Recent variations of water area in the Middle Atlas lakes (Morocco): A response to drought severity and land use changes

Abdelaziz EL-BOUHALI (abdelaziz.elbouhali@usmba.ac.ma)
Sidi Mohamed Ben Abdellah University
Mhamed AMYAY
Sidi Mohamed Ben Abdellah University
Khadija EL OUAZANI ECH-CHAHDI
Sidi Mohamed Ben Abdellah University

Research Article

Keywords: Middle Atlas, Lake, Recent variations, Severe drought, Land use

Posted Date: August 10th, 2023

DOI: https://doi.org/10.21203/rs.3.rs-3224966/v1

Additional Declarations: No competing interests reported.

Abstract

The lakes represent important surface water resources and form an integral part of wetlands. The most concerning aspect of the degradation of these areas is the complete drying up of the lakes. In the Mediterranean basin, successive changes in land use practices in the context of climate change have strongly influenced wetland areas. In this study, we opted to use Landsat satellite images to monitor the extent of the water surface in two representative lakes (Aoua and Ifrah) of the tabular Middle Atlas (TMA). The results obtained from the processing of satellite images show a significant regression in the surface area of the lakes, with periods of complete drying for Aoua lake, endangering their fragile ecosystems and biodiversity.

This very critical situation of the two lakes is linked to the conjunction of natural and anthropogenic factors. The analysis of climatic data shows a significant climate change from the 1980s, with long periods of drought. In parallel, the study area has undergone remarkable modifications in land use, mainly characterized by a significant extension of irrigated agricultural areas to the detriment of grazing and rainfed crop lands. In three decades, the area of irrigated crops has increased from approximately 1300 hectares in 1985 to 7070 hectares in 2022, representing an increase of 542%. The findings presented in this study reveal the extent of lake degradation in the TMA and reflect the alarming decline in groundwater levels. This indicates that the development of a strategy for the protection of water resources should be considered as a matter of urgency.

1. Introduction

The lakes represent important surface water resources and form an integral part of wetlands (Williamson et al. 2009). The most concerning aspect of the degradation of these areas is the complete drying up of the lakes. In the Mediterranean basin, successive changes in land use (LU) practices in the context of climate change (CC) have strongly influenced wetland areas. According to Beltrame et al. (2015), they have lost 50% of their surface area during the 20th century. The processes of modifications in wetland areas in general, and lakes in particular, are the result of complex interactions between climate and LU practices. Over the past few decades, lakes have experienced concerning variations (expansion, shrinkage, and drying up) in different countries around the globe. The works recently focused on the study of lakes in various locations show that the variation in their surface areas (expansion or shrinkage) is explained by CC (Abdelhalim et al. 2020; Emami and Zarei 2021; Zhang et al. 2021; Kayastha et al. 2022; Gbetkom et al. 2023). Therefore, lakes are considered sensitive and reliable indicators of CC (Zhang et al. 2023). Others have indicated that changes in LU have influenced hydrological processes (Davraz et al. 2019; Liu et al. 2022), imposing impacts on available water resources and watershed runoff patterns worldwide (Liu et al. 2022).

In Morocco, the lakes located in the Middle Atlas have faced significant pressure due to changes in climate and LU, essentially marked by the intensification of agricultural practices based on irrigation. The aspects of pressure exerted on the lakes in this strategic area of the Moroccan mountains are locally manifested by a significant regression in the water surface area (WSA). Studies conducted on the lakes of the Middle Atlas (Amyay et al. 2000; Sayad et al. 2011) highlight their responses to CC and the strong anthropogenic pressure. These studies were based on the utilization and analysis of hydrological and climatic data obtained from the Sebou Hydraulic Basin Agency (SHBA) and sometimes the interpretation of aerial photographs. However, these data are not always available, incomplete, expensive, and do not cover all the lakes in the region. To address the data issue, we proposed the use of remote sensing data to monitor the dynamics of water areas in two representative lakes of the tabular Middle Atlas (TMA).

The identification and mapping of lake water areas (LWA) and the detection of their changes using remote sensing, have drawn significant attention from researchers in different domains (Wang et al. 2020). Remote sensing technology is widely accepted as an effective and suitable means to extract the evolution of water bodies in various areas and temporal scales (Bastawesy et al. 2008; Davraz et al. 2019; Eid et al. 2020; Wang et al. 2020; Gu et al. 2021; Jumaah et al. 2022; Cazzaniga et al. 2023; Su et al. 2023; Wang et al. 2023). For this reason, significant efforts have been made to develop robust techniques for lake monitoring using available satellite images, such as Landsat (TM, OLI, OLI-2) and Sentinel-2 (Urbanski 2022). Remote sensing data can make a significant contribution in addressing the issue of data availability concerning lakes (Emami and Zarei 2021). In recent years, time series of satellite images, particularly from missions Landsat, have been extensively used to monitor water areas in lakes, as they provide accurate information with high spatial and temporal resolution. Jawak et al. (2015) have indicated that this data will be a valuable source for assessing water levels and their changes over the coming decades.

At the global scale, several studies have shown the capacity and precision of remote sensing in the study of lakes. In this context, this study relies on the use of multi-sensor Landsat satellite images (TM, OLI and OLI-2) to monitor recent variations in the water area of Aoua and Ifrah lakes. The objective is to understand how they respond to environmental changes, including climate and LU alterations. Therefore, this study proposes high-temporal resolution spatial remote sensing data to detect water areas in the TMA lakes over more than three decades (1984 à 2022). It also focuses on the analysis of available climate data and the quantification of irrigated surfaces as driving factors for lake degradation. Indeed, understanding the hydrological impacts of climate and LU changes is imperative for water resource planning and management (Vorosmarty et al. 2020) and for preserving the ecosystem and meeting the increasing water needs of local populations.

2. Materials and Methods

2.1. Study Area

The study area (Fig. 1) is located in the TMA, considered one of the strategic areas in Morocco, often referred to as the “water tower of Morocco.” It covers an area of 805 km² and is administratively part of the Sefrou and Ifrane provinces. The elevations in this area range from 870 meters in low depressions (Sahb Achar) to over 1800 meters in the mountains (Jebel Medouar). The geometry of tectonic accidents has facilitated the formation of an alternation of depressions and more or less extensive mounds in the area. These depressions, due to their richness in soil and water, are today highly coveted for agricultural practices. The dominance of faulted lithological formations with a high coefficient of permeability (Bentayeb and Leclerc 1977), coupled with significant precipitation (985 mm on average at the Ifrane station), fosters abundant water resources. This wealth of water has led to a significant increase in irrigated surfaces in the valley bottoms and intramountain depressions.

Similar to other mountainous regions in Morocco, this area has undergone significant landscape changes in recent decades (El-Bouhali 2023). The main aspects of these major modifications include the extension of irrigated crops to the detriment of grazing lands and rainfed agricultural areas. This dynamic is the result of a combination of natural factors (precipitation and water resources) and human factors (increasing population and state interventions). According to Jennan (1986), the transformations occurring in the Middle Atlas reflect the desire to better capitalize on the richness of this region. Thus, the processes leading to this evolution are generated by the intentions of both indigenous and non-indigenous actors, and the state through the various programs and incentive plans for the development of agriculture (El-Bouhali 2023). The observed modifications in the study area have led to a decline in groundwater levels and have resulted in a significant retreat of the water area in the lakes. This region was mainly selected due to its biological, geological, landscape, and socio-economic importance, which is highly threatened by the ongoing decrease in groundwater levels.

2.2. Satellite Data Processing

In this study, we used Landsat satellite images to map LU and track changes in the water area of Aoua and Ifrah lakes from 1984 to 2022. All the data were obtained from the freely accessible archives of the U.S. Geological Survey (USGS). Satellite images from Landsat are widely used in the field of remote sensing (Ozdogan et al. 2010), due to their significant temporal resolution, making them valuable for studying the Earth’s surface. Currently, this data have become essential for monitoring ecosystems at different spatial and temporal scales (Bian et al. 2020). Remote sensing data provided by USGS require radiometric and atmospheric pre-processing to facilitate classification and interpretation. The pre-processing was performed using the Semi-Automated Classification (SCP) extension installed in the QGIS software. The SCP plugin was used to apply the Dark Object Subtraction (DOS1) radiometric correction algorithm and to convert the raw pixel values (DN) to TOA reflectance. This powerful package (Correia et al. 2018) is widely used for satellite images pre-processing (Yawson et al. 2918; Obodai et al. 2019; Congedo 2021; Belenok et al. 2021).

Satellite image pre-processing is followed by classification to extract LU classes and LWA. The extraction of information from the raw images is performed using several supervised classification algorithms (ML, RF, SVM), unsupervised algorithms (K-means, ISO Cluster), and spectral index calculations (NDVI, EVI, NDWI). In this study, we used the supervised classification algorithm Support Vector Machine (SVM), which is widely used by researchers (Zheng et al. 2015; Rana and Venkata Suryanarayana 2020). Due to its high accuracy in classification results (Kumar Sharma et al. 2018), this non-parametric algorithm has been used extensively in recent years. The results obtained in the study area also demonstrate the power and overall accuracy of SVM (Fig. 2), which exceeds 0.9 (Table 1). The distinction of the water area of the lakes from other LU classes in a satellite image is relatively easy due to the separability of spectral reflectance. Water always exhibits very low reflectance in the near-infrared (NIR) compared to other classes such as vegetation and bare lands.

Table 1
Confusion matrix for the classification of Landsat OLI image (14.08.1985)

LU classes	Forests	Bare land	Lake	Irrigated crops	Total	U_Accuracy	Kappa
Forests	488	4	4	3	499	0.98	
Bare land	2	496	0	0	498	1.00	
Lake	3	0	496	0	499	0.99	
Irrigated crops	7	0	0	497	504	0.99	
Total	500	500	500	500	2000	0.00	
P_Accuracy	0.98	0.99	0.99	0.99		0.99	
Kappa							**0.98**

The selection of satellite images is based on ground observations and spectral reflectance monitoring. These two sources of information have allowed us to choose the most suitable month for studying irrigated surfaces and extracting the water area of the lakes. The agricultural calendars conducted on the field and the analysis of remote sensing data throughout the year has revealed that the month of August is the most suitable for conducting this type of study. In August, the area of irrigated lands experiences a remarkable increase, which puts significant pressure on groundwater resources. The monitoring of the lake areas from August 1984 to August 2022 is very interesting for assessing the impact of irrigation on water resources in the TMA. However, ground samples were used in the classification process (training data) and in validating the results.

2.3. Climate Data Processing

Precipitation data was obtained from the SHBA. The processing of precipitation time series for the Ifrane and Sefrou stations was based on the Nicholson Pluviometric Index (Eq. 1) and the Normalized Precipitation Index (Eq. 2). The calculation of the two indices was done using the RStudio software.

The Nicholson Pluviometric Index (IP) has been used in Africa to study fluctuations in precipitation patterns (Nicholson et al. 2018). It helps to identify the periods of precipitation deficits, highlighting changes in the precipitation time series. Defined as a centered and standardized variable (Soro et al. 2011), this index measures deviations from the average.

$$\varvec{X}_{\varvec{i}} = \left(\varvec{X}_{\varvec{i}} - \bar{\varvec{X}}\right)/\varvec{\sigma}$$

1

Where:

I $_{i}$ is the rainfall index for year i;

X $_{i}$ is the rainfall for year i;

$\bar{\mathbf{X}}$ is the average annual rainfall over the study period;

σ is the standard deviation of rainfall over the study period.

The Standardized Precipitation Index (SPI) (McKee et al. 1993) is recommended by the World Meteorological Organization (WMO). This index has been used in over 70 countries (WMO 2012) to identify wet and dry periods based on long-term precipitation data. The intensity of drought varies depending on the SPI values, as presented in Table 2. Negative anomalies (starting from − 1.0) indicate periods of drought, and they end when the SPI values become positive.

$$\mathbf{DI}\left(\mathbf{SPI}\right) = \left(\varvec{X}_{\varvec{i}} - \varvec{X}_{\varvec{m}}\right)/\mathbf{SD}$$

2

Where:

DI is the drought index;

X $_{i}$ annual, seasonal and monthly precipitation;

X $_{m}$, long-term mean;

SD standard deviation.

Table 2
SPI values (McKee et al. 1993)

SPI value	Class
2.0+	Extremely wet
1.5 to 1.99	Very wet
1.0 to 1.49	Moderately wet
-0.99 to 0.99	Near normal
-1.0 to -1.49	Moderately dry
-1.5 to -1.99	Severely dry
-2 and less	Extremely dry

3. Results and Discussion

3.1. Variation of the water area in Aoua and Ifrah lakes

The monitoring of the water area in Aoua and Ifrah lakes (Fig. 4) using multi-date satellite images revealed significant changes. However, the rate of increase, shrinkage, and drying up varies from one lake to another depending on the factors influencing this dynamic. The total area of the lakes has significantly decreased between 1984 and 2022, with a regression of 70 ha for Aoua lake and 136 ha for Ifrah lake (Figs. 5 and 6).

Figure 5 illustrates the spatial distribution and quantification of the water area in Aoua lake from August 1984 to August 2022. Between the two dates, the water area has undergone distinct fluctuations, ranging between 0 ha (complete drying) and 116 ha. Over a period of more than three decades, Aoua lake has experienced significant fluctuations, with periods of complete drying (2001–2002; 2008; 2018 to 2022). In recent years, the hydrological deficit of the lake has increased in a worrying manner. Locally, this is manifested by the total drying of the lake for an extended period (2018 to 2022). Before the year 2000, the lake experienced variations in its area, reaching a minimum value of 11.5 ha in 1995 and a maximum of 96.7 ha in 1992. Since the year 2000, the water area has significantly decreased (2000–2003; 2005–2008; 2016–2022), with some exceptions of increasing in water area during certain periods, notably in 2004 (85 ha) and from 2009 to 2015. Figure 5b) shows that Aoua lake exhibits rapid variations in its area. From year to another, the lake undergoes significant changes (2003–2004; 2008–2009, and 2015–2016). There are rapid increases and decreases in the surface area (from 8 ha in 2003 to 85 ha in 2004 and from 0 ha in 2008 to 120 ha in 2009). The transition from complete drying (0 ha) to nearly full filling (116 ha) and vice versa occurs in a very short period.

Figure 6 shows the changes in the area of Ifrah lake from August 1984 to August 2022. During this period, the lake underwent fluctuations in its area, ranging from 159 ha in 1984 to 15 ha in 2001. Over three decades, Ifrah lake experienced significant variations, with periods of concerning regression (2000–2008; 2021–2022). Three periods of variations in the area of the lake can be distinguished. The first period extends from August 1984 to August 2001 and is characterized by a significant shrinking of the water area, with a change of 144 ha over 17 years. The second period (2001 to 2008) experienced a slight increase in the area. In the third period, there was an increase in the water surface until 2015 due to the rise in precipitation between 2009 and 2012. This phase was followed by a new trend of the lake regressing until 2022. The decrease in the area of Ifrah lake (23 ha in 2022) indicates the very critical situation of the groundwater in recent years. Figure 6b) illustrates that the regression and progression of Ifrah areas occur at a slower rate compared to Aoua lake, which is characterized by a very rapid variation pattern.

The results obtained from Landsat satellite images indicate that the water area in both lakes has significantly decreased. The continuous regression of LWA in the TMA reflects the concerning situation of water resources, influenced by changes in hydrological parameters and radical modifications in traditional LU practices, giving way to modern practices based on irrigation.

3.2. Effect of drought severity and LU on lakes water areas variation

The changes in LWA in the TMA are often considered accurate and sensitive representations of climate parameter changes and profound modifications in LU practices. In three decades, the Imouzzer and Aoua depressions have experienced a progressive development of rosaceous orchards. The spatiotemporal evolution of irrigated areas in the TMA has led to notable transformations in landscape structures. These changes in LU practices have coincided with long periods of severe drought that have affected Morocco since the 1980s (Barakat and Handoufe 1997; Stour and Agoumi 2008).

3.2.1. Drought severity

Precipitation Variability

In this study, the variability and trend of precipitation over an 80-year period are highlighted through the analysis of data series from two representative climate stations (Ifrane and Sefrou). The pluviometric data presented in Fig. 7 show the variation of precipitation in the stations of Ifrane and Sefrou. The amounts of precipitation recorded between 1935 and 2015 vary from one station to another and from one year to another, with the highest values recorded at the Ifrane station. Thus, Fig. 7 highlights a strong seasonal contrast in precipitation. The lowest values are concentrated in the summer period. This period coincides with the increased pressure on water resources for the irrigation of agricultural areas in the depressions of the TMA. Seasonal precipitation is extremely variable. Overall, the highest precipitation values have been recorded in winter, while the lowest values occur in summer.

Standardized Precipitation Index (SPI)

The SPI allows measuring the intensity and severity of drought. The selection of the period for calculating the SPI is precisely defined by Guttman (1999); short-term durations can be important for agronomic studies, while very long-term durations are suitable for hydrological issues. The calculation of SPI for Ifrane and Sefrou stations over a period of 12 and 24 months allows showing wet and dry periods. The results presented in Figs. 8 and 9 demonstrate that wet and dry periods are more clearly visible for SPI 24 months (Fig. 8) compared to SPI 12 months (Fig. 9). For the stations of Ifrane and Sefrou, two major periods have been distinguished (Fig. 9). The first is characterized by a remarkable dominance of wet to very wet years of long duration, with positive anomalies exceeding 2. In the second period, a continuous drought was observed, with long periods of severe to very severe droughts (negative anomalies reaching values greater than − 2) and short wet spells. The frequency and intensity of drought increased significantly after 1980. The increase in the number of long-lasting droughts from the 1980s has strongly influenced the water area of the lakes. During wet periods, the lakes in the TMA show significant extension of their water area. However, an alarming decrease in the LWA, or even total drying during periods of severe drought.

Nicholson Rainfall Index (RI)

The analysis of pluviometric data at the Ifrane station between 1935 and 2015 indicates a clear alternation of wet and dry periods (Fig. 10). The pluviometric index clearly shows the number of wet years (33 years) and deficit years (47 years) over a period of 80 years. The station recorded a long period of drought from 1934 to 1954. This period was followed by a new upward trend in precipitation until 1971. From 1972, the number of deficit years saw a remarkable increase, with 29 dry years compared to 15 wet years, indicating a trend towards drought in the climate over the last decades. As for the Sefrou station, we have identified two major periods. The first period, spanning from 1935 to 1979 (45 years), is characterized by an alternation of wet years (29 years) and dry years (16 years) with a remarkable predominance of wet periods. However, the second period extends from 1980 to 2017 (35 years) and is distinguished by a remarkable decrease in wet years. The dominance of deficit years is perfectly visible in the RI (26 years) compared to 9 years for wet years. Thus, within the second period, we observed a short wet period which extends over three years from 2009 to 2011. The comparison between the two periods highlights a significant decrease in rainfall, with 16 deficit years for the first period and 26 deficit years for the second period. While until 1980, dry years were less frequent, they have become the norm for almost 40 years, indicating that this climatic drought condition has likely become structural.

In parallel with this abrupt change in precipitation and the dominance of long periods of drought since the 1980s, temperatures have recorded a significant increase in positive anomalies, as highlighted in the official reports of the Intergovernmental Panel on Climate Change (IPCC 2007, 2013). The trend of decreasing precipitation, rising temperatures, and the progressive expansion of irrigated areas in the TMA have contributed significantly to the amplification of hydrological deficits. Locally, this is manifested by the decline in groundwater levels and, consequently, the drying up of springs, reduced river flows, and alarming depletion of lakes, especially in recent years.

3.2.2. LU changes

Studies focused on the Middle Atlas confirm that this region of Morocco was primarily used for pastoral activities (Amyay et al. 2000; Badidi 1995; El-Jihad 2016; Jennan 1986; Tag 1996; El-Bouhali 2023) with a limited area devoted to rainfed and irrigated crops. However, with population growth, increased connectivity to other regions, the desire to exploit natural resources, and government subsidies, these areas have witnessed significant rural development, resulting in profound landscape changes. This includes the expansion of irrigated agriculture and orchards at the expense of grazing lands and rainfed crop areas. The rates of changes, the processes implemented, and the actors involved in this dynamic have not been the same throughout this period (El-Bouhali 2023).

Over the past decades, the Imouzzer and Aoua depressions have witnessed a continuous extension of agricultural practices based on irrigation. The LU map derived from the Landsat image of August 2022 clearly shows a significant increase in irrigated areas compared to the year 1985 (Fig. 11). The development and arrangement of land for irrigation have expanded in all directions. Irrigated lands are now found on the slopes of depressions, marshlands, grasslands, and even at the edges of forests. The profit generated by irrigated crops, government incentives, and the influx of external capital into the region are the driving forces behind this development. The irrigation of these new farms is provided exclusively by groundwater. The water extraction from the aquifer in these areas withdraws significant volumes of water.

The mapping and quantification of LU in the depressions of Imouzzer and Aoua (Fig. 11 and Table 3) have highlighted a significant landscape dynamic characterized by a significant increase in irrigated agricultural areas. Between 1985 and 2022, the area of irrigated land increased from 1300 hectares to 7070 hectares (+ 7.16% of the total area), representing a growth of 542% over 37 years. This extension of irrigated areas often occurred at the expense of uncultivated lands (pasturelands), which decreased from approximately 32,000 hectares to 26,000 hectares, experiencing a reduction of about 6000 hectares (-7.44% of the total area). The total water surface of the lakes in this area significantly decreased, from approximately 205 hectares in 1985 to only 27 hectares in 2022, resulting in a decrease of 178 hectares.

Table 3
Evolution of LU (ha) from 1985 to 2022

LU classes	**Surface in**					
	1985		**2022**		**1985–2022**	
	ha	**%**	**ha**	**%**	**ha**	**%**
Irrigated crops	1304	1.62	7071	8.78	5767	7.16
Forests	46948	58.29	47100	58.48	152	0.19
Bare land	32050	39.79	26055	32.35	-5995	-7.44
Lake	205	0.25	27	0.03	-178	-0.22
Habitats	33	0.04	287	0.36	254	0.32

Between the two dates, the depressions of Imouzzer and Aoua have experienced a significant landscape transformation, primarily characterized by a progressive increase in irrigated agriculture. The shift of population activities towards irrigation and the adoption of modern water exploitation techniques have led to the regression of traditional society. Alongside the extension of irrigated areas, the demand for irrigation water has increased, exerting significant pressure on the groundwater resources of the TMA. The consequences of modifications in LU, within the context of CC, have had a striking impact on the water resources in the study area. The intensification of irrigation and the continuous increase in water extraction downstream of Aoua lake and in the vicinity of Ifrah lake have greatly contributed to the disruption of the hydrological regime. Consequently, the complete drying of Aoua lake for extended periods (2018–2022) reflects the extremely critical condition of the groundwater level, characterized by a significant and widespread decline. Although this decline dates back to the mid-1990s, its magnitude has become alarming today.

4. Conclusion

With multi-sensor Landsat satellite images (TM, OLI, and OLI-2), we studied changes in the LWA in the TMA over a period of 38 years. The results obtained demonstrate the effectiveness of remote sensing data in monitoring variations in the LWA, with an overall accuracy exceeding 0.9. During the studied period, the lakes of Aoua and Ifrah exhibited remarkable variations. However, in recent years, the LWA has shown a general trend of regression. Between 1984 and 2022, the lake of Aoua lost 100% of its area (from 70 ha to complete drying) and the lake of Ifrah lost 87% of its area (from 159 ha to 23 ha). This clearly indicates that the pressure exerted on the lakes in the TMA region directly reflects into a significant reduction in the water area, with periods of complete drying, endangering fragile ecosystems and biodiversity.

The highly critical situation of the lakes is a result of the interplay between natural and anthropogenic factors. The mapping and quantification of LU in the study area indicate significant changes. It is a remarkable extension of irrigated surfaces to the detriment of uncultivated lands. Over the course of three decades, the area of irrigated crops has increased significantly, representing a growth of 542%. The progressive trend of irrigated agricultural areas has coincided with long periods of drought that have affected Morocco since the 1980s (as indicated by the IP and SPI). The combination of precipitation deficits and intense human pressure on water resources has led to a decline in groundwater levels in the depressions of the TMA. The results presented in this study demonstrate the concerning variations in LWA and reflect the alarming decline in groundwater levels. This highlights the urgent need for the development of a strategy to protect water resources in this strategic sector of Moroccan mountains.

Declarations

Acknowledgments

The authors are grateful to the USGS for providing the Landsat TM, OLI and OLI-2 satellite images. The authors also thank the Sebou Hydraulic Basin Agency (SHBA) for providing precipitation data.

References

1. Abdelhalim A, Sefelnasr A, Ismail E (2020) Response of the interaction between surface water and groundwater to climate change and proposed megastructure. Journal of African Earth Sciences 162: 103723. https://doi.org/10.1016/j.jafrearsci.2019.103723.
2. Amyay M, Laaouane M, Akdim B (2000) La pression anthropique sur les ressources en eau souterraine dans le Moyen Atlas. Exemple de la dépression d'Afourgagh. Mosella XXV (3–4): 341–351.
3. Badidi B (1995) La révolution des vergers de rosacées dans le Moyen-Atlas. Thèse de doctorat, Faculté des Lettres et Sciences Humaines, Limoges: 448 p.
4. Barakat F, Handoufe A (1997) La sécheresse agricole au Maroc. Sustainabilityof Water Resources under Increasing Uncertainty, Proceedings of the Rabat Symposium SI, IAHS Publ. (240): 31–41.
5. Bastawesy MA, Khalaf FI, Arafat SM (2008) The use of remote sensing and GIS for the estimation of water loss from Tushka lakes, southwestern desert, Egypt. Journal of African Earth Sciences 52: 73–80. https://doi.org/10.1016/j.jafrearsci.2008.03.006.
6. Belenok V, Noszczyk T, Hebryn Baidy L, Kryachok S (2021) Investigating anthropogenically transformed landscapes with remote sensing. Remote Sensing Applications: Society and Environment 24: 100635. https://doi.org/10.1016/j.rsase.2021.100635.
7. Beltrame C, Perennou C, Guelmami A (2015) Évolution de l'occupation du sol dans les zones humides littorales du bassin méditerranéen de 1975 à 2005. Méditerranée 125: 97–111. doi:https://doi.org/10.4000/mediterranee.8046.
8. Bentayeb A, Leclerc C (1977) Le Moyen Atlas, le causse moyen atlasique, ressources en eau du Maroc tome 3 domaines atlasique et sud atlasique. Service géologique du Maroc, Rabat: 37–65.

9. Bian J, Lia A, Leia G, Zhanga Z, Nana X (2020) Global high-resolution mountain green cover index mapping based on Landsat images and Google Earth Engine. ISPRS Journal of Photogrammetry and Remote Sensing 162: 63–76. https://doi.org/10.1016/j.isprsjprs.2020.02.011.
10. Cazzaniga I, Zibordi G, Alikas K, Kratzer S (2023) Temporal changes in the remote sensing reflectance at Lake Vänern. Journal of Great Lakes Research 49: 357–367. https://doi.org/10.1016/j.jglr.2023.01.006.
11. Congedo L (2021) Semi-Automatic Classification Plugin: A Python tool for the download and processing of remote sensing images in QGIS. Journal of Open Source Software 6 (64): 3172. https://doi.org/10.21105/joss.03172.
12. Correia R, Duarte L, Teodoro AC, Monteiro A (2018) Processing Image to Geographical Information Systems (PI2GIS)-A Learning Tool for QGIS. Educ. Sci, 8 (2): 83. doi:10.3390/educsci8020083.
13. Davraz A, Sener E, Sener S (2019) Evaluation of climate and human effects on the hydrology and water quality of Burdur Lake, Turkey. Journal of African Earth Sciences 158: 103569. https://doi.org/10.1016/j.jafrearsci.2019.103569.
14. Eid ANM, Olatubara CO, Ewemoje TA, El-Hennawy MT, Farouk H (2020) Inland wetland time-series digital change detection based on SAVI and NDWI indecies: Wadi El-Rayan lakes, Egypt. Remote Sensing Applications: Society and Environment 19: 100347. doi :https://doi.org/10.1016/j.rsase.2020.100347.
15. El-Bouhali A (2023) L'évolution des surfaces irriguées et leur impact sur les ressources en eau dans le contexte climatique actuel au Moyen Atlas tabulaire. Thèse de doctorat. Université Sidi Mohamed Ben Abdellah – Fès: 301 p.
16. El-Jihad MD (2016) Climate Change and Rural Development in the Middle Atlas Mountains and Fringe Areas (Morocco). Journal of Alpine Research | Revue de géographie alpine 104 (4). https://doi.org/10.4000/rga.3465.
17. Emami H, Zarei A (2021) Modelling lake water's surface changes using environmental and remote sensing data: A case study of lake Urmia. Remote Sensing Applications: Society and Environment 23: 100594. https://doi.org/10.1016/j.rsase.2021.100594.
18. Gbetkom PG, Crétaux JF, Tchilibou M, Carret A, Delhoume M, Bergé-Nguyen M, Sylvestre F (2023) Lake Chad vegetation cover and surface water variations in response to rainfall fluctuations under recent climate conditions (2000 – 2020). Science of the Total Environment 857: 159302. http://dx.doi.org/10.1016/j.scitotenv.2022.159302.
19. Gu Z, Zhang Y, Fan H (2021) Mapping inter- and intra-annual dynamics in water surface area of the Tonle Sap Lake with Landsat time-series and water level data. Journal of Hydrology 601: 126644. https://doi.org/10.1016/j.jhydrol.2021.126644.
20. Guttman NB (1999) Accepting the Standardized Precipitation Index: A calculation Algorithm. Journal of American Water Ressources Association 35 (2): 311–322. https://doi.org/10.1111/j.17521688.1999.tb03592.x.

21. IPCC (2007) Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, Pachauri, R.K and Reisinger, A. (eds.)]. IPCC, Geneva, Switzerland: 104 p.
22. IPCC (2013) Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA: 1535 p.
23. Jawak SD, Kulkarni K, Luis AJ (2015) A Review on Extraction of Lakes from Remotely Sensed Optical Satellite Data with a Special Focus on Cryospheric Lakes. Advances in Remote Sensing 4 (3): 196–213. DOI: 10.4236/ars.2015.43016.
24. Jennan L (1986) Mutations récentes des campagnes du Moyen Atlas et de ses bordures. Revue Méditerranée 59 (4), Villes et campagnes au Maroc: 49–62. DOI: https://doi.org/10.3406/medit.1986.2426.
25. Jumaah HJ, Ameen MH, Mohamed GH, Ajaj QM (2022) Monitoring and evaluation Al-Razzaza lake changes in Iraq using GIS and remote sensing technology. The Egyptian Journal of Remote Sensing and Space Sciences 25: 313–321. https://doi.org/10.1016/j.ejrs.2022.01.013.
26. Kayastha MB, Ye X, Huang C, Xue P (2022) Future rise of the Great Lakes water levels under climate change. Journal of Hydrology 612: 128205. https://doi.org/10.1016/j.jhydrol.2022.128205.
27. Kumar-Sharma A, Hubert-Moy L, Buvaneshwari S, Sekhar M, Ruiz L, Bandyopadhyay S, Corgne S (2018) Irrigation history estimation using multitemporal satellite images: Application to an intensive groundwater irrigated agricultural watershed in india. Remote Sensing 10: 893. doi:https://doi.org/10.3390/rs10060893.
28. Liu Y, Wu G, Fan X, Gan G, Wang W, Liu Y (2022) Hydrological impacts of land use/cover changes in the Lake Victoria basin. Ecological Indicators 145: 109580. https://doi.org/10.1016/j.ecolind.2022.109580.
29. McKe TB, Doesken NJ, Kleist J (1993) The relationship of drought frequency and duration of time scales. Eighth Conference on Applied Climatology, American Meteorological Society: 179–184.
30. Nicholson SE, Funk C, Fink AH (2018) Rainfall over the African continent from the 19th through the 21st century. Global and Planetary Change 165: 114–127. https://doi.org/10.1016/j.gloplacha.2017.12.014.
31. Obodai J, Adjei KA, Odai SN, Lumor M (2019) Land use/land cover dynamics using landsat data in a gold mining basin-the Ankobra, Ghana. Remote Sensing Applications: Society and Environment 13: 247–256. https://doi.org/10.1016/j.rsase.2018.10.007.
32. Ozdogan M, Yang Y, Allez G, Cervantes C (2010) Remote Sensing of Irrigated Agriculture: Opportunities and Challenges. Remote Sensing 2: 2274–2304. https://doi.org/10.3390/rs2092274.
33. Rana VK, Venkata-Suryanarayana TM (2020) Performance evaluation of MLE, RF and SVM classifcation algorithms for watershed scale land use/land cover mapping using sentinel 2 bands.

Remote Sensing Applications: Society and Environment 19: 100351. doi:https://doi.org/10.1016/j.rsase.2020.100351.

34. Sayad A, Chakiri S, Martin C, Bejjaj Z, Charfaoui H (2011) Effet des conditions climatiques sur le niveau du lac Sidi Ali (Moyen Atlas, Maroc). Physio-géo 5: 251–268. https://doi.org/10.4000/physio-geo.2145.
35. Soro TD, Soro N, Oga YMS, Lasm L, Soro G, Ahoussi KE, Biémi J (2011) La variabilité climatique et son impact sur les ressources en eau dans le degré carré de grand-lahou (sud-ouest de la côte d'ivoire). Physio-Géo 5 (1): 55–73. doi:https://doi.org/10.4000/physiogeo.1581.
36. Stour L, Agoumi A (2008) Climatic drought in Morocco during the last decades. Hydroécol. Appl. 16: 215–232. doi:http://dx.doi.org/10.1051/hydro/2009003.
37. Su Y, Ran Y, Zhang G, Li X (2023) Remotely sensed lake area changes in permafrost regions of the Arctic and the Tibetan Plateau between 1987 and 2017. Science of the Total Environment 880: 163355. http://dx.doi.org/10.1016/j.scitotenv.2023.163355.
38. Tag B (1996) Development possibilities in the eastern Middle Atlas Mountains and their assessment by local actors. Revue de géographie alpine 84 (4): 51–60. DOI: https://doi.org/10.3406/rga.1996.3885.
39. Urbanski JA (2022) Monitoring and classifcation of high Arctic lakes in the Svalbard Islands using remote sensing. International Journal of Applied Earth Observations and Geoinformation 112: 102911. https://doi.org/10.1016/j.jag.2022.102911.
40. Vorosmarty CJ, Green P, Salisbury J, Richard B (2020) Global water resources: vulnerability from climate change and population growth. Science 289 (5477): 284–288. DOI: 10.1126/science.289.5477.284.
41. Wang C, Xie W, Li T, Wu G, Wu Y, Wang Q, Xu Z, Song H, Yang Y, Pan X (2023) Analysis of Spatial and Temporal Variation in Water Coverage in the Sub-Lakes of Poyang Lake Based on Multi-Source Remote Sensing. Remote Sensing 15 (11): 2788. https://doi.org/10.3390/rs15112788.
42. Wang J, Ding J, Li G, Liang J, Yu D, Aishan T, Zhang F, Yang J, Abulimiti A, Liu J (2019) Dynamic detection of water surface area of Ebinur Lake using multi-source satellite data (Landsat and Sentinel-1A) and its responses to changing environment. Catena 177: 189–201. https://doi.org/10.1016/j.catena.2019.02.020.
43. Williamson CE, Saros JE, Vincent WF, Smol JP (2009) Lakes and reservoirs as sentinels, integrators, and regulators of climate change. Limnol. Oceanogr. 54(6, part 2): 2273–2282. https://doi.org/10.4319/lo.2009.54.6_part_2.2273.
44. WMO (World Meteorological Organization)., 2012. Standardized Precipitation Index User Guide, 24 p.
45. Yawson DO, Adu MO, Osei KN (2018) Spatial assessment of sugarcane (Saccharurn spp. L.) production to feed the Komenda Sugar Factory, Ghana. Heliyon 4 (11): e00903. https://doi.org/10.1016/j.heliyon.2018.e00903.
46. Zhang R, Zhu L, Ma Q, Chen H, Liu C, Zubaida M (2021) The consecutive lake group water storage variations and their dynamic response to climate change in the central Tibetan Plateau. Journal of

Hydrology 60: 126615. https://doi.org/10.1016/j.jhydrol.2021.126615.

47. Zhang Y, An CB, Zheng LY, Liu LY, Zhang WS, Lu C, Zhang YZ (2023) Assessment of lake area in response to climate change at varying elevations: A case study of Mt. Tianshan, Central Asia. Science of the Total Environment 869: 161665. http://dx.doi.org/10.1016/j.scitotenv.2023.161665.
48. Zheng B, Myint SW, Thenkabail PS, Aggarwal RM (2015) A support vector machine to identify irrigated crop types using time-series Landsat NDVI data. International Journal of Applied Earth Observation and Geoinformation, 34: 103–112. https://doi.org/10.1016/j.jag.2014.07.002.

Figures

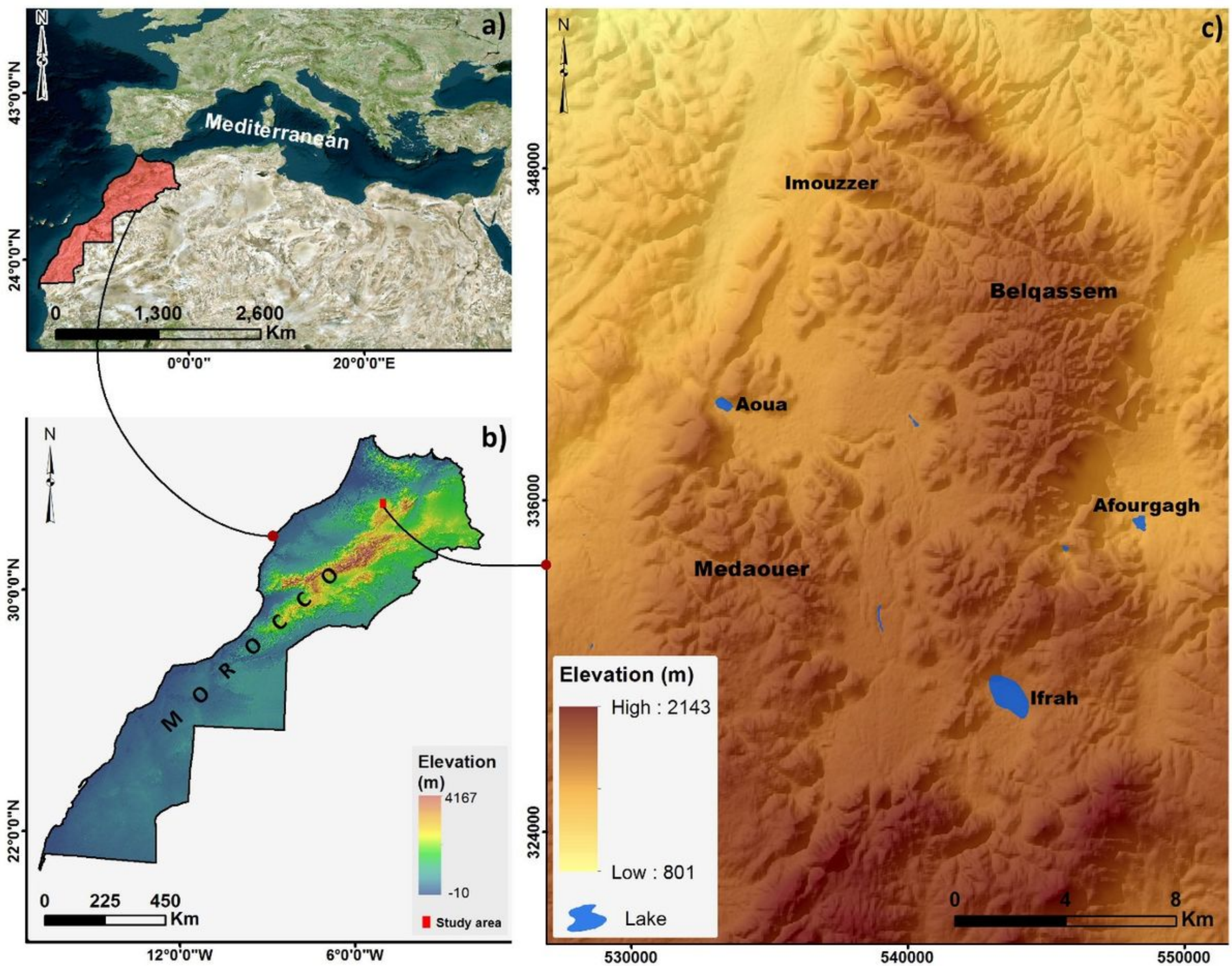

Figure 1

Geographical location of the study area: a). The position of Morocco within the Mediterranean basin; b). Location of the study area in Morocco; c). Study area

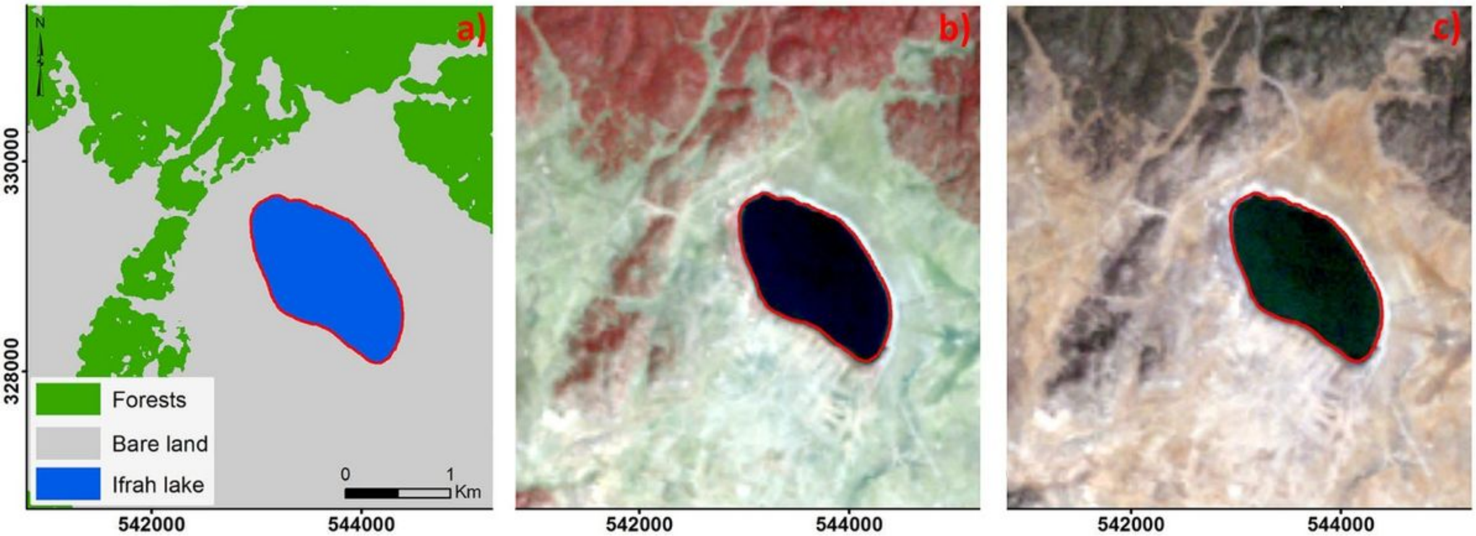

Figure 2

The comparison between a classified satellite image and a raw image, dated August 14, 1985. a). Classified image; b). Raw image in false colors; c). Raw image in true colors

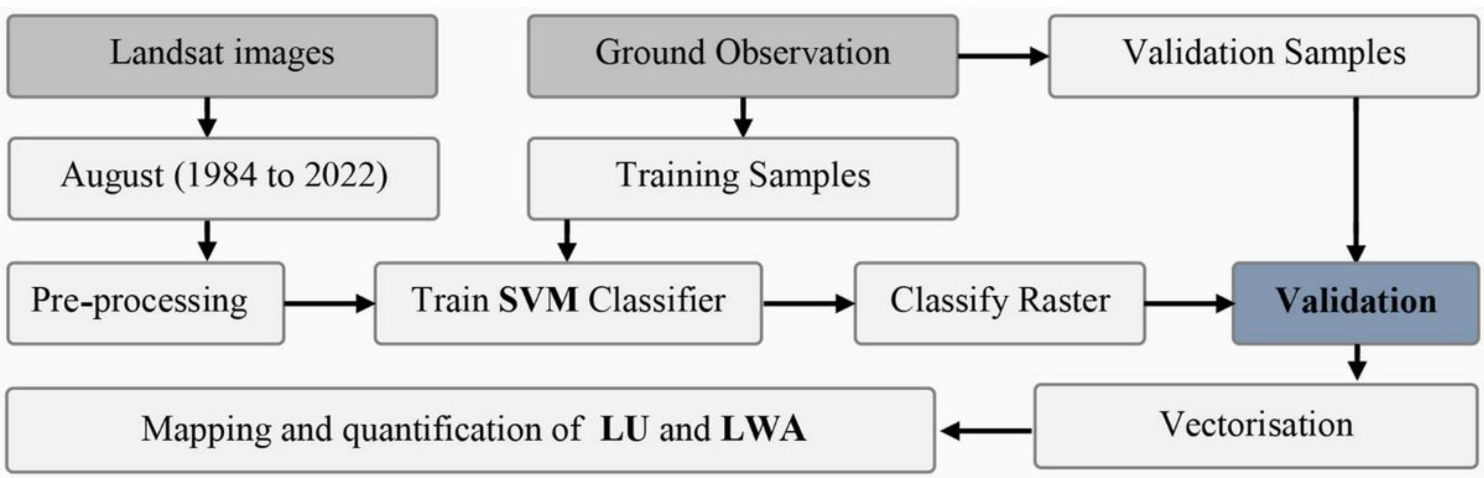

Figure 3

The flowchart of the used methodology

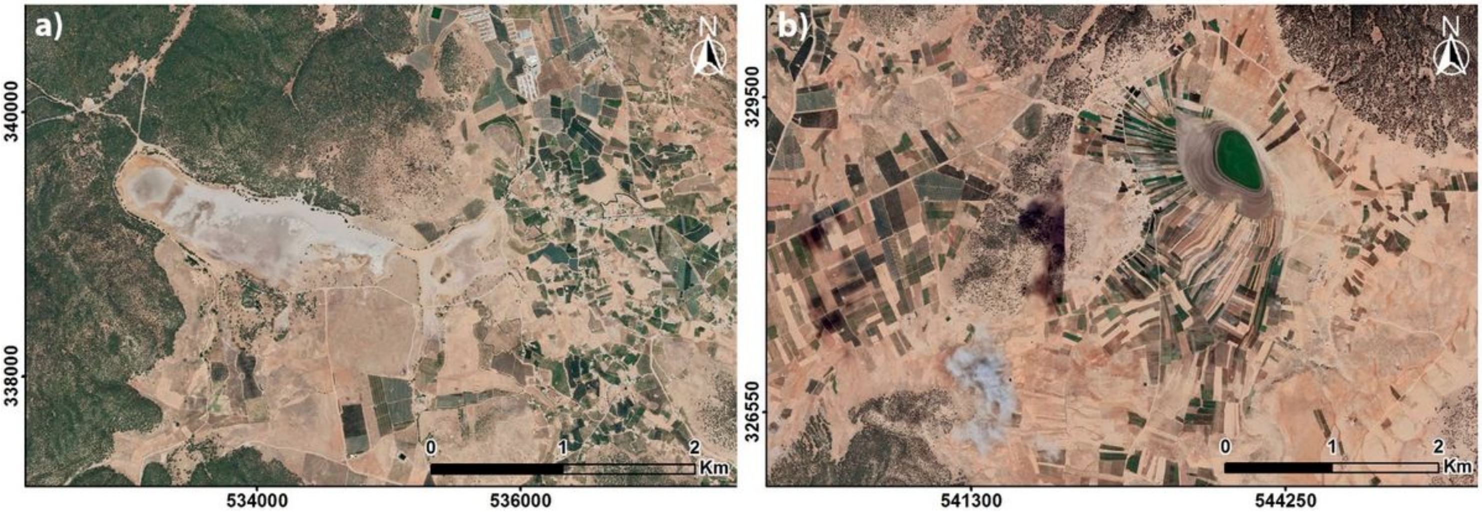

Figure 4

Situation of the lakes in July 2022 (Google Earth images). a). Aoua lake; b). Ifrah lake. The two maps show the alarming regression of the water surface and the remarkable extension of irrigated areas around the lakes.

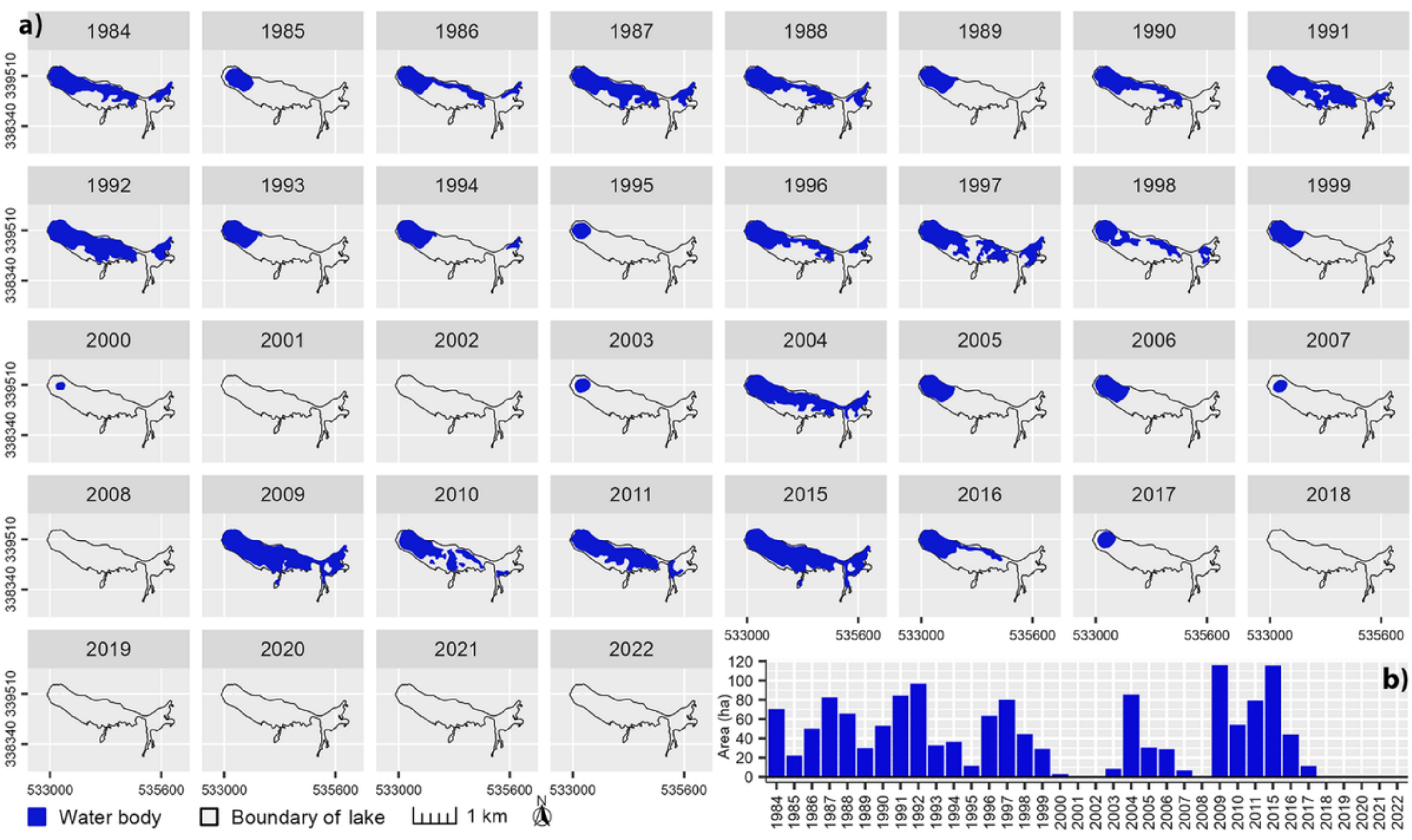

Figure 5

Variation in area (ha) of Aoua lake from August 1984 to August 2022 (Landsat satellite images TM, OLI and OLI-2)

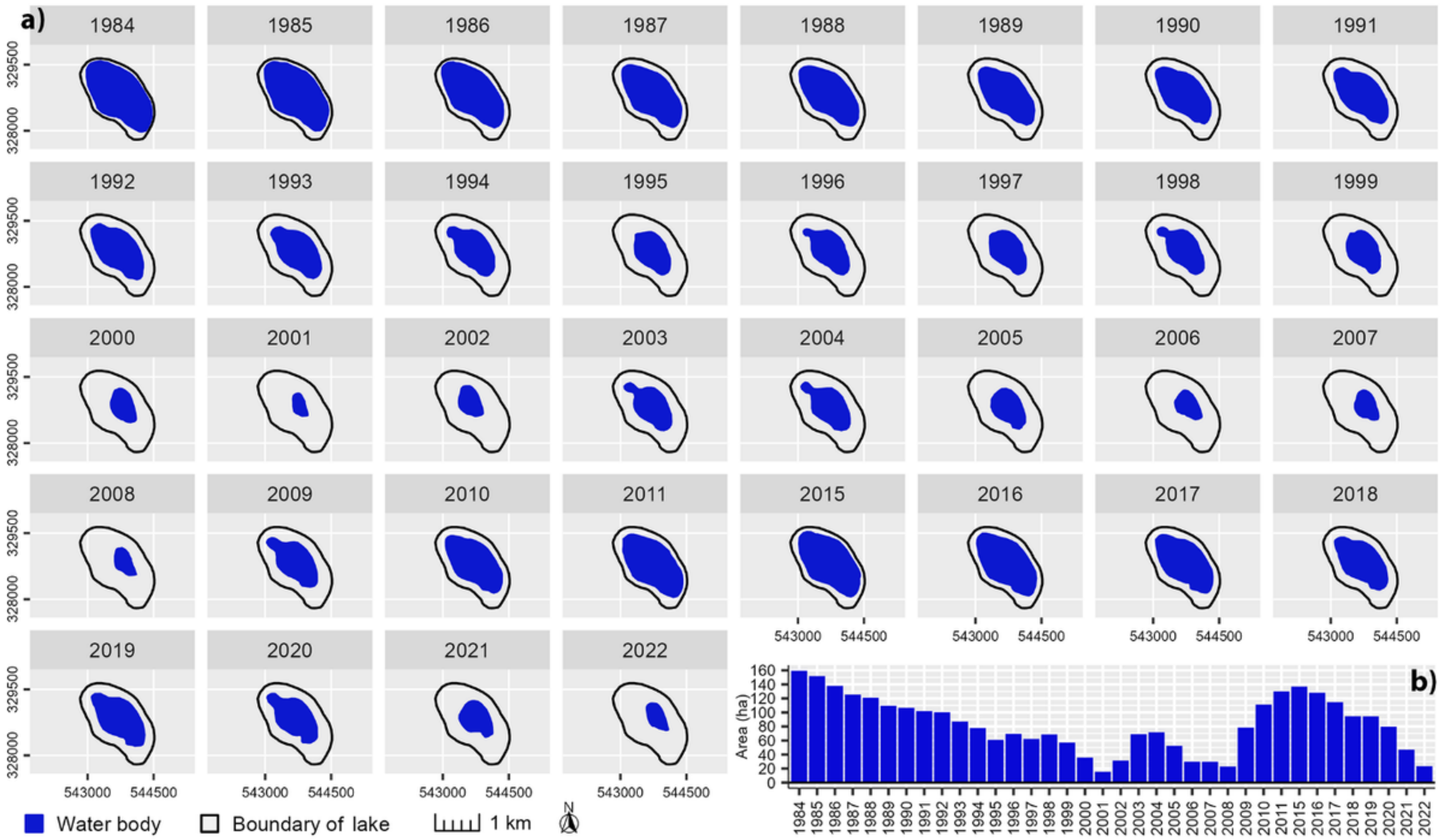

Figure 6

Variation in area (ha) of Ifrah lake from August 1984 to August 2022 (Landsat satellite images TM, OLI and OLI-2)

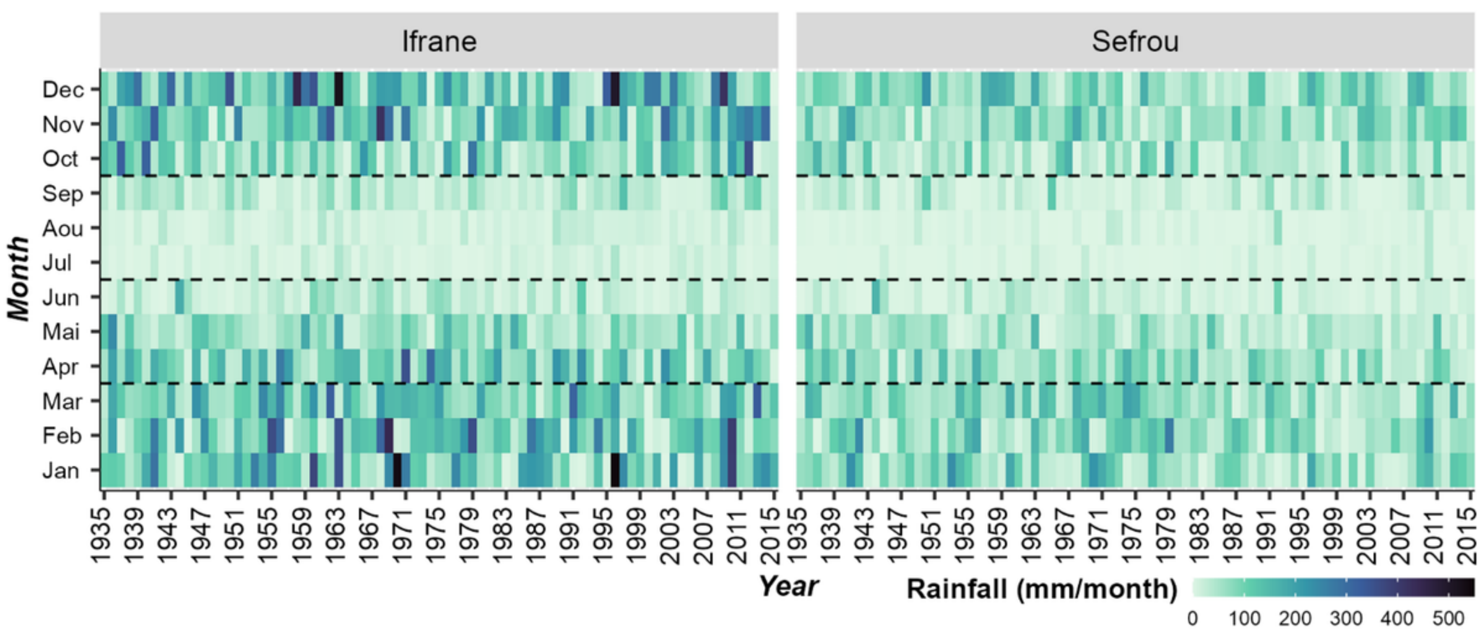

Figure 7

Rainfall Variability in the Sefrou and Ifrane stations between 1935 and 2015

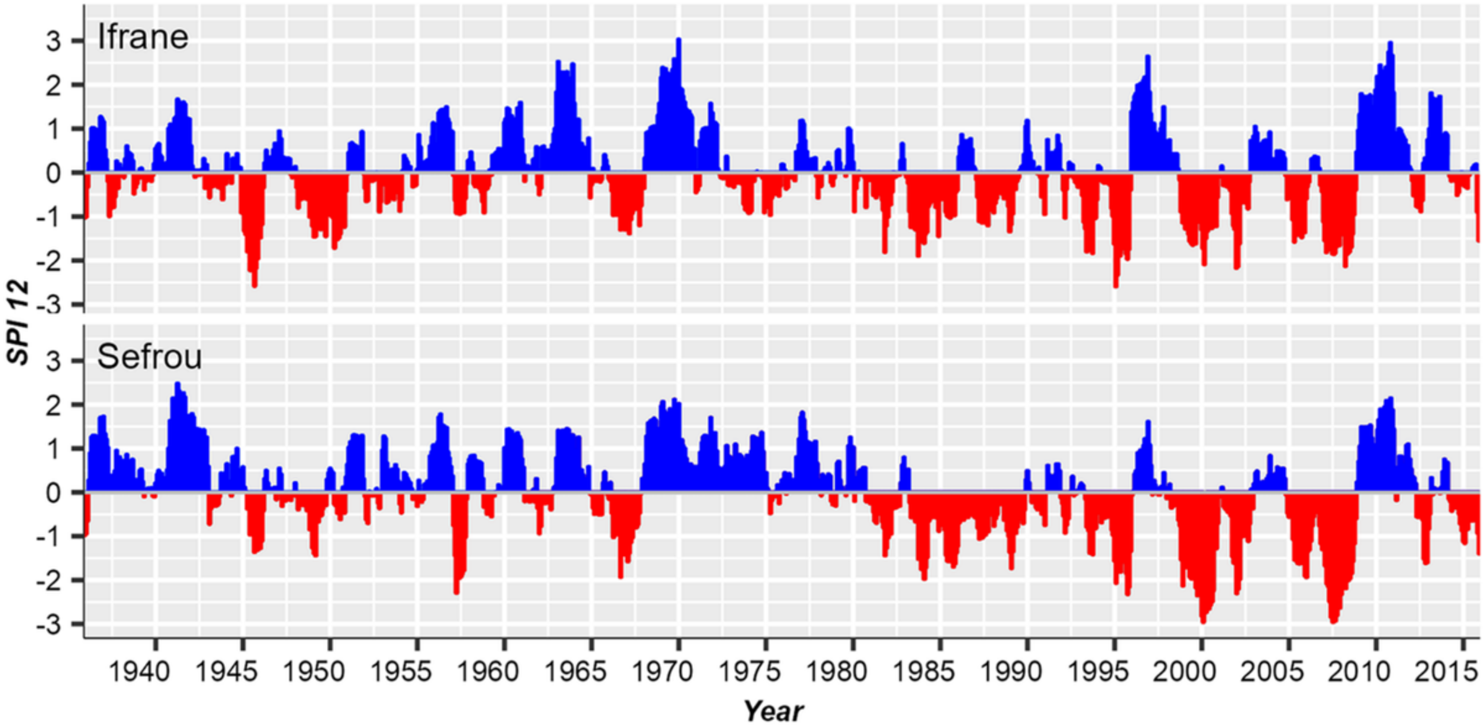

Figure 8

Temporal variation of the SPI at the 12-month scale in Ifrane and Sefrou stations

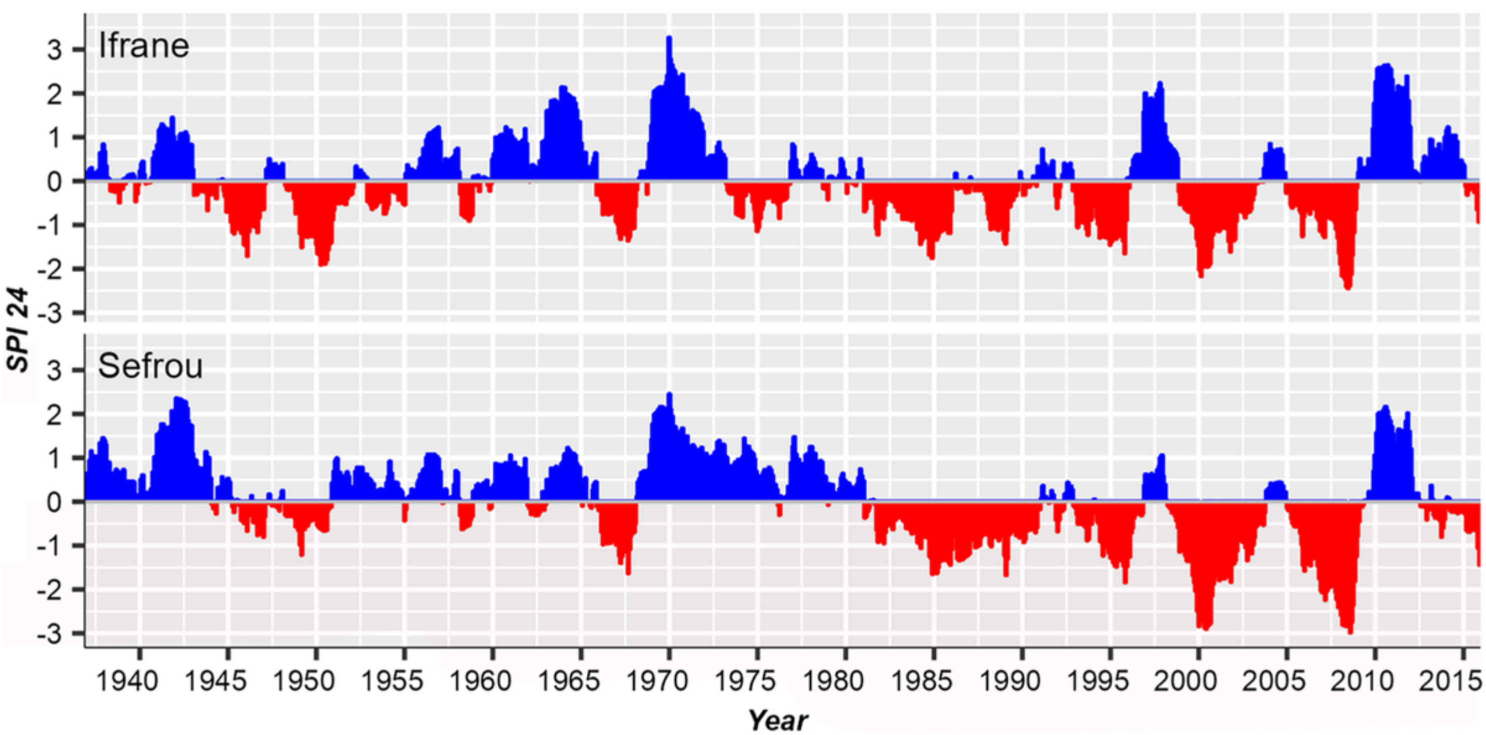

Figure 9

Temporal variation of the SPI at the 24-month scale in Ifrane and Sefrou stations

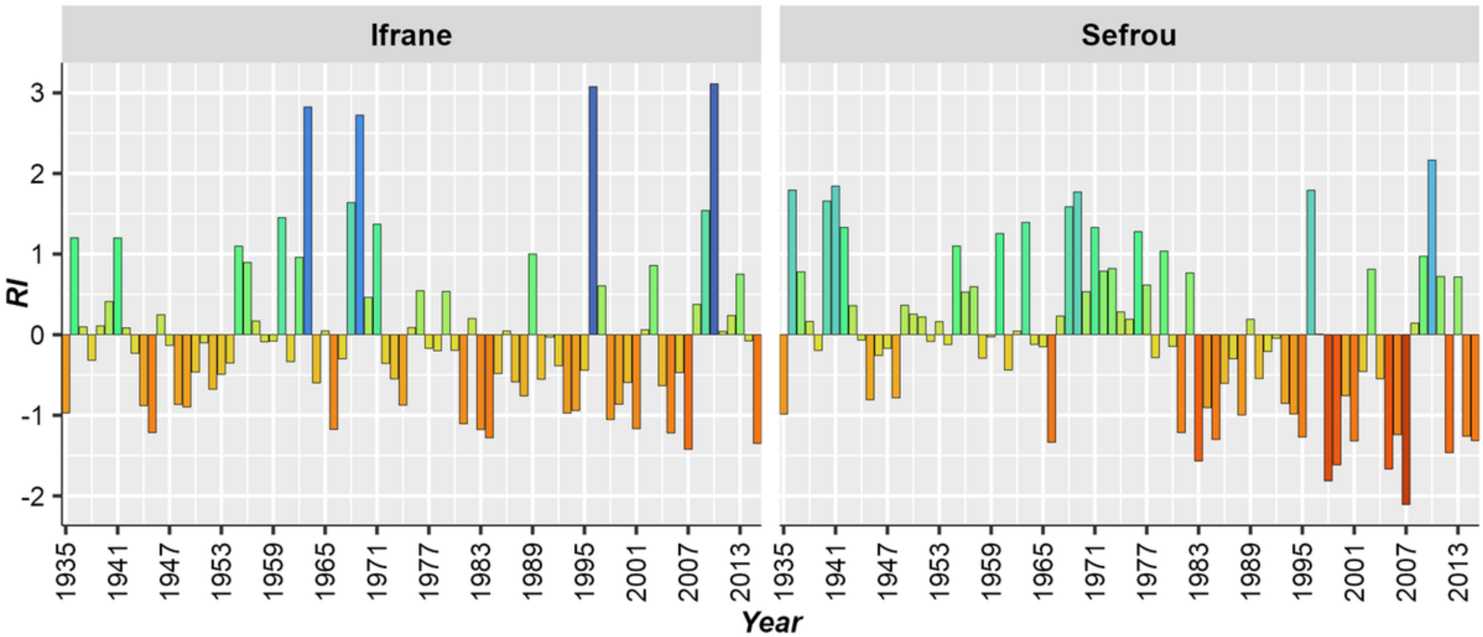

Figure 10

Rainfall index in Sefrou and Ifrane stations (1935-2015)

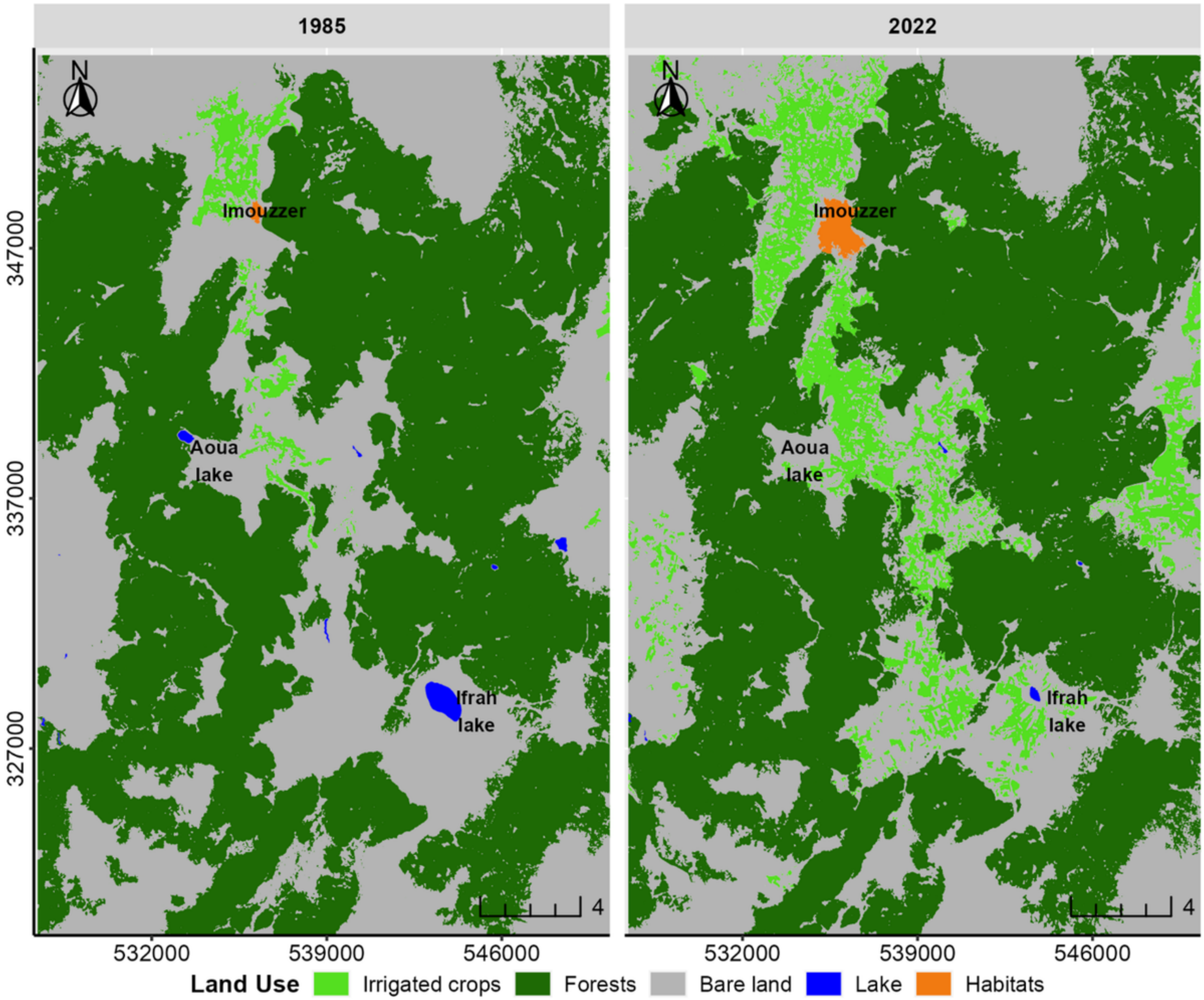

Figure 11

Dynamics of irrigated areas in Imouzzer and Aoua depressions (Landsat TM and OLI-2 satellite images)