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Changes in water surface area of the Middle Atlas-Morocco lakes: A response to climate and human effects

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Abstract

The lakes represent crucial surface water resources and 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 region, successive changes in land use practices in the context of climate change have strongly influenced wetland areas. In this study, we used Landsat TM, OLI, and OLI-2 satellite images to monitor the water surface area in two representative lakes (Aoua and Ifrah) of the Tabular Middle Atlas and to map land use across the entire study area. To extract information related to lakes and land use, we employed the Support Vector Machine machine learning algorithm, widely used in remote sensing studies. However, we identified drought periods from precipitation data using the Standardized Precipitation Index (SPI) recommended by the World Meteorological Organization (WMO). The results obtained from the processing of Landsat satellite images indicate a significant reduction in the surface area of the lakes, with periods of drying for Aoua lake, endangering their fragile ecosystems and biodiversity. The critical situation of the two lakes is attributed to a combination 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 patterns, mainly characterized by a significant extension of irrigated agricultural surfaces to the detriment of grazing and rainfed 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 situation indicates the necessity of formulating a strategy to protect water resources and wetlands in the Middle Atlas.

1. Introduction

Managing water resources in the 21st century is increasingly challenging [1]. In many regions of the world, water scarcity has appeared as a principal risk affecting sustainable development [2]. The United Nations report on Sustainable Development goals has shown an increase in water scarcity in most countries [3]. Also, this report indicates that «worldwide, 32 countries are experiencing water stress of between 25 and 70 per cent; 22 countries experience it above 70 per cent and are considered to be seriously stressed. This concerning situation is linked to climate change and anthropogenic pressure [4,5]. Increasing water withdrawals for agriculture and urban areas in the context of climate change will exacerbate water stress by 2050 [6]. Generally, aspects of water resource degradation manifest as declining groundwater levels, reduced flows from springs and rivers, and the drying up of lakes. Indeed, the lakes represent precise indicators to measure the effects of factors affecting the hydrological system, such as land-use alterations, changes in precipitation patterns, and increasing water extraction for agricultural and urban purposes.

The lakes represent crucial surface water resources and an integral part of wetlands [7]. The most concerning aspect of the degradation in these areas is the complete drying of the lakes. In the Mediterranean region, successive changes in land use (LU) practices in the context of climate change (CC) have strongly influenced wetland areas. According to [8], 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, stem from complex interactions between climate and LU practices. Over the past few decades, lakes have experienced concerning variations in different countries. Several works recently focused on the study of lakes in various locations show that the variation in their surface areas, such as extension or shrinkage, is explained by CC [9-13]. Therefore, lakes are considered sensitive and reliable indicators of CC [14]. Others have indicated that changes in LU have influenced hydrological processes [15-16], imposing impacts on available water resources and watershed runoff patterns worldwide [16].

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 [17-19]. The pressure exerted on the lakes in this strategic sector of the Moroccan mountains is manifested locally by a significant reduction in the water surface area (WSA). Studies conducted on the lakes of the Middle Atlas [19] highlight their responses to CC and anthropogenic pressure. These studies relied on analysis of hydrological and climatic data obtained from the Sebou Hydraulic Basin Agency (ABHS) and sometimes the interpretation of aerial photographs. However, this data is not always available and does not cover all lakes. To address the data issue, we used remote sensing data (Landsat data) to monitor the dynamics of water areas in two representative lakes of the Tabular Middle Atlas (TMA).

The mapping of lake water surface areas (LWA) and their change detection using remote sensing have garnered notable interest across diverse research domains [20]. 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 [15,21-27]. 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 [28]. Remote sensing data can significantly contribute to addressing the issue of data availability concerning lakes [10]. In recent years, time series of satellite images, notably from missions Landsat, have been extensively used to monitor water areas in lakes, as they provide accurate information with high spatial and temporal resolution. [29] 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 studying lakes. This study relies on multi-sensor Landsat satellite images (TM, OLI and OLI-2) to monitor recent variations in the water area of Aoua and Ifrah lakes in the TMA. The objective is to understand how they respond to environmental changes, including climate and LU alterations. Therefore, this study proposes remote sensing data to detect water areas in the TMA lakes over more than three decades (1984 to 2022). It also emphasizes the analysis of existing climate data and the quantification of irrigated surfaces as driving factors in the degradation of lakes. Indeed, understanding the hydrological impacts of climate and LU changes is imperative for water resource planning and management [30] and for preserving the ecosystem and meeting the increasing water needs of local populations.

2. Materials and method

2.1. Study area

The study area (Figure 1) is located in the TMA, considered among the strategic sectors of Morocco, often referred to as the "water tower of Morocco. It covers an area of 805 km^2 and is administratively part of the Sefrou and Ifrane provinces. The elevations in this area range from 870 m in low depressions (Sahb Achar) to over 1800 m in the mountains (Jebel Medouar). The geometry of tectonic faults has facilitated the formation of an alternation of depressions and more or less extensive mounds in the area. These depressions, rich in soil and water resources, are today highly converted for agricultural practices. The dominance of faulted lithological formations, characterized by a high permeability coefficient [31] and substantial precipitation (averaging 985 mm annually at the Ifrane station), contributes to abundant water resources. The abundance of water has resulted in a notable extension of irrigated areas in the valleys and intramountain depressions.

Similar to other mountainous regions in Morocco, this area has undergone significant landscape changes in recent decades [32]. The main aspects of these major modifications include the expansion of irrigated crops to the detriment of grazing lands and rainfed agricultural areas. This dynamism results from the interplay of natural factors, encompassing precipitation and water resources, and anthropogenic factors, including population growth and government interventions. According to [33], 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 different programs and incentive plans for the development of agriculture [32]. Thus, the study area is marked by a remarkable urban extension, particularly in the center of Imouzzer-kandar, reflecting a significant increase in population. Information on population changes in this region is available in the general population and housing census. The observed changes in the landscape within the study area may generate adverse effects on the environment. We selected this region for its significant biological, geological, landscape, and socio-economic importance, strongly threatened by inappropriate anthropogenic interventions in the climate change context.

2.2. Satellite data processing

In this study, we utilized Landsat satellite images to map LU and track changes in the water area of Aoua and Ifrah lakes from August 1984 to August 2022. For the years 2002 and 2011, we used the September and July images, respectively (Table 1). 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 remote sensing field [34] due to their significant temporal resolution, making them valuable for studying the Earth's surface. This data has become essential for monitoring ecosystems at different spatial and temporal scales [35]. Remote sensing data provided by USGS require radiometric 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 radiometric correction algorithm to convert the raw pixel values (DN) to TOA reflectance. This powerful package [36] is widely used for satellite image pre-processing [37-40].

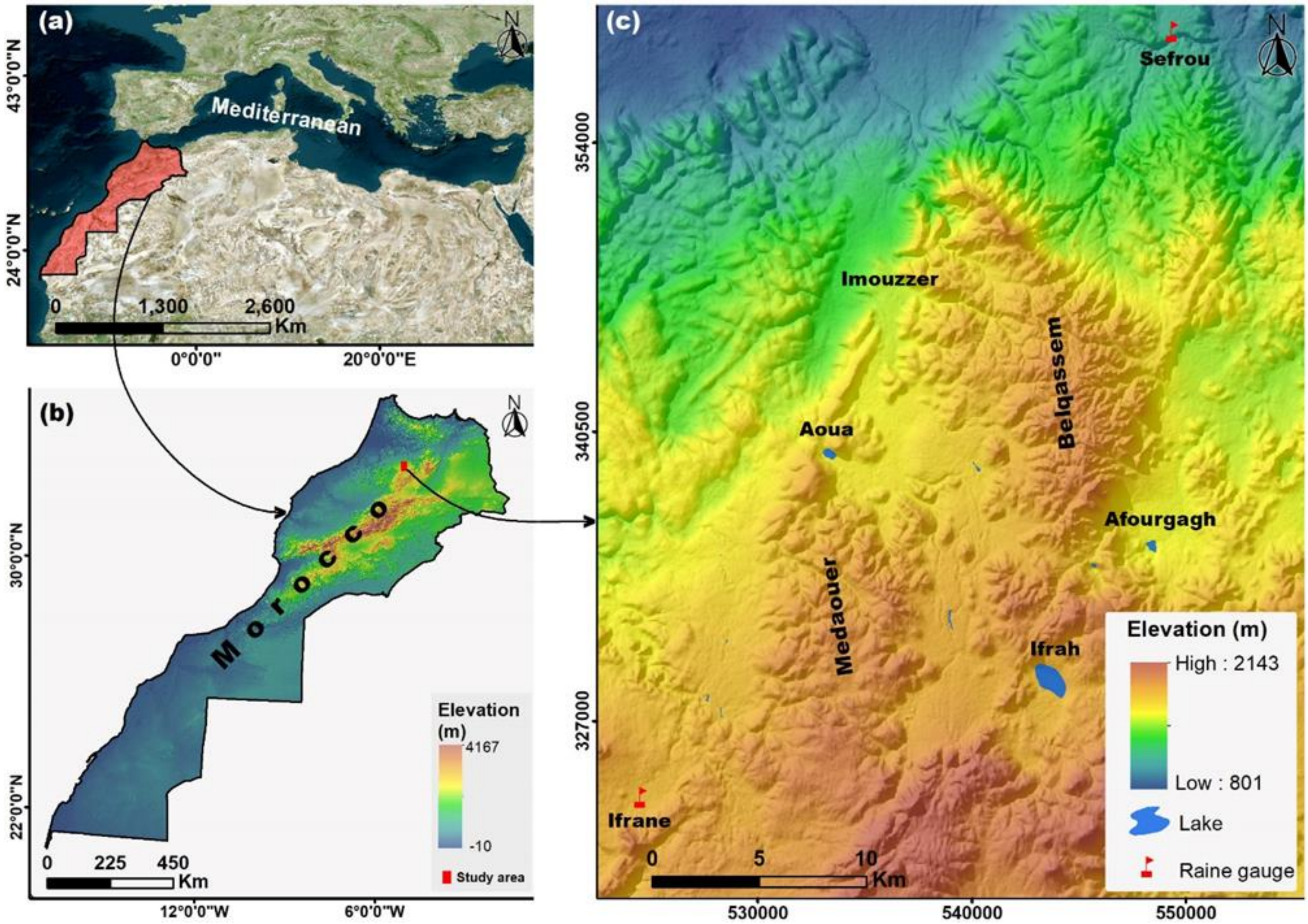

Figure 1. Geographical location of the study area: a) Morocco within the Mediterranean Basin; b) location of the study area in Morocco; c) Study area.

Table 1. Landsat satellite images used in this study [41].

Acquisition date	Sensor	Acquisition date	Sensor	Source	Spatial resolution
August 18, 1984	TM	September 16, 2002	TM	USGS	30 m
August 14, 1985	TM	August 23, 2003	TM	USGS	30 m
August 17, 1986	TM	August 18, 2004	TM	USGS	30 m
August 20, 1987	TM	August 12, 2005	TM	USGS	30 m
August 06, 1988	TM	August 08, 2006	TM	USGS	30 m
August 09, 1989	TM	August 11, 2007	TM	USGS	30 m
August 03, 1990	TM	August 20, 2008	TM	USGS	30 m
August 22, 1991	TM	August 07, 2009	TM	USGS	30 m
August 17, 1992	TM	August 03, 2010	TM	USGS	30 m
August 11, 1993	TM	July 28, 2011	TM	USGS	30 m
August 07, 1994	TM	August 01, 2015	OLI	USGS	30 m
August 01, 1995	TM	August 19, 2016	OLI	USGS	30 m
August 12, 1996	TM	August 22, 2017	OLI	USGS	30 m
August 15, 1997	TM	August 09, 2018	OLI	USGS	30 m
August 09, 1998	TM	August 12, 2019	OLI	USGS	30 m
August 21, 1999	TM	August 05, 2020	OLI	USGS	30 m
August 14, 2000	TM	August 08, 2021	OLI	USGS	30 m
August 17, 2001	TM	August 03, 2022	OLI-2	USGS	30 m

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 and SVM), unsupervised algorithms (K-means, ISO Cluster) and spectral index calculations (NDVI, EVI and NDWI). In this study, we used the Support Vector Machine (SVM) supervised classification algorithm, which is widely used by researchers [34,42]. Due to its high accuracy in classification results [42-45], this non-parametric algorithm has been used extensively in recent years. The results obtained in the study area also demonstrate the power of SVM in extracting the LWA (Figure 2). Figure 3 illustrates the statistical evaluation performance of the satellite image classification on August 14, 1985, using the SVM algorithm. In this example, overall accuracy and the Kappa coefficient perfectly illustrate the quality of the classification, with values of 0.98 (98%) and 0.99 (99%) respectively. 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.

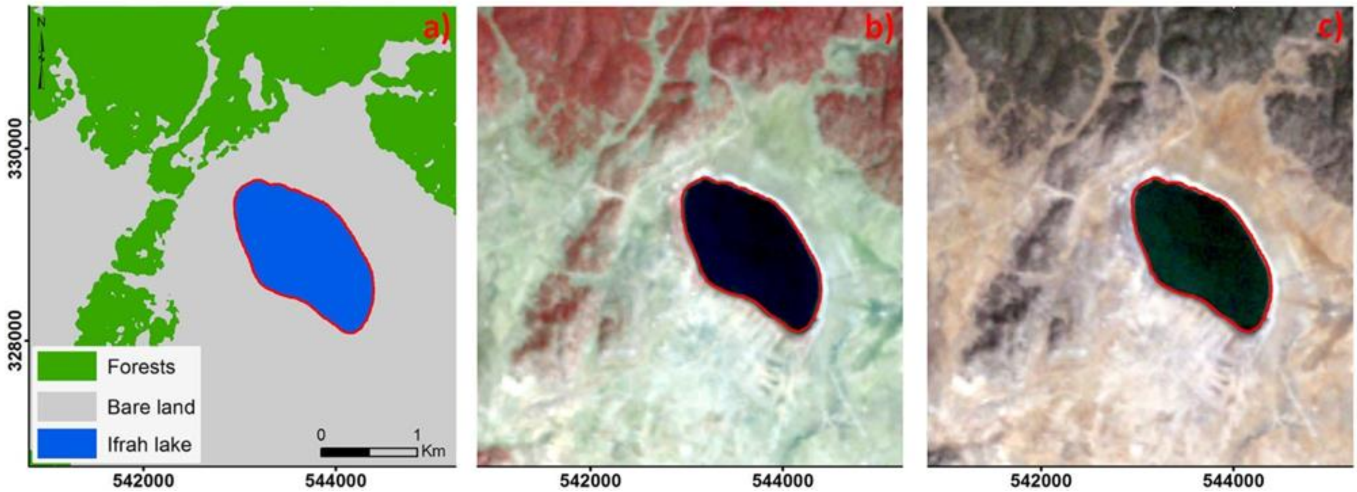

Figure 2. The comparison between a classified satellite image and a raw image, dated August 14, 1985. a) Classified image; b) Raw image in false color; c) Raw image in true color.

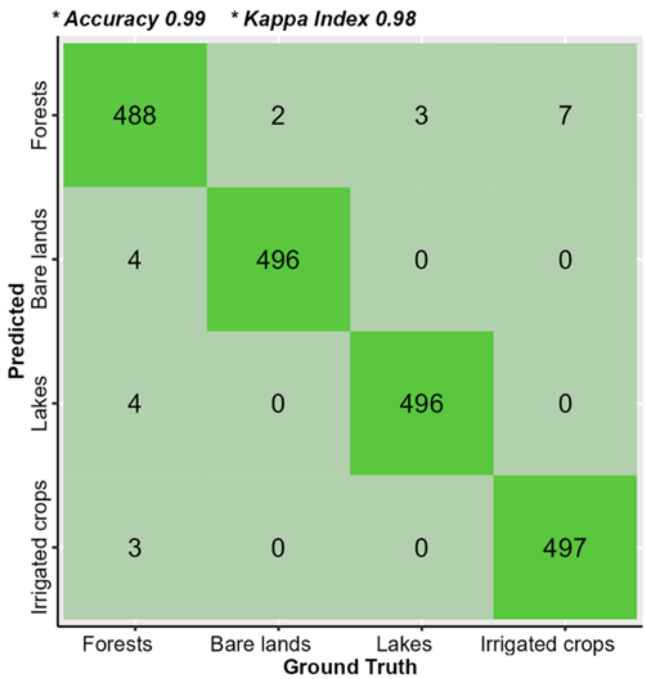

Figure 3. Classification accuracy of land use classes: example of Landsat TM satellite image: August 14, 1985.

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 in the field and the analysis of remote sensing data throughout the year have revealed that August is the most suitable for achieving this type of study. In August, the area of irrigated lands experienced a remarkable increase, which puts significant pressure on groundwater resources. The tracking of lake water areas from August 1984 to August 2022 is very interesting to assess the impact of irrigation on water resources in the TMA. However, we used ground samples in the classification process (training data) and in validating the results. The methodology employed to map land use and the water surface area of the lakes is depicted in Figure 4.

2.3. Climate data processing

We used the SPEI package in R-statistical software to calculate the Normalized Precipitation Index (Equation 1) from the precipitation time series for the Ifrane and Sefrou stations. The Standardized Precipitation Index (SPI) [46] is recommended by the World Meteorological Organization (WMO). This index has been used in over 70 countries [47] to identify wet and dry periods based on long-term precipitation data. Drought intensity 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. SPI allows measuring the intensity and severity of drought. The selection of the period for calculating the SPI is precisely defined by [48]; short-term durations can be important for agronomic studies, while long-term durations are suitable for hydrological issues.

$$SPI= (X_i- X_m) / \sigma \quad (1)$$

Where:
SPI: is the drought index;
X_i: annual, seasonal and monthly precipitation;
X_m: long-term mean;
σ: standard deviation.

Table 2. SPI values [46].

SPI value	Class
More than 2	Extremely wet
1.5 to 1.99	Very wet
1.0 to 1.49	Moderately wet
0 to 0.99	Mildly wet
-0.99 to 0	Milddly dry
-1.0 to -1.49	Moderately dry
-1.5 to -1.99	Severely dry
-2 and less	Extremely dry

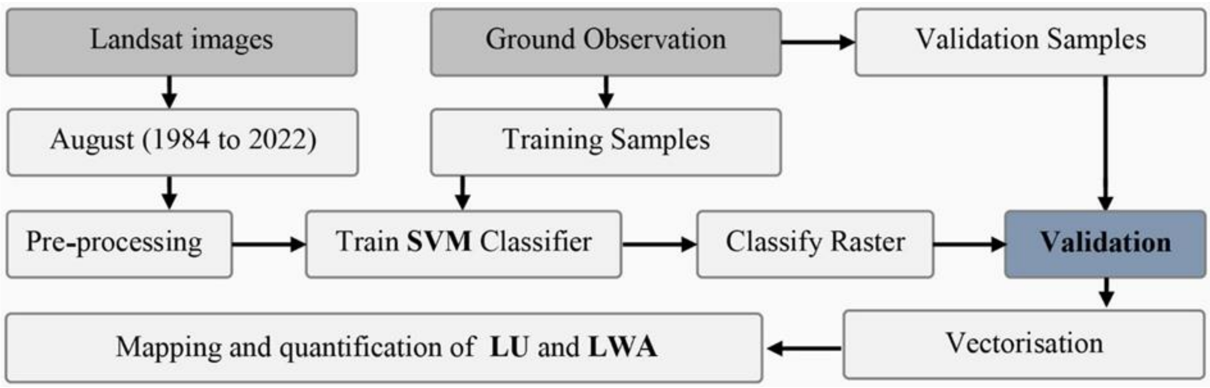

Figure 4. The flowchart of the used methodology for LU and LWA extraction.

3. Results and discussion

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

Monitoring the water area in Aoua and Ifrah lakes (Figure 5) 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 dynamism. The total area of the lakes has significantly decreased between 1984 and 2022, with a reduction of 70 ha for Aoua lake and 136 ha for Ifrah lake (Figure 6 and 7).

Figure 6a 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. These fluctuations range between 0 ha or complete drying and 116 ha. Over more than three decades, Aoua lake has experienced significant oscillations, with periods of complete drying (2001-2002; 2008; 2018 to 2022). In recent years, the hydrological deficit of the lake has increased worryingly. Locally, this is manifested by the total drying of the lake for an extended period (2018 to 2022). Before 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 2000, the water area has significantly decreased (2000-2003; 2005-2008; 2016-2022), with some exceptions of increasing in water area during specific periods, notably in 2004 (85 ha) and from 2009 to 2015. Figure 6b indicates the rapid variations in the surface area of Aoua lake. Over the years, the lake underwent significant changes, especially in 2003-2004, 2008-2009, and 2015-2016. These variations illustrate a rapid increase and decrease in lake water 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 to nearly full filling (116 ha) and vice versa occurs rapidly.

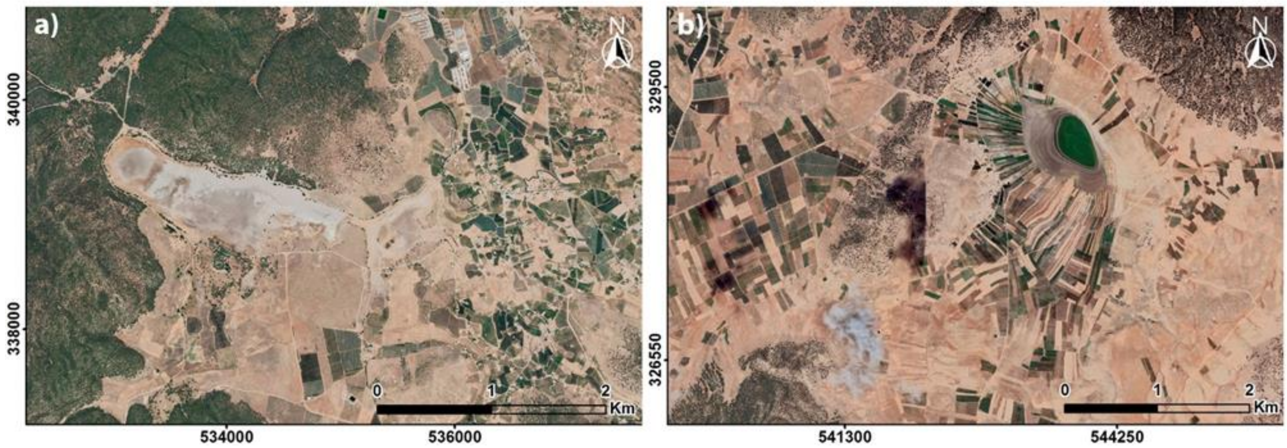

Figure 5. Situation of the lakes in July 2022 (Google Earth images). a) Aoua lake; b) Ifrah lake. The two maps show the alarming reduction of the water surface and the remarkable extension of irrigated areas around the lakes.

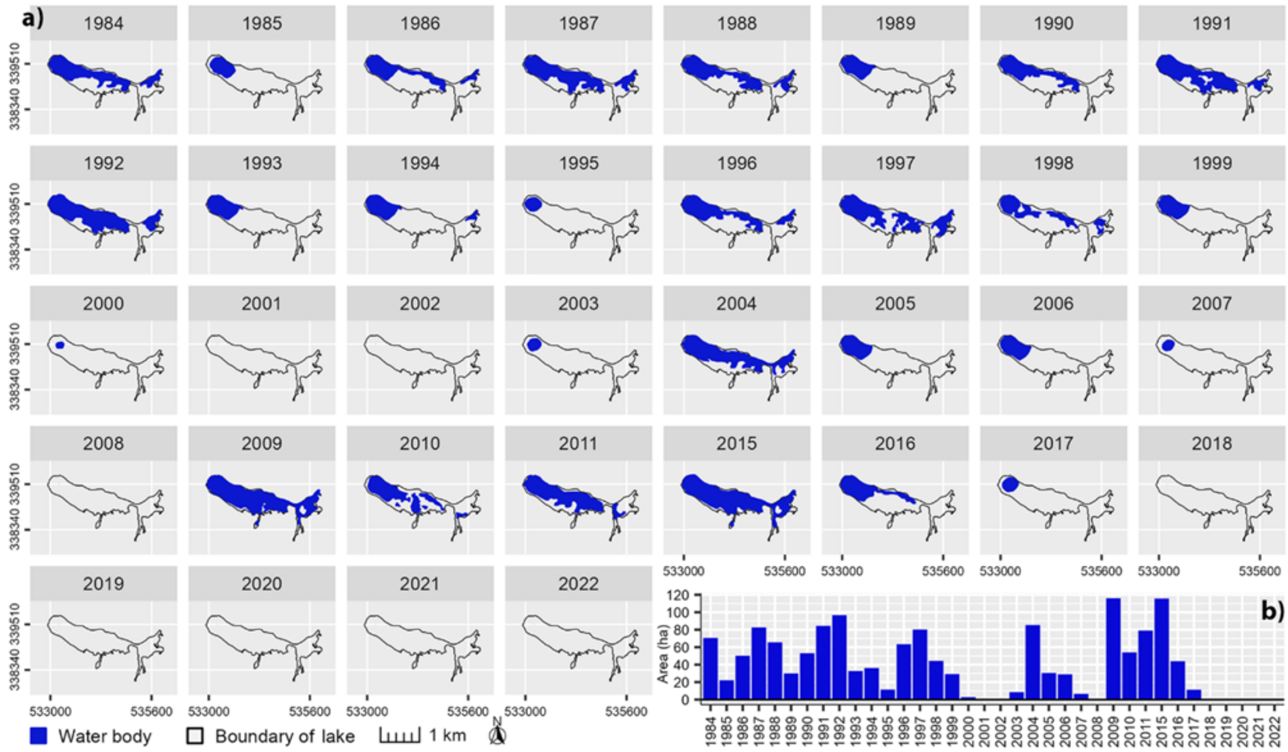

Figure 6. Variation in surface area (ha) of Aoua lake from August 1984 to August 2022 (Landsat satellite images: TM, OLI and OLI-2).

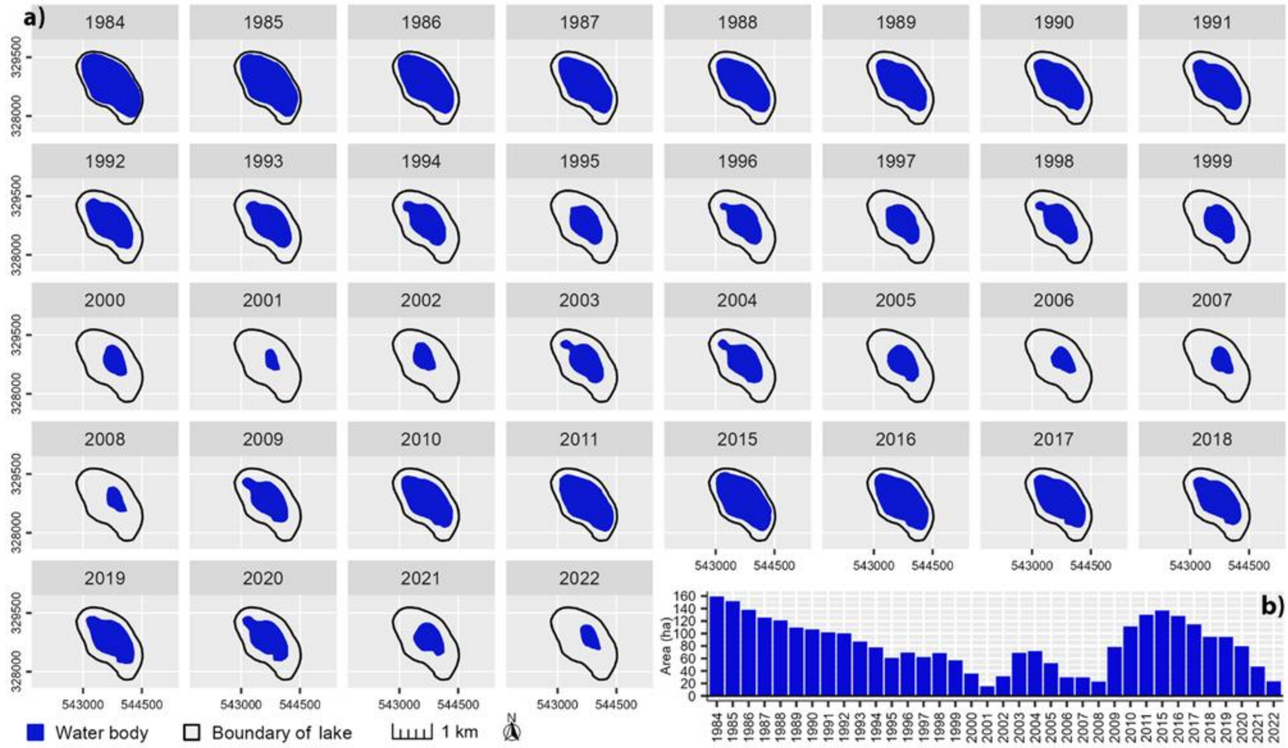

Figure 7. Variation in surface area (ha) of Ifrah lake from August 1984 to August 2022 (Landsat satellite images: TM, OLI and OLI-2).

Figure 7a shows the changes in the water area of Ifrah lake from August 1984 to August 2022. During this period, the lake fluctuated 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 reduction (2000-2008; 2021-2022). We distinguished three periods of variations in the lake water area. 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, from 2001 to 2008, experienced a slight increase in the water 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 7b illustrates that the reduction and progression of Ifrah areas occur slowly compared to Aoua lake, which is characterized by a rapid variation pattern.

The results obtained from Landsat satellite images indicate a significant decrease in the water area in both Aoua and Ifrah lakes. The continuous reduction 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 [49,50].

3.2.1. Drought severity

The calculation of SPI for Ifrane and Sefrou stations over 24 months shows wet and dry periods. The results presented in Figure 8 and 9 demonstrate that the wet and dry periods are more clearly visible for SPI 24 months (Figure 8) compared to SPI 12 months (Figure 9). For the stations of Ifrane and Sefrou, we distinguished two principal periods, from 1935 to 1979 and 1980 to 2015. 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, we observed a persistent drought characterized by extended periods, indicated by negative anomalies exceeding -2, interspersed with brief 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, even complete drying, occurs during severe drought periods.

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 [51,52]. The trend of decreasing precipitation, rising temperatures, and the progressive extension 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. Land use changes

Studies on the Middle Atlas confirm that this region of Morocco was primarily used for pastoral activities [17, 32,33, 53-55], 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. These transformations include the extension of irrigated agriculture and orchards at the expense of grazing lands and rainfed crop areas. The change rates, the processes implemented, and the actors involved in this dynamic have been different throughout this period [32].

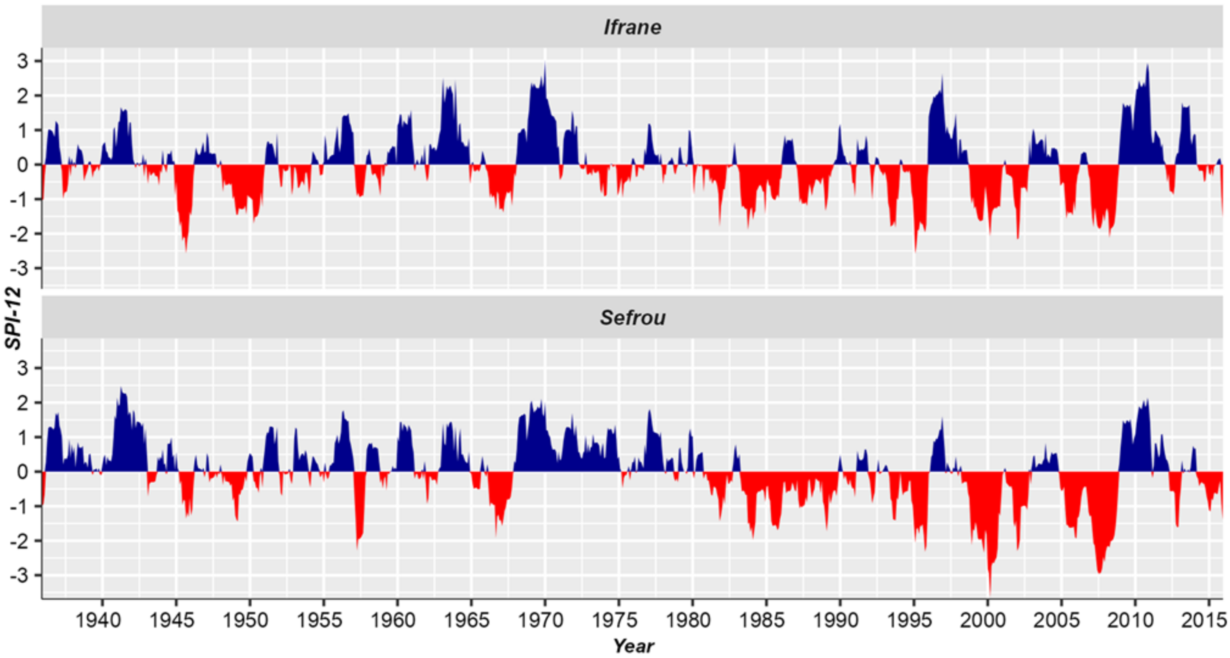

Figure 8. Temporal variation of the SPI at the 12-month scale in Ifrane and Sefrou stations.

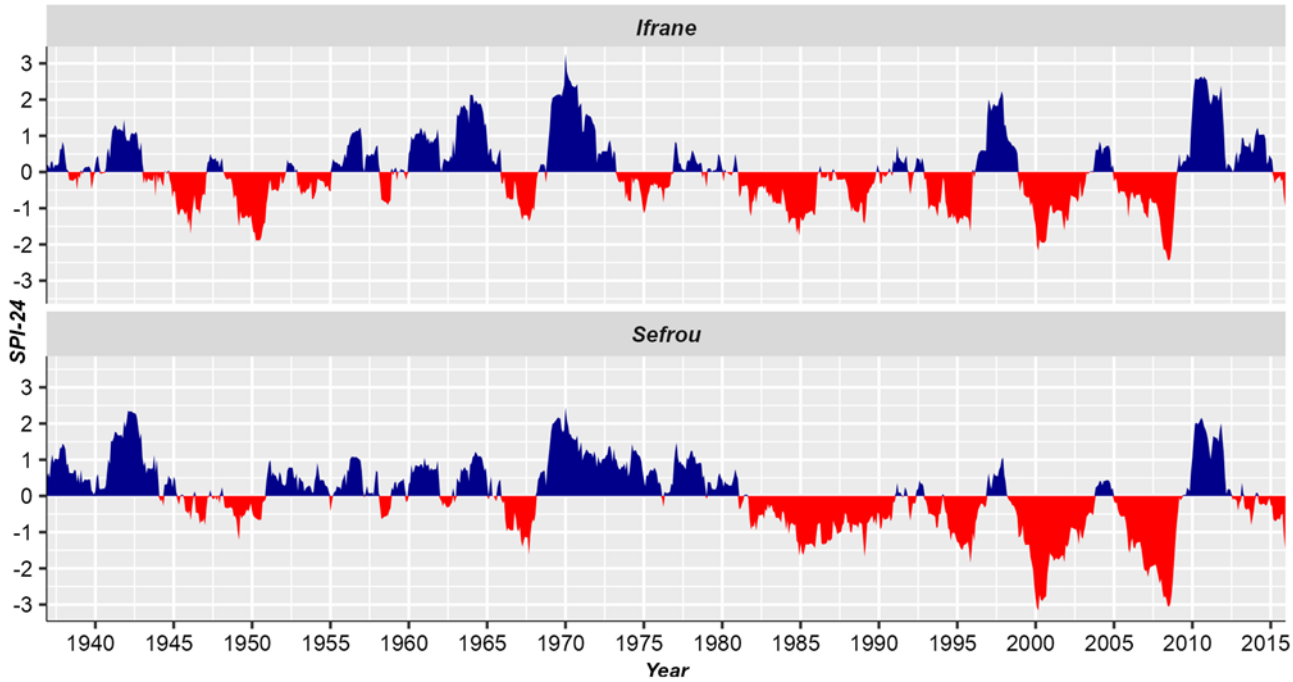

Figure 9. Temporal variation of the SPI at the 24-month scale in Ifrane and Sefrou stations.

Over the past decades, the Imouzzer and Aoua depressions have witnessed a continuous extension of agricultural practices based on irrigation. LU map derived from the Landsat image of August 2022 clearly shows a significant increase in irrigated areas compared to 1985 (Figure 10). 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 study area (Figure 10 and Table 3) have highlighted a significant landscape dynamic characterized by a marked increase in irrigated agricultural areas and built-up lands. 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 entire 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. Thus, we observed a notable increase in built-up within the study area, especially in the center of Imouzzer-Kandar. Between the two dates, the built-up area increased from approximately 33 ha to 287 ha, representing a growth of 254 ha. The forest area remains almost stable, with a slight estimated positive change of 0.19%.

Between 1985 and 2022, the study area experienced a significant landscape transformation, primarily characterized by a progressive increase in irrigated agriculture and built-up areas. The shift of population activities towards irrigation and adopting modern water exploitation techniques have led to the decline 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 widely contributed to the disruption of the hydrological regime. Consequently, the complete drying of Aoua lake for extended periods (2018-2022) reflects the deeply 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

While lakes are crucial surface water resources and rich ecosystems in biodiversity, they have experienced a significant shrinking over the past decades, endangering their ecological, biological, and landscape diversity. Studies on lakes indicate that this critical situation is primarily linked to the interaction of natural factors such as CC and anthropogenic factors like rapid urbanization, extension of irrigated areas, groundwater extraction, and dam construction. Consequently, changes in LU practices in the context of reduced rainfall and increased temperatures have accelerated the negative variation in lake water surface areas. Monitoring lake surface areas from satellite images in different countries reveals their alarming situation. In this context, Zhang et al. [56]

demonstrated that Ebinur lake has undergone drastic fluctuations, with a significant loss of water surface area. Between 2003 and 2015, the lake's surface area decreased from 817.63 km^2 to 384.60 km^2 in 2015, representing a decrease of over 50% of its surface. Davraz et al. [15] indicated that the water level of Burdur lake has consistently decreased. The lake's surface area experienced a remarkable shrinkage between 1975 and 2016, declining from 210 km^2 to 131 km^2, presenting a 37% reduction. Xu et al. [57] showed that, since the 1990s, many lakes in Inner Mongolia have significantly decreased with varying rates based on each lake's characteristics. In this study, we mapped the surface area of two lakes in the Tabular Middle Atlas to understand their responses to environmental changes, including climate and LU.

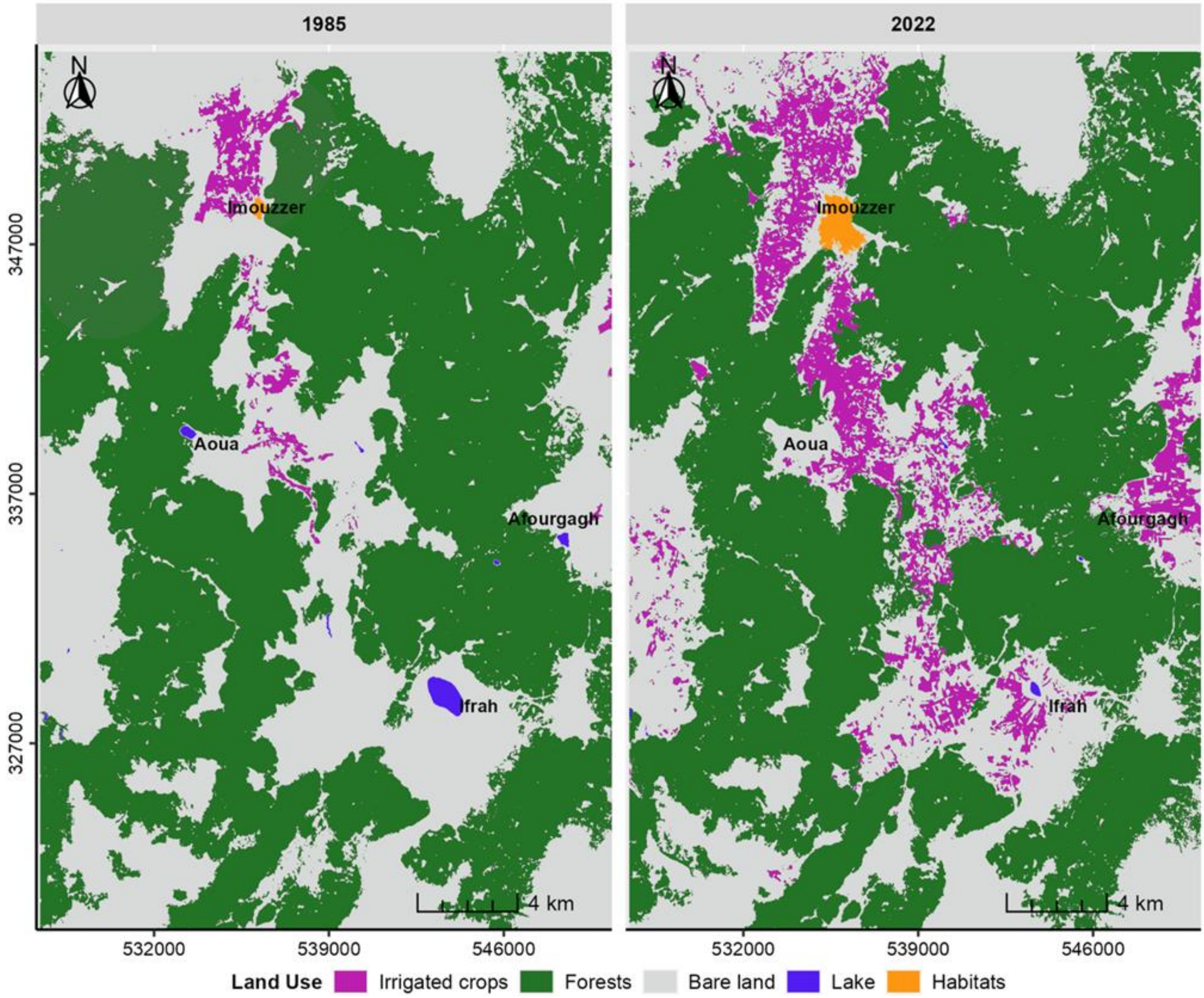

Figure 10. Changes of irrigated areas in Imouzzer and Aoua depressions (Landsat TM and OLI-2 satellite images).

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

LU classes	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 lands	32050	39.79	26055	32.35	-5995	-7.44
Lakes	205	0.25	27	0.03	-178	-0.22
Habitats	33	0.04	287	0.36	254	0.32

With multi-sensor Landsat satellite images (TM, OLI, and OLI-2), we studied changes in the LWA in the TMA over 38 years. The results 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. Recently, we have observed a general trend of decreasing lake surface area. Between 1984 and 2022, Aoua lake lost 100% of its area (from 70 ha to complete drying), and Ifrah lake lost 87% of its surface area (from 159 ha to 23 ha). This finding indicates that the pressure exerted on the lakes in the TMA region directly reflects a significant reduction in the water area, with periods of complete drying, endangering fragile ecosystems and biodiversity.

The highly critical situation of the lakes results from 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 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 SPI index). 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 situation highlights the need to formulate a strategy to mitigate the impacts of CC and reduce anthropogenic pressure.

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Author contributions

Abdelaziz El-Bouhali: Methodology, Software, Investigation, Data analysis, Writing – original draft. **Mhamed Amyay:** Supervision, Conceptualization, Writing – review & editing, Validation. **Khadija El Ouazani Ech-Chahdi:** Data analysis, Writing - Review & editing.

Conflicts of interest

The authors declare no conflicts of interest.

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