracted from multispectral remote sensing products are commonly employed to monitor the variations of water bodies (Normalized Difference Water Index, Modified Normalized Difference Water Index, Normalized Difference Moisture Index, etc.) (Montero *et al.,* 2023). Although multiple databases have been set to help establish various calculations of spectral indices, many obstacles still prevent the remote sensing community from fully exploiting them. The remote sensing community still faces several obstacles whilst exploiting the resources available for querying and computing spectral indices (Montero et *al.,* 2023). However, by using analysis-ready Landsat and Sentinel-2 data collections that have been corrected, calibrated, and orthorectified, researchers have been able to overcome these challenges by depending on cloud-based geospatial analytical tools that specialize in spatial Big Data. In Morocco, numerous studies on the impact of climate changes on the lakes of the Middle Atlas are conducted using various tools, such as Dayet Aoua (Abdelaziz El-Bouhali *et al.,* 2024) and Aguelmam Sidi Ali (Haddout *et al.,* 2018), Lake Ifrah (Nourelbait *et al.,* 2015) and Aguelmam Azigza (Adallal 2019; Jouve *et al.,* 2019a; Id Abdellah *et al.*, 2021), However, no study has addressed the case of Aglmam Abkhan, hence the significance of this study, which aims to highlight the impact of climate changes on this region. Due to the lack of in-situ data, free hydrological modeling tools were employed in the present approach, utilizing open and parsimonious codes (Thirel *et al.,* 2022) and to characterize droughts, the calculations were based on indices that are widely used in various regions of the world. These indices allow the classification of this event based on intensity and the determination of the threshold signifying drought at various periods. While for the quantification of irrigated areas as determining factors of lake degradation, Sentinel-2 satellite images were used, which are commonly used in remote sensing thanks to their good performance in terms of data quality (Gascon *et al.,* 2017). In fact, understanding the hydrological impacts of climate changes and land uses are essential for the rational management of water resources (Santosh S. Palmate *et al.,* 2023). Leading to the sustainability of wetlands ecosystems.

## MATERIALS AND METHODS

### Study site

Aguelmam Abekhan indicated in (Figure 1) is part of the Middle-Atlas region wetlands; it is

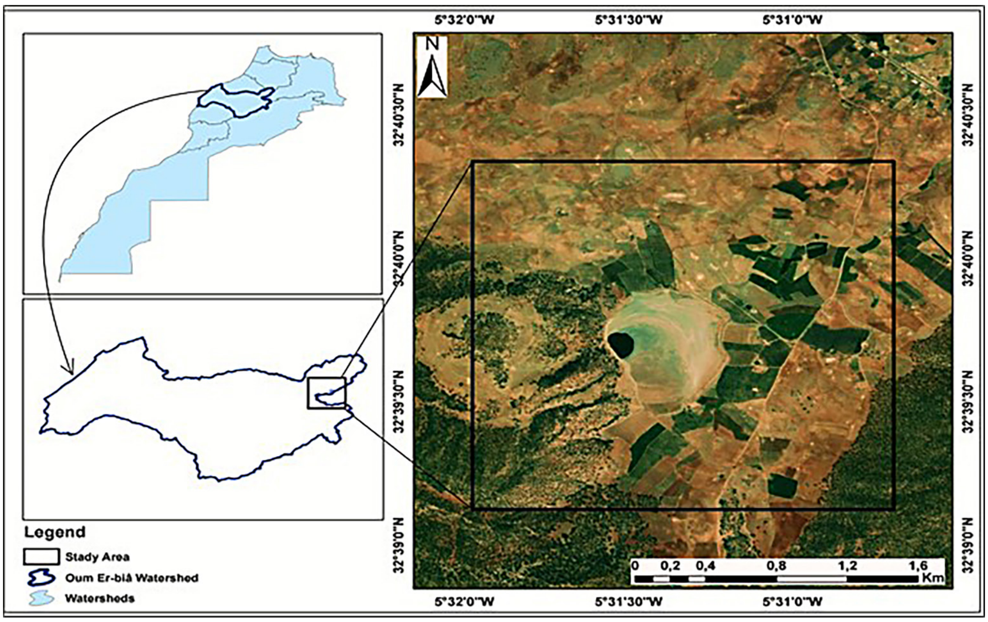


**Figure 1.** Location of the Abkhane lake, Morocco

a permanent mountain lake, endoreal, of karst origin, and oval-shaped. Overlooking the west are reliefs covered with holm oak, while to the east, the adjacent flat land is transformed into apple farms and potato fields (Chillasse *et al.,* 2001). The lake holds a classification as a site of biological and ecological interest, with a protection status of order 3 (medium term) (Chillasse and Dakki 2004). It depends primarily on rainfall and runoff, sourced in part from snowmelt. Water losses from the lake predominantly result from evaporation, given the endoreal form of the lake basin, and withdrawals for agricultural activities (Dakki *et al.,* 2015).

*Morphometric characters*

The morphometric characters presented in the Table 1 below, present precise measurements of the Lake Abkhane (Chillasse and Dakki, 2004).

## Lake ecology

Lake Abkhane is home to a huge variety of aquatic and avian species, representing a highly biodiverse wetland ecosystem. Approximately 20 species of crustaceans and 15 species of birds have been recorded in the area (Dakki *et al*., 2015), with approximately 2.000 wintering birds, primarily diving species such as the common coot and yellow duck. The lake's distinctive characteristics make it an important stopover for waterfowl during the summer (Dakki *et al*., 2015), as well as a habitat for amphibians and reptiles, particularly the Emyde leprosa.

## Climate data

For the monitoring of precipitation and temperature time series at lake level, climate data were extracted from the Climate Hazards group Infrared Precipitation with Stations (CHIRPS) (Funk *et al.,* 2015) and the Copernicus Climate Change Service (ERA5). Subsequently, the results were represented (Figures 2 and 3) (Huntington *et al.,* 2017). The study of interannual climate variability (Figure 2) reveals that annual rainfall experiences strong fluctuations, with peaks recorded in (2006, 2010, and 2018). However, from 2018 onward, there is a notable decline in precipitation.

For the average annual temperatures recorded between 1990 and 2022 (Figure 3), the values fluctuate around an average of 15 °C. Notably, from 2018 onward, there is an increase in the average annual temperature compared to 15 °C. These findings align with the future projections of (Aoubouazza *et al.,* 2019), which indicate that in Morocco, there will be an increase in temperature between 1.7 and 2.6 °C between 1961 and 2050. Additionally, there is a projected reduction in rainfall between 15 and 22% from 1981–2000 to 2050, posing a risk to the water availability cycle.

## Satellite data processing

To analyze and visualize the long-term changes in the lake waters, the Water Observations from Space (WOfS) product (Mueller *et al.,* 2016) from Digital Earth Africa, an operational

**Table 1.** Morphometric characteristics of Lake Abkhan

| Lake | Altitude(m) | S (ha) | L (m) | l (m) | P (m) | Pmax (m) | Pmean (m) | Coordinates |
|---|---|---|---|---|---|---|---|---|
| Abkhane | 1670 | 45 | 906 | 400 | 2 156 | 12 | 1,58 | 32° 66' N<br>05° 52' W |

**Note:** *S* – area; *L* – length; *W* – width; *P* – perimeter; $P_{max}$ – maximum depth; $P_{mean}$ – average depth.

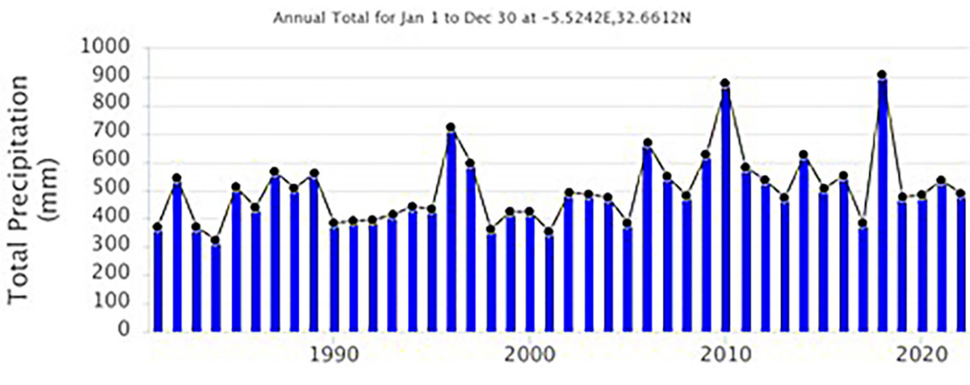


**Figure 2.** Annual precipitation at lake level (1980–2022) Climate Engine (2023)

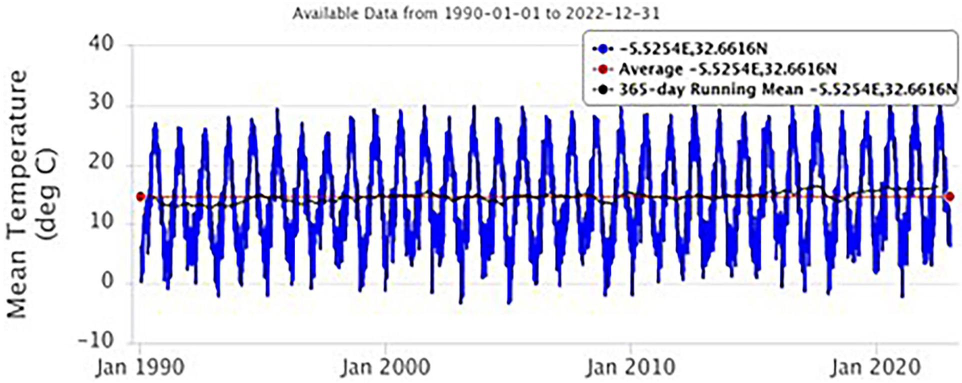


**Figure 3.** Variations in mean annual temperature at lake level (1990–2022) Climate Engine. (2023)

platform providing analysis-ready data, was employed. This was connected to a Python3 analysis library. The WOfS product utilizes a regression tree classification of individual bands and band ratios for water detection, based on Landsat imagery. Covering decades of data with records dating back to 1984 in some locations, it accurately identifies water areas in 93% of cases (Mueller *et al.,* 2016). For mapping land cover and monitoring the evolution of Lake Abkhane's area between 2015 and 2023, Sentinel-2 satellite images were utilized. These images are widely recognized in remote sensing for their good performance in terms of data quality, encompassing radiometric and geometric accuracy (Gascon *et al.,* 2017). The data presented in this work originates from the Copernicus archives. To facilitate classification and interpretation of Sentinel-2 Level 1C images, radiometric and atmospheric pretreatment was required (Obregón *et al.,* 2019). The semi-automated classification (SCP) extension built into the QGIS program was used to carry out this pre-processing. The SCP plug-in translated raw pixel values (DN) to top-of-atmosphere reflectance (TOA) by using the dark object subtraction radiometric correction technique (DOS1). The photos were then categorized in order to obtain the water surface and land use classes. Several classification methods were examined, including SVM (support vector machine), a technique that researchers frequently employ (Elhamdouni *et al.,* 2022), due to its high accuracy in classification results.

## Climate data processing

In this work, the analysis of precipitation and temperature time series centered around three drought monitoring indices:

### *The standardized precipitation index*

The standardized precipitation index (SPI) was created to characterize precipitation deficits for a given period (Equation 1) (Chand and Dhaliwal, 2024), The fundamental strength of this index is that it can be calculated for a variety of time scales (1, 3, 6, 12, 24 and 48 months), allowing us to monitor short- and long-term water supplies (Mishra et al., 2023). Drought intensity is arbitrarily defined for SPI values in the following categories (Table 2). In this study, in order to detect hydrological droughts and their effects on the water resource (Lake Abkhane), we chose to calculate the SPI (12 months) (Vicente-Serrano *et al.,* 2016), using the R Studio software version 4.3.0.

$$SPI = (pi - pm)/\sigma \quad (1)$$

where: $Pi$ – precipitation of year I, $Pm$ – average precipitation, $\sigma$ – standard deviation.

### *Standardized precipitation-evapotranspiration index*

Standardized precipitation-evapotranspiration index (SPEI) is calculated by combining precipitation and potential evapotranspiration. It has an advantage over the SPI because it considers PET's impact on drought severity (Hailesilassie *et al.,* 2023). As a result of its multi-scalar characteristics, drought can be identified, and their

**Table 2.** Classification of drought severity according to (Vicente-Serrano et al., 2016)

| SPI values | Classification of drought |
|---|---|
| [0 -0.99] | Slight drought |
| [-1.00 -1.49] | A moderate drought |
| [1.5 -1.99] | Intense dry spell |
| ≤ -2.00 | Acute drought |

impacts analyzed in relation to global warming. The SPEI is calculated using the monthly (or weekly) difference between precipitation and PET (Vicente-Serrano *et al.,* 2016), representing a simple climate water balance calculated at different time scales to obtain the SPEI. In this work, we calculated the SPEI from SPEI base v.2.8 (Beguería *et al.,* 2023). This index is particularly well-suited for detecting, monitoring, and studying the consequences of global warming on drought conditions (Vicente-Serrano *et al.,* 2016).

*Palmer drought severity index (PDSI)*

The PDSI stands as a widely utilized meteorological drought index, calculated from soil moisture and precipitation data from preceding months (Table 3). The PDSI algorithm was originally developed by Palmer (1965). It gauges the difference between the observed precipitation and the atmospheric evaporation demand (Tufaner and Özbeyaz., 2020). The PDSI calculated in this study was extracted from TerraClimate, a dataset covering the monthly climate and climate water balance of global land surfaces (Abatzoglou *et al.,* 2018).

## RESULTS AND DISCUSSION

### Abkhane lake's water area variation

The generated images depict changes in the frequency of Lake Abkhane's waters. However, starting from 2018, there is a discernible trend towards the drying up of the lake, potentially attributed to insufficient rainfall and/or the recorded temperature increase since 2018 (Figures 2 and 3). Notably, the lake primarily fills due to rainfall and runoff (Handuo Tang *et al.,* 2023) (Figure 4).

The calculation of the lake water area over the years, considering pixels classified as water (if 'the frequency is > 0.20', then the pixel is considered regular open water during the year), enabled the graphical representation of the annual open water area (Figure 5). Additionally, a comparison was made between two periods representing the maximum (2010) and minimum (2022) surface water area (Figure 6).

Analyzing Figures 5 and 6 reveals a significant difference in the lake's area between 2010, characterized by substantial rainfall (Figure 2) and a low average annual temperature (Figure 3), and 2022, which saw a notable decline in precipitation (Figure 2) and an increase in the average annual temperatures (Figure 3).

The assessment of water area changes (gained, lost, and stable) between these two periods (Figure 7) underscores a pronounced variability in water extent in recent years. Notably, there is an exceptionally low water area in 2022, indicating that the lake has not rebounded in water levels but instead shows a concerning trend towards dewatering.

### Effect of drought severity and land uses on lake water areas variation

Like the other lakes of the Middle Atlas, which have all experienced in recent decades, a significant water deficit due to continuous droughts and land overexploitation by human activities, including: Dayet Aoua (Abdelaziz El-Bouhali *et al.,* 2024), Aguelmam Sidi Ali (Haddout *et al.,* 2018). Lake Ifrah (Nourelbait *et al.,* 2015) and Aguelmam Azigza (Adallal 2019; Jouve *et al.,* 2019b), Lake Abkhane could not escape this pattern of trend towards water scarcity in the Middle Atlas. Hence the interest in elucidating the potential impacts of the combination of climate changes and anthropogenic activity on the hydrological behavior of this lake system through drought indices.

### Drought severity

*The standardized precipitation index*

The SPI was calculated on a 12-month time scale (Figure 8), which highlighted wet and dry periods and measured drought intensity and severity at the study site. The annual SPI made

**Table 3.** Characteristics of the PDSI (Vicente-Serrano et al., 2016)

| Index name | Calculation | Classification of drought | Strength |
|---|---|---|---|
| Palmer drought severity index (PDSI) | PDSI calculates the water balance's deviation from ideal conditions using a two-layer bucket water balance model. | ≥ 4.0: extreme drought.<br>[3.0 -3.99]: severe drought.<br>[2.0 -2.99]: moderate drought.<br>[1.0 -1.99]: mild drought.<br>[0.5-0.99]: drought begins.<br>[0.49 -0.49]: close to normal | Taking into account both water supply (rainfall) and demand (potential evapotranspiration) |

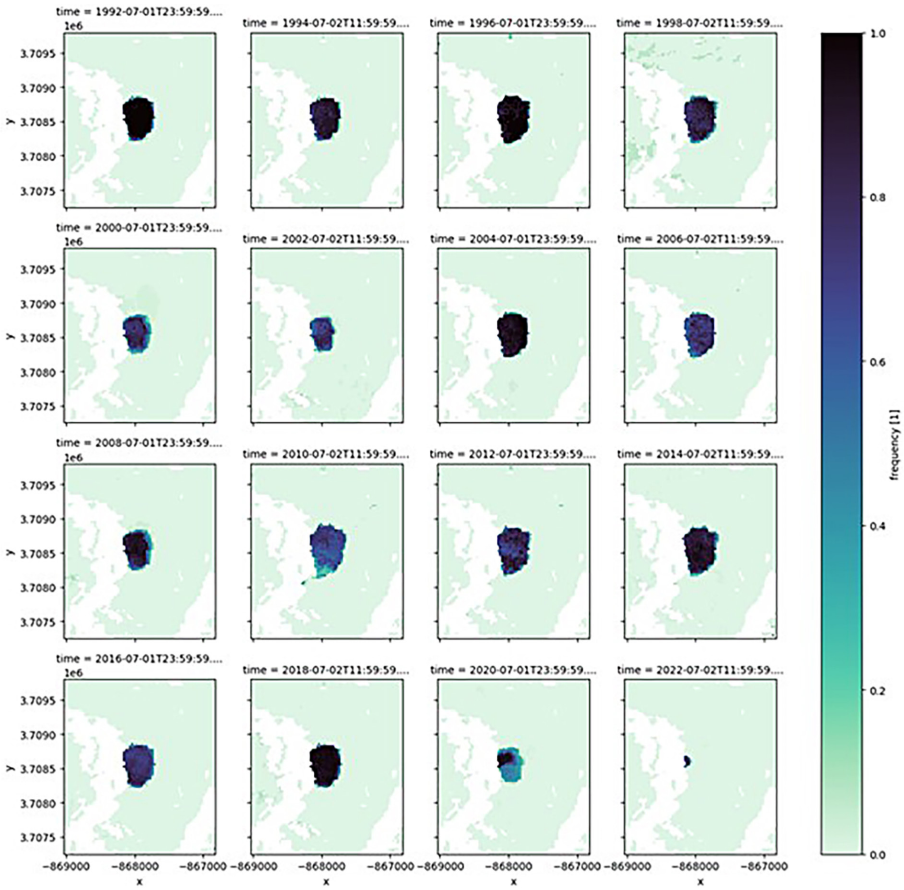


**Figure 4.** Facet plot of a subset of WOfS annual summaries of Lake Abkhane waters

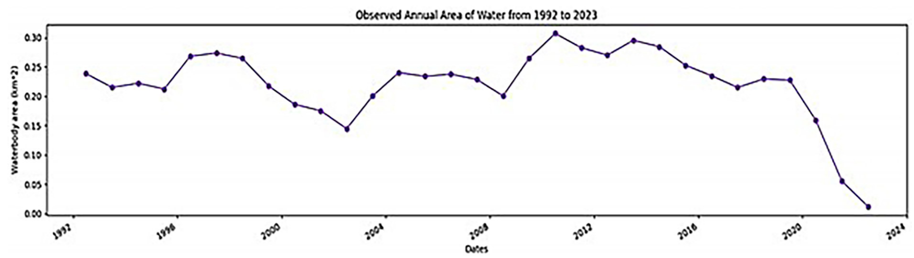


**Figure 5.** Change in lake surface area over time (between 1990 and 2022)

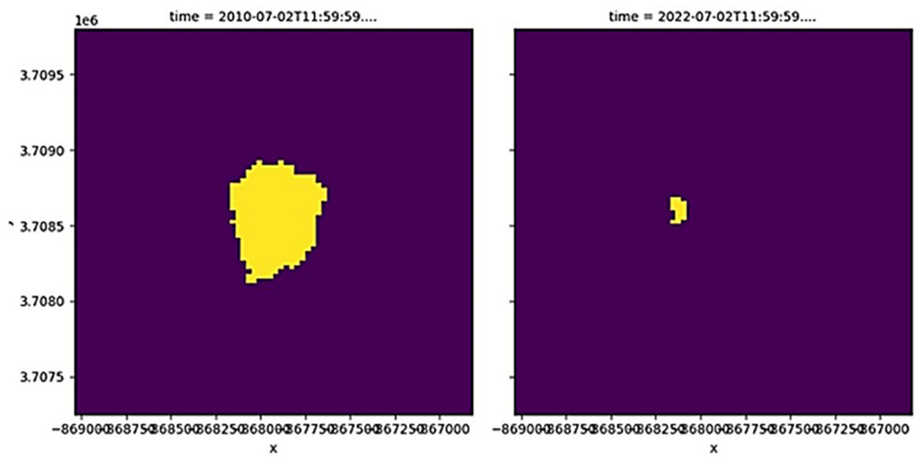


**Figure 6.** Map showing the maximum (2010) and minimum (2022) surface water extent

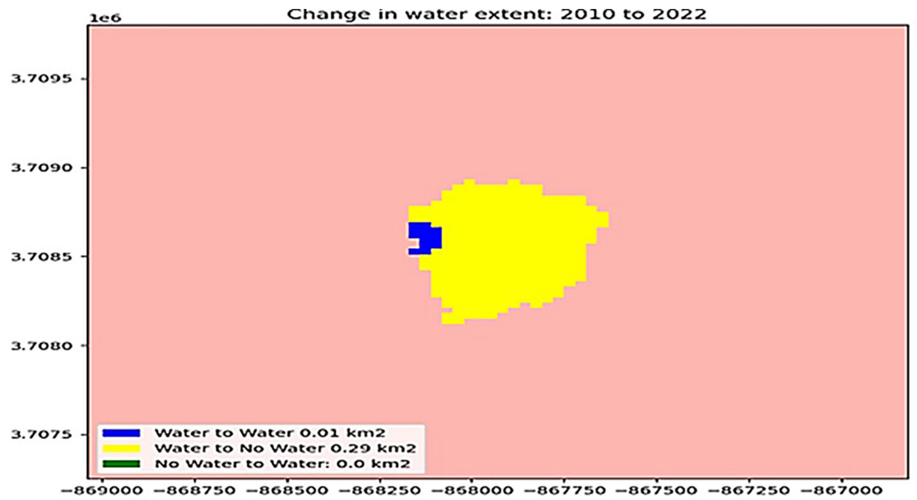


**Figure 7.** Map showing the area of water gained, lost and stable between 2010 and 2022

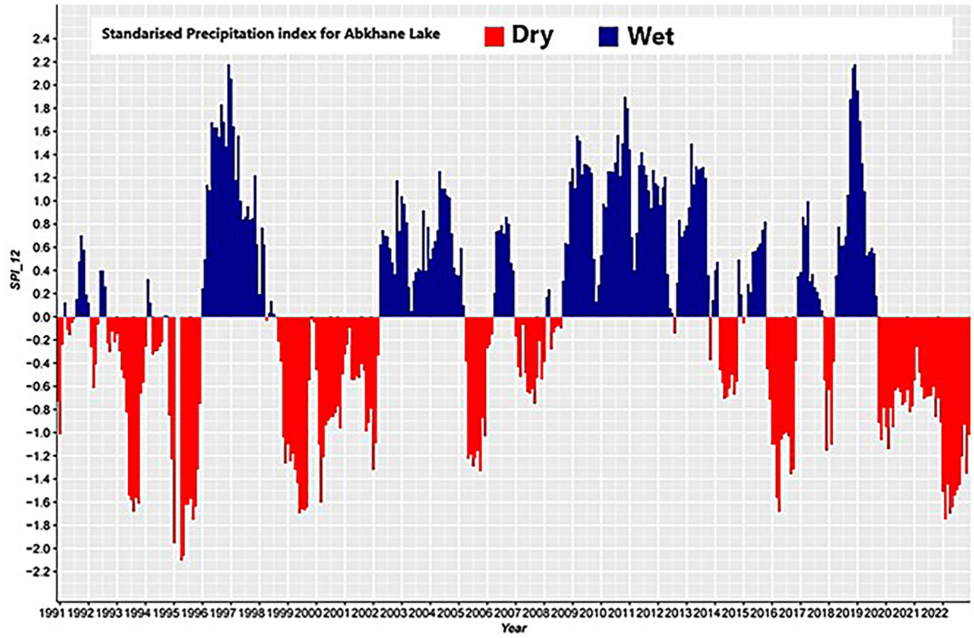


**Figure 8.** Standardized precipitation index calculated for Abkhane lake, 1990–2022 using time scale of 12 months

it possible to distinguish two major periods of severe drought (SPI ≤ -2), the first began in 1998, a second towards the end of 2019 and has lasted until today, these two periods of severe drought coincide with periods of water deficit recorded at the lake (Figure 5). However, the year 2010 is characterized by a significant wet period, in perfect agreement with the increase in the surface area of the lake recorded during the same year (Figure 5). To confirm this association between drought (expressed by SPI) and lake water area, a simple linear regression

**Table 4.** Estimation of correlation parameters between lake area and SPI_12 (1990–2022)

| Coefficients | Estimate | Std. error | t value | Pr (>\|t\|) |
|---|---|---|---|---|
| Intercept | 0.220141 | 0.009381 | 23.468 | < 2e-16 *** |
| SPI_12 | 16.352 | 0.011178 | 3.827 | 0.000639 *** |

**Note:** Signif. codes: 0***, 0.001**, 0.01*, 0.05; Standard deviation residuals: 0.05221 on 29 degrees of freedom; multiple R-squared: 0.3355; adjusted R-squared: 0.3126; F-statistic: 14.64 on 1 and 29 DF, p = 0.0006392.

model was established between these two parameters (Figure 9 and Table 4).

The results obtained confirm that successive droughts in the region have caused a water shortage that has significantly impacted ($p = 0.000639 < 0.05$) the renewal of the lake's water resource, since an increase in the SPI by one point will result in an increase in the lake's water surface area of 0.043 $km^2$. Using the coefficient of determination, 31% of the variation in lake surface area can be explained by rainfall, while 69% can be explained by other factors (evaporation, irrigation pumping, etc).

### *Standardized precipitation-evapotranspiration index*

To account for the impact of temperature on the advancement of the drought by a simple water balance calculation, this index is built on the same principles as the SPI but additionally includes temperature. According to Vicente-Serrano et al., (2016), there is an intensity scale with which positive and negative values can be calculated to represent wet and dry events. A perfect concordance between the variations in the lake's area (Figure 5) and the alternating wet and dry episodes is shown by the calculation of the study site's SPEI on a 12-month scale (Figure 10). This is because the wet periods correspond with periods of increase in the lake's waters, while the dry seasons are characterized by a decrease in this area.

### *Palmer drought severity index*

The site's Palmer drought severity index (PDSI), which is derived from monthly temperature and precipitation data and enhanced by soil water-retention capacity, was taken from Terra Climate data (Figure 11). It considers the humidity in the soil as well as the humidity that is received (precipitation), as the loss of humidity might result in temperature changes (Tuttle and Salvucci, 2016). The variations in the PDSI are perfectly consistent with the changes in the surface area of the lake (Figure 5) since the drought episodes

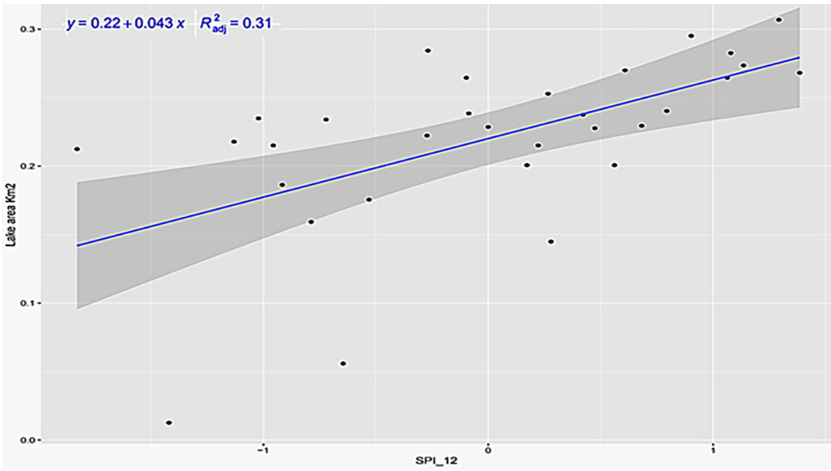


**Figure 9.** Linear regression curve showing the correlation between the surface area of Lake Abkhane and SPI_12


**Figure 10.** Standardised precipitation-evapotranspiration index for Abkhane lake, 1990–2022 using time scale of 12 months

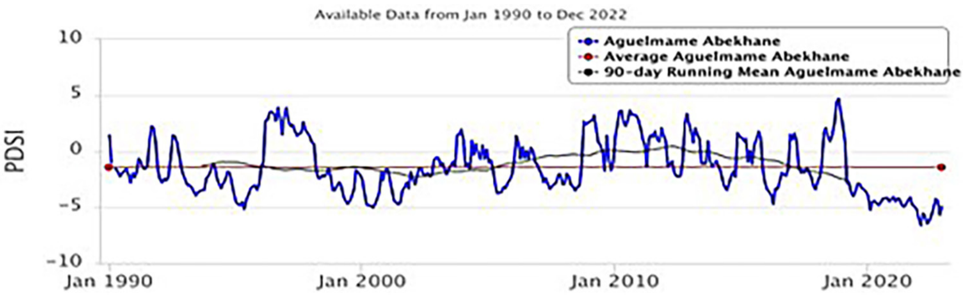


**Figure 11.** Palmer drought severity index for Lake Abkhane between 1990 and 2022

coincide with the decrease in the surface area of the lake while the humidity episodes reveal the opposite. From 2020, this index presents the region as experiencing an extreme drought (PDSI < -4) which has undoubtedly caused the water deficit recorded at the lake.

## Land use

In Morocco, over recent decades, the Middle Atlas lakes have faced substantial pressures attributed to climate change and land use (LU) changes, particularly characterized by the intensified adoption of irrigation-based agricultural practices (El-Bouhali *et al.,* 2024). The land use map, generated from Sentinel-2 images from September 2023, clearly shows a remarkable expansion of irrigated areas compared to 2015. This expansion is correlated with a significant reduction in water levels in Lake Abkhane (Fig. 12). This expansion of agricultural activities is mainly linked to the profits generated by irrigated crops (arboriculture and potatoes) and subsidies from the Green Morocco plan, initiated in 2008 (government financial incentives).

This shift in the utilization of mountainous lands, traditionally dedicated to pastoral practices, towards hydrovorous arboriculture, has led to a marked reduction in water reserves, diminished

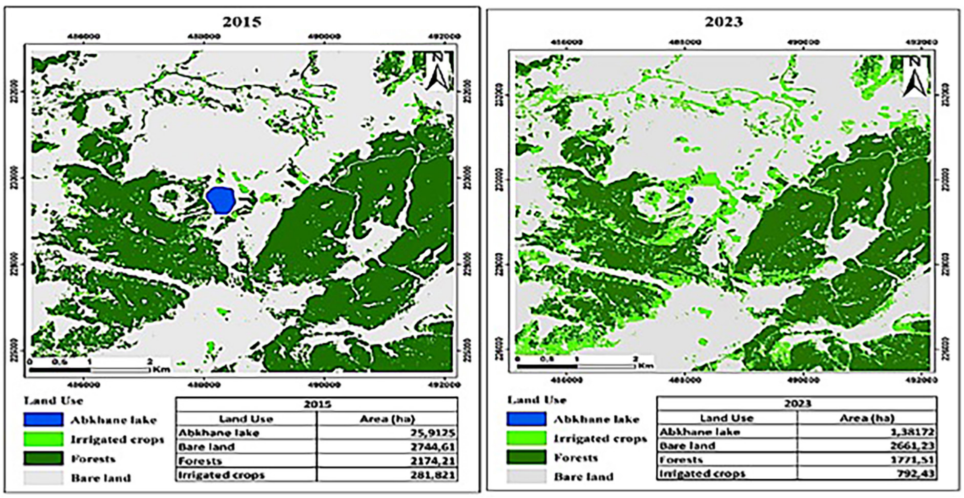


**Figure 12.** Maps showing changes in land use between 2015 and 2023 in the study area

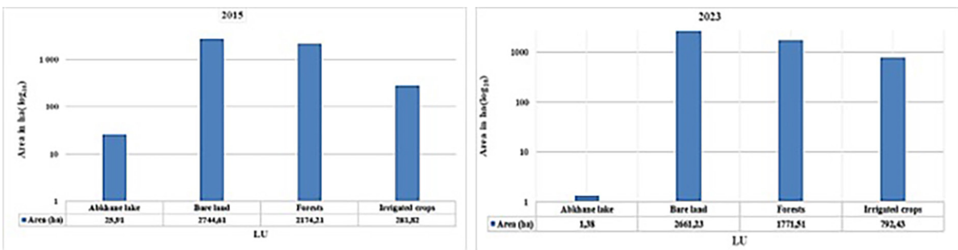


**Figure 13.** Comparison of LU’s development between 2015 and 2023

**Table 5.** Confusion matrix for classification of Sentinel-2 L1C images from 20/09/2023

| LU classes | Irrigated crops | Forests | Bare land | Abkhane lake | User accuracy | Kappa coefficient |
|---|---|---|---|---|---|---|
| Irrigated crops | 79240 | 2 | 1 | 0 | 99.996 | |
| Forests | 3 | 177148 | 0 | 0 | 99.999 | |
| Bare land | 0 | 0 | 266123 | 0 | 100 | |
| Abkhane lake | 0 | 0 | 0 | 139 | 100 | |
| Total | 79243 | 177150 | 266124 | 139 | 0.00 | |
| Producer accuracy | 99.996 | 99.998 | 100 | 100 | 0.999 | |
| Kappa coefficient | | | | | | 99.998 |

rangelands, and a notable regression in forest cover (Fig. 13). The validation dataset's accuracy assessment reveals a 99.99% overall accuracy (Table 5).

## CONCLUSIONS

This study highlights the precarious state of the lake ecosystem, which is influenced by a combination of climatic and anthropogenic factors. The analysis has provided clear evidence of the impacts of climate change, notably a decrease in precipitation and a rise in temperature, resulting in the reduced frequency of wet years. These climatic shifts have intensified the occurrence and severity of droughts, as confirmed by multiple drought indices that have reflected corresponding changes in lake water levels and hydrodynamic patterns.

The findings underscore the intricate relationship between climate variability and human-induced pressures. Rising temperatures and precipitation variability, together with shifts in land use practices, have significantly weakened the lake's capacity for natural recovery and disrupted its hydrological balance. These trends align with observations from similar studies on Middle Atlas lakes, suggesting a broader regional phenomenon of water scarcity. Given the severity of these challenges, immediate intervention is required from water resource management authorities. Key recommendations include:

- Designating protected buffer zones around the lake to safeguard water quality and quantity
- Regulating water-intensive agricultural activities to reduce stress on the ecosystem
- Formulating and implementing integrated conservation plans to preserve the lake's ecological integrity

These insights provide a robust scientific basis for environmental managers and policymakers to adopt urgent protective measures. Moreover, the study lays the groundwork for future research aimed at developing targeted conservation strategies and policies for the preservation of this ecologically significant wetland. Continuous monitoring and further studies will be essential to support the sustainable management and resilience of this critical water resource.

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