Revista de Estudios Andaluces (REA) | Núm. 48, julio (2024) | e-ISSN: 2340-2776
https://dx.doi.org/10.12795/rea.2024.i48 | © Editorial Universidad de Sevilla 2024
https://editorial.us.es/es/revistas/revista-de-estudios-andaluces
https://revistascientificas.us.es/index.php/REA

Combined impact of drought and land use changes on water resources in the Tabular Middle Atlas, Morocco

El impacto combinado de la sequía y los cambios en el uso del suelo sobre los recursos hídricos en el Tabular Atlas Medio, Marruecos

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INFO ARTÍCULO

Received: 19-02-2024
Revised: 25-04-2024
Accepted: 09-05-2024

KEYWORDS

Water resources
Drought
Irrigated areas
Tabular Middle Atlas

ABSTRACT

The quantitative degradation of water resources in the Tabular Middle Atlas is linked to climate and changes in agricultural practices. The relationship between these variables is identified through the analysis of hydroclimatic data, fieldwork, and the processing of Landsat satellite images in two representative sectors of the Middle Atlas. Interviews with local populations and piezometric measurements performed in the Guigou depression show that the groundwater table has dropped from a few meters deep to over 45 meters in several locations. Additionally, monitoring of the surface water area of Aoua lake between September 1984 and September 2022 from satellite images indicates remarkable variations, with periods of prolonged drying. The critical situation of water resources in this sector of Morocco is explained by the recurrence of drought periods of varying severity, increasing temperatures, and the progressive extension of irrigated areas across the depressions. In three decades, irrigated areas have multiplied by more than five in the Guigou depression and by more than three in the Imouzzer-Aoua depressions. Changes in climatic parameters associated with modifications in agricultural practices have strongly influenced water resources in the Tabular Middle Atlas.

PALABRAS CLAVE

Recursos hídricos
Sequía
Áreas irrigadas
Tabular Atlas Medio

RESUMEN

La degradación cuantitativa de los recursos hídricos en el Tabular Medio Atlas está vinculada al clima y a las modificaciones en las prácticas agrícolas. La identificación de la relación entre estas variables se aborda mediante el análisis de datos hidroclimáticos, el trabajo de campo y el procesamiento de imágenes satelitales Landsat en dos sectores representativos del Medio Atlas. Las entrevistas con la población y las mediciones piezométricas realizadas en la depresión de Guigou muestran que el nivel freático ha descendido de unos pocos metros de profundidad a más de 45 metros en varios lugares. Además, el seguimiento del área superficial del lago Aoua entre septiembre de 1984 y septiembre de 2022 a partir de imágenes satelitales indica que ha experimentado variaciones notables, con períodos de sequía prolongada. La situación muy crítica de los recursos hídricos en este sector de Marruecos se explica por la recurrencia de períodos de sequía de gravedad variable, el aumento de la temperatura y la extensión progresiva de las áreas irrigadas en todas las depresiones. En tres décadas, las áreas irrigadas se han multiplicado por más de cinco en la depresión de Guigou y por más de tres en las depresiones de Imouzzer-Aoua. Los cambios en los parámetros climáticos asociados a las modificaciones en las prácticas agrícolas han influido fuertemente en los recursos hídricos en el Medio Atlas Tabular.

DOI: https://dx.doi.org/10.12795/rea.2024.i48.10
Formato de cita / Citation: El-Bouhali, A., Amyay, M., & El Ouazani Ech-Chahdi, K. (2024). Combined impact of drought and land use changes on water resources in the Tabular Middle Atlas, Morocco. *Revista de Estudios Andaluces,*(48), 202-220. https://dx.doi.org/10.12795/rea.2024.i48.10
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1. INTRODUCTION

Climate and land use practices changes are factors that significantly affect water resources. In this context, several studies demonstrate that the degradation of groundwater is closely linked to climate change (Bahir *et al*., 2021; El Assaoui *et al*., 2021; Hughes *et al*., 2021; Secci *et al*., 2021). Others explain the ongoing degradation of groundwater as the result of a combination of observed climate changes over the past decades and increased pressure from anthropogenic activities due to changes in land use practices (Abera *et al*., 2019; Brunner *et al*., 2021; Samal & Gedam, 2021; Yifru *et al*., 2021; Pei *et al*., 2022). Thus, changes in climatic conditions, including decreased precipitation and the advancement of summer drought, have prompted farmers to increase the irrigation of agricultural lands to mitigate the issue of declining yields (Worqlul *et al*., 2019; Peltonen-Sainio *et al*., 2021; Ward, 2022).

During the last decades, the Mediterranean region has experienced significant socio-economic, spatial, and environmental dynamics (Delgado-Artés *et al*., 2022). Mountains and rural areas are considered among the most affected by these dynamics. Recent studies focusing on the Mediterranean region demonstrate the overall collapse of traditional activities and systems (Jiménez-Olivencia *et al.,* 2021; Delgado-Artés *et al*., 2022) and the increasing disconnection of populations from their ways of life. Furthermore, several Mediterranean landscapes are subjected to growing anthropogenic pressure (Ruiz *et al*., 2020; Quintas-Soriano *et al*., 2022) and continuous changes in land use (such as urbanization expansion and intensification of irrigation-based agricultural practices). Overall, socio-economic and socio-spatial changes at the scale of the Mediterranean region in the context of climate change have led to environmental degradation and exacerbated hydrological deficits. The progressive extension of irrigated agricultural land in the context of climate change has led to increased pressure on water resources. This pressure results locally in adverse impacts on the functioning of natural ecosystems (Majola *et al*., 2022), particularly lakes and wetlands. In the Mediterranean region, different optimistic and pessimistic scenarios indicate a decrease in precipitation, an increase in temperature (IPCC, 2018; Tramblay *et al*., 2020; De Girolamo *et al*., 2022), a decline in groundwater levels (Rocha *et al*., 2020; Al Atawneh *et al*., 2021), and a continuous extension of irrigated areas as a form of adaptation to climate change (Nunes *et al*., 2017) and as an essential measure to improve land productivity.

In Morocco, water resources in different regions have been the subject of several studies in recent years (El Assaoui *et al*., 2015; Bahir *et al*., 2020; Qadem *et al*., 2020; Ahmed *et al*., 2021; El Assaoui *et al*., 2021). The results indicate a continuous decline in the piezometric level of groundwater across the Moroccan territory (Souss Massa, El Gharb, Saïs, Middle Atlas, Tadla, Chtouka, etc.). Generally, the extent of groundwater degradation varies from one region to another depending on climatic and hydrogeological characteristics and the degree of exploitation. In some areas like Essaouira, the groundwater level has decreased by varying amounts between 5 meters and 17 meters over three decades (Bahir *et al*., 2021). In the Berrechid aquifer, the piezometric level continuously decreased between 1980 and 2008 (El Assaoui *et al*., 2015). In the Saïss aquifer, measurements conducted by the Sebou Hydraulic Basin Agency (ABHS) between 1968 and 2017 show a significant decrease in the groundwater table (ABHS *in* Qadem *et al*., 2020). The findings from these studies indicate that water resources have reached a critical stage. This situation may worsen in the coming years.

According to climate predictions, Morocco will record a continuous decrease in precipitation and an increase in temperature in the coming years (IPCC, 2013). This situation will lead to the degradation of precipitation-based activities, particularly rainfed agriculture, and consequently, an increased reliance on irrigation from groundwater resources. This concerning situation in a country already facing water stress (Seif-Ennasr *et al*., 2016) necessitates increased efforts and a deeper scientific understanding of the relationship between water, human activities, and climate change to propose adaptation strategies and water resource management measures that align with current realities and future scenarios. Overall, the scientific community agrees on the impacts of climate change and land use modifications on groundwater resources. Both factors (climate and land use) are considered the main drivers contributing to the decline in groundwater levels. Analyzing the three interdependent themes - land use, climate, and water - provides a solid foundation for planning and implementing land use projects and developing sustainable water resource management strategies and human activities.

 e-ISSN: 2340-2776 | doi: https://dx.doi.org/10.12795/rea.2024.i48.10

This study aims to emphasize the current status of water resources in the Tabular Middle Atlas by conducting piezometric measurements in the Guigou depression and tracking changes in the water surface area of Aoua lake. Thus, a discussion of the factors contributing to the quantitative degradation of water resources will be addressed, namely climate and land use. To achieve these objectives, we adopted an approach that relies primarily on fieldwork (piezometric measurements, land use inventory, and surveys with farmers), processing of Landsat satellite images (TM, OLI, and OLI2) to extract the water surface area of Aoua lake and detect changes in irrigated areas in two sectors of the Tabular Middle Atlas (Imouzzer-Aoua depressions and Guigou depression), as well as the analysis of precipitation data series using the standardized precipitation index (SPI) to determine drought periods.

2. STUDY AREA

The mountains hold a significant place in Morocco's geography. The Moroccan mountain ranges (High Atlas, Middle Atlas, Anti Atlas, and Rif) stand out for their rich ecological, landscape, historical, and cultural diversity. Over the past decades, they have experienced significant socio-spatial dynamics. This study focuses on the Tabular Middle Atlas, a pivotal feature of the Moroccan mountain ranges, commonly known as the "water tower of Morocco". Situated within the Sebou hydraulic basin, the study area (figure 1) is characterized by a highly faulted geological structure and the dominance of permeable lithological formations, notably limestone and dolomites (Bentayeb & Leclerc, 1977). These formations are located at altitudes ranging from 2 432 m at the Northern Middle Atlas Fault to 500 m in the Sais plain. Generally, they decrease from south to north. Altitudes in the study area are predominantly between 1 000 m and 2000 m. Despite the high altitudes, the low slopes (less than 10 degrees) constitute approximately 70% of the study area.

These physical characteristics promote better infiltration of precipitation water into karstic reservoirs. The Quaternary formations, which overlay the Lias formations, constitute valley bottoms and intramountain depressions (such as the Guigou, Imouzzer and Afourgagh depressions) in the form of slope erosion deposits. The study area is situated within the Middle Atlas plateau aquifer, delimited by the folded Middle Atlas to the south and the Fez-Meknes aquifer to the north and characterized by the presence of two types of aquifers: the limestone-dolomite aquifer of the Lias and the subdivided Quaternary basaltic aquifer (ABHS). These features result in a variety of water resources variety (springs, lakes, and wadis) that play a crucial role in the development of irrigation-based agricultural activities in the depressions of the Tabular Middle Atlas. Surface flows are low except for a few wadis linked to springs in the karst and basalt (Akdim *et al*., 2011). The spatial organization of the hydrographic network is characterized by low density in the permeable formations and relatively dense in the borders towards the North and West (Sais and Tigrigra plains). The heterogeneity of the spatial organization of flows in the study area is linked to the complex combination of topographic and hydrogeological factors. In the Tabular Middle Atlas, springs are concentrated in the limestone formations of the Lias, in the basaltic formations of the Quaternary, and areas of contact with other formations (transition zone with the Tabular Middle Atlas). The climate is Mediterranean, influenced by continentality and marked by a strong contrast between summer (hot) and winter (cold). Thus, the Middle Atlas is considered one of the rainiest areas in Morocco. The quantity of precipitation varies depending on the stations, with the highest values recorded at the Ifrane station (902 mm on average from 1980 to 2022).

Although the study area features filtering lithology, lakes can form in depressions filled with clay. It includes six lakes (Aoua, Ifrah, Afourgagh, Iffer, Hachelaf, and Sidi Mimoun), all located at an altitude exceeding 1 350 m. Their surface area ranges from 5 ha for Iffer lake to over 190 ha for Ifrah lake. The lakes of the Middle Atlas constitute wetlands of high ecological value. In recent years, they have experienced significant disturbances due to the intensification of anthropogenic activities and the succession of dry years. The various aspects of their degradation manifest locally through shrinkage in their water area and the complete drying out of several of them, such as the Aoua and Hachlaf lakes.

Until the 1980s, the Middle Atlas was an example of sparsely populated areas and subject to significant rural exodus. Agricultural land there was very limited except for a few irrigated areas (Jennan, 1986). In recent decades, the Middle Atlas has experienced a growth in rural populations and rapid expansion of cities (Ifrane, Imouzzer) and urban centers (Guigou, Timahdite). In the Middle Atlas, water is a decisive factor in the settlement of populations and the development of territories. For a long time, local populations have been trying to find the most suitable techniques for water management. Initially, they adopted traditional arrangements. Today, the strategies for sharing, mobilizing, and utilizing resources have experienced significant transformations. In parallel with the evolution of these techniques, intramountain depressions undergo very profound landscape, economic, environmental, and social modifications as a result of the combination of multiple natural and anthropogenic factors (El-Bouhali, 2023). The main aspects of transformations lie in the decline of traditional land use practices and the advancement of modern land exploitation techniques. Indeed, the Middle Atlas has transitioned from an economy based on conventional irrigation techniques for crops on river terrace lands to a society that employs new strategies, often drawing water from wells at depths exceeding a hundred meters. Additionally, it has shifted from a local economy centred on pastoralism to one based on advanced agriculture coupled with animal husbandry. The successive changes in land use in the Tabular Middle Atlas, within the context of precipitation deficits, have exerted significant pressure on water resources.

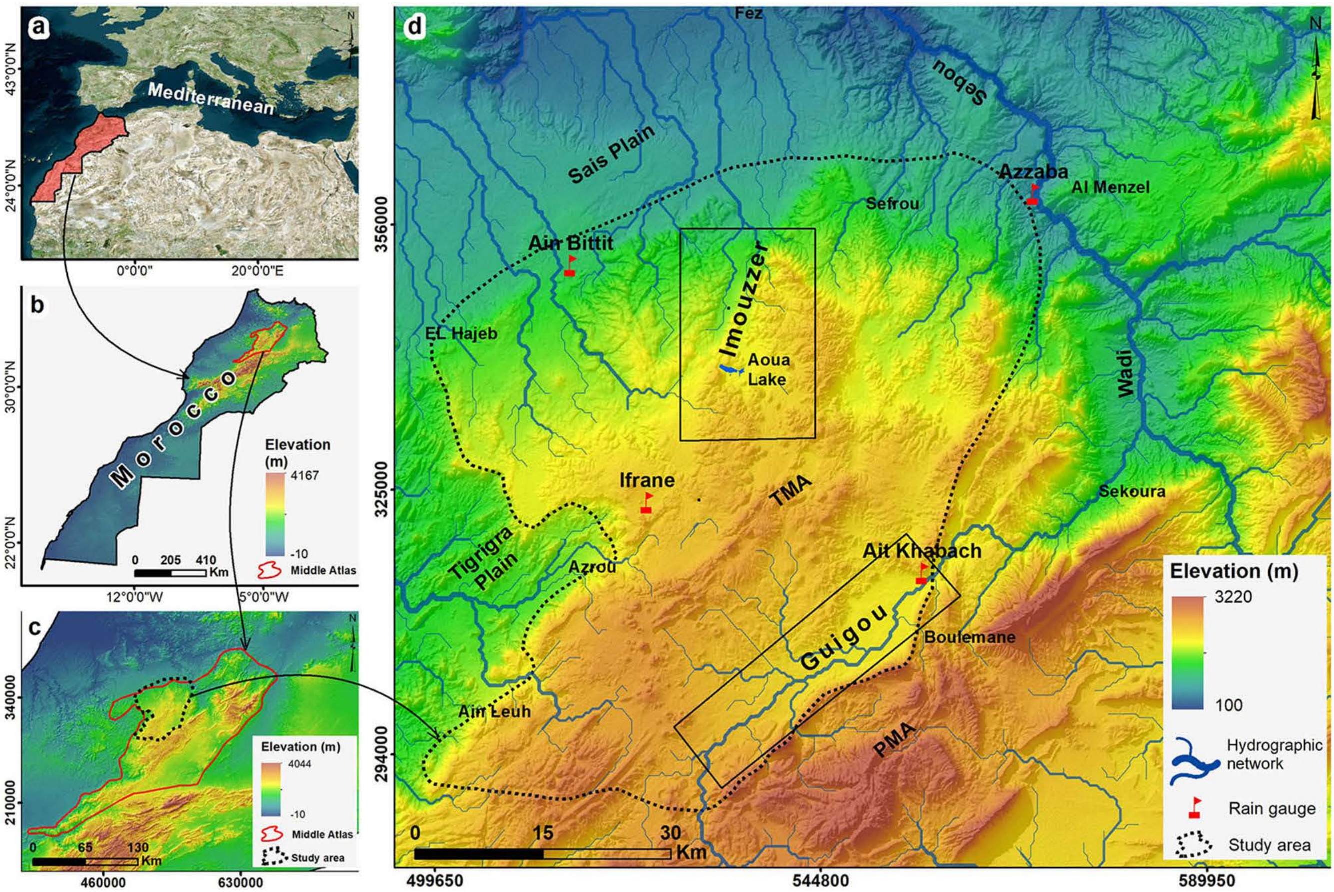

Figure 1. Geographical location of the study area. a) Location of Morocco in the Mediterranean region. b) Situation of the Middle Atlas within Morocco. c) Position of the study area within the Middle Atlas. d) Study area. TMA: Tabular Middle Atlas. PMA: Pleated Middle Atlas. Source: own elaboration based on Digital Elevation Model (30 m) and Google Earth satellite images.

3. METHODOLOGY AND DATA

The objectives highlighted in this study are addressed by utilizing multi-source and multi-date data (satellite images, climatic data, fieldwork) and following a multidisciplinary methodology. The processing of data and the application of methodological steps were based on R-statistical software and geographic information systems (GIS). The exploitation of data from various sources has allowed for outlining the situation of water resources in the Tabular Middle Atlas and providing crucial information on the factors contributing to their quantitative degradation.

3.1. Inventory of land use and piezometric measurements

The identification of the dynamics of irrigated areas in the Tabular Middle Atlas required identifying the different land use classes in the depressions selected for this study. Successive field missions have revealed that the Imouzzer-Aoua depressions are characterized by a significant prevalence of rosaceous orchards (apple, peach, nectarine, etc.). Additionally, the Guigou depression is notable for the extension of irrigated vegetable crops (potato, onion, carrot, etc.). On a high-resolution spatial map (figure 2a), we located the different land use classes in the studied depressions. Thus, we used the samples collected directly in the field for land use classification. In March 2020, we conducted piezometric measurements in the Guigou depression using a piezometric probe (figure 2b). The data from these measurements serve as a basis to illustrate the piezometric level of the groundwater table in different locations of the Guigou depression. Concurrently with the measurements, we conducted interviews with the local populations about the current and past water resources situation. We used the information obtained from the surveys to address the issue of data on the historical situation of the Guigou groundwater table.

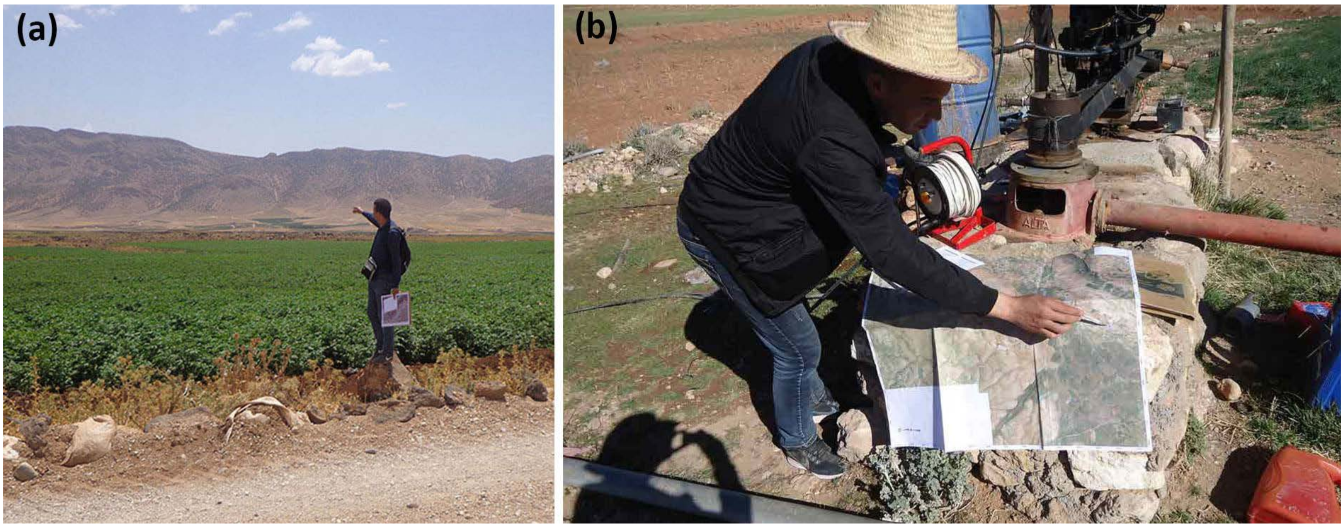

Figure 2. Illustration of the fieldwork in the Guigou depression. a) Identification of land use classes (August 2018). b) Conducting piezometric measurements and locating wells (March 2020). Source: authors.

3.2. Satellite data processing

Remote sensing provides crucial data for producing land use maps in many locations worldwide and under various environmental conditions (Thenkabail *et al*., 2009; Xie & Lark, 2021). The advancement of geographic information systems (GIS) and remote sensing has contributed to a sustained increase in publications in the field of land cover mapping at various scales: local, regional, and continental (Bhatnagar *et al*., 2020; Bretreger *et al*., 2020; Maselli *et al.,* 2020). While most remote sensing studies utilize satellite imagery to study land cover comprehensively, few explicitly include irrigation as a distinct class (Xie & Lark, 2021). Alongside the increased availability of satellite data (Landsat, MODIS, Sentinel), researchers have developed machine learning algorithms (Support Vector Machine, Random Forest, Maximum Likelihood, etc.) and spectral indices (Normalized Difference Vegetation Index, Soil Adjusted Vegetation Index, Normalized Difference Water Index, Enhanced Vegetation Index, etc.) to extract information from raw satellite images.

In this study, we used Landsat satellite images (TM, OLI, and OLI-2) to extract irrigated areas in two sectors of the Tabular Middle Atlas and to monitor the water surface area of Aoua lake. These images are freely available on the U.S. Geological Survey website (https://earthexplorer.usgs.gov). To map the variation in the water surface area of Aoua lake, we exploited Landsat satellite images from September 1984 to September 2022 (table 1). Remote sensing data has been widely accepted as an effective means to extract changes in

 e-ISSN: 2340-2776 | doi: https://dx.doi.org/10.12795/rea.2024.i48.10

water bodies worldwide, and several researches have demonstrated their capacity in lake studies (Eid *et al*., 2020; Wang *et al*., 2020; Jumaah *et al*., 2022; Su *et al*., 2023). The extraction of information regarding Aoua lake over 36 years was conducted by calculating the Normalized Difference Water Index based on Equation 1 (Eq. 1).

$$NDWI = (Green - NIR) / (Green + NIR) \quad (Eq. 1)$$

Where, NDWI: in the Normalized Difference Water Index, Green: Visible Green (Landsat TM: band 2, Landsat OLI and OLI-2: band 3), NIR: Near Infrared (Landsat TM: band 4, Landsat OLI and OLI-2: band 5).

Table 1. Landsat satellite images (TM, OLI and OLI-2) used to extract water surface area of Aoua lake.

Acquisition date	Sensor	Acquisition date	Sensor	Source	Spatial resolution
September 12, 1984	TM	September 16, 2002	TM	USGS	30 m
September 22, 1985	TM	August 23, 2003	TM	USGS	30 m
September 09, 1986	TM	August 25, 2004	TM	USGS	30 m
September 12, 1987	TM	September 22, 2005	TM	USGS	30 m
September 07, 1988	TM	September 25, 2006	TM	USGS	30 m
September 01, 1989	TM	September 19, 2007	TM	USGS	30 m
September 13, 1990	TM	September 14, 2008	TM	USGS	30 m
August 22, 1991	TM	September 08, 2009	TM	USGS	30 m
August 24, 1992	TM	September 04, 2010	TM	USGS	30 m
September 05, 1993	TM	September 14, 2011	TM	USGS	30 m
September 08, 1994	TM	September 18, 2015	OLI	USGS	30 m
September 27, 1995	TM	September 11, 2016	OLI	USGS	30 m
September 13, 1996	TM	September 07, 2017	OLI	USGS	30 m
September 23, 1997	TM	September 13, 2018	OLI	USGS	30 m
September 03, 1998	TM	September 29, 2019	OLI	USGS	30 m
September 22, 1999	TM	September 15, 2020	OLI	USGS	30 m
September 08, 2000	TM	September 02, 2021	OLI	USGS	30 m
September 18, 2001	TM	September 05, 2022	OLI-2	USGS	30 m

Source: all data are available on the USGS website https://earthexplorer.usgs.gov TM: Thematic Mapper, OLI: Operational Land Imager, OLI-2: Operational Land Imager-2.

To track changes in irrigated areas over time, we used Landsat TM and OLI images taken in August 1985, 1998, 2010, and August 2018 (table 2). Indeed, August corresponds to the maturation period of irrigated crops and the high demand for water for irrigation. Quantifying the dynamics of irrigated areas at the scale of two sectors of the Tabular Middle Atlas (Guigou depression and Imouzzer-Aoua depressions) was based on supervised classification using the Support Vector Machine (SVM) algorithm, widely used in remote sensing. This non-parametric algorithm is characterized by its accuracy in classification results using a small number of training samples (Zheng *et al*., 2015). A detailed explanation of the methodological steps followed for the extraction and quantification of irrigated areas from satellite images falls within the objectives of this study.

 e-ISSN: 2340-2776 | doi: https://dx.doi.org/10.12795/rea.2024.i48.10

Table 2. Landsat TM and OLI satellite images used to extract irrigated areas in the Tabular Middle Atlas depressions.

Acquisition date	Sensor	Source	Spatial resolution
August 14, 1985	TM	USGS	30 m
August 02, 1998	TM	USGS	30 m
August 03, 2010	TM	USGS	30 m
August 09, 2018	OLI	USGS	30 m

Source: all data are available on the USGS website https://earthexplorer.usgs.gov

Remote sensing data provided by space agencies require preprocessing to facilitate automatic classification and visual interpretation. The Landsat satellite images (TM, OLI and OLI-2) selected for this study undergo radiometric and atmospheric preprocessing. Radiometric correction of the satellite images converts the raw pixel values to top-of-atmosphere (TOA) reflectance. Furthermore, we used the Dark Object Subtract 1 (DOS 1) model to perform atmospheric correction, which helps remove atmospheric effects. The radiometric and atmospheric corrections were executed using the Semi-Automatic Classification Plugin (SCP) integrated into the QGIS software. This widely-used package in the remote sensing field (Obodai *et al.,* 2019; Congedo, 2021) provides a practical solution that simplifies and automates the preprocessing processes for various types of satellite images (Landsat, Sentinel, etc.).

3.3. Characterization of drought

Changes in climatic parameters can have immediate and lasting repercussions on the environment and humans at various scales. The study of climate variability relies on the application of several methods. In this work, we based the statistical analysis of rainfall data from the Sebou Hydraulic Basin Agency on the Standardized Precipitation Index (SPI) (McKee *et al*., 1993). This index, recommended by the World Meteorological Organization (WMO), is used in over 70 countries (WMO, 2012) to study drought at different time scales (1, 3, 6, 12, and 24 months). These scales allow for distinguishing between meteorological droughts (1 month), agricultural droughts (3 to 6 months), and hydrological droughts (12 and 24 months). Thus, the SPI is widely used to assess drought severity based on precipitation data. The drought severity varies according to the index values, with negative values (starting from -1.0) indicating drought periods, which end when the index anomalies become positive. The time scale choice for calculating the SPI depends on the study objective; shorter durations may be valuable for studying agricultural drought, while longer durations are suitable for studying hydrological drought. To illustrate hydrological drought in the study area, we analyzed the SPI at a 24-month scale from 1980 to 2017. The SPI calculation was based on the SPEI package installed in the R-statistical software. We computed the SPI index using the following equation (Eq. 2):

$$SPI = (x_i - x_m) / \sigma \quad \text{(Eq. 2)}$$

Where, SPI: is the Standardized Precipitation Index, x_i: is the precipitation of the selected period during the year i, x_m: long-term mean precipitation, σ: standard deviation for the selected period.

4. RESULTS

The consequences of rainfall deficit and pressure from anthropogenic activities on water are observed in several regions of Morocco (El Assaoui *et al*., 2015; Qadem *et al.*, 2020; Bahir *et al.,* 2021). In the Tabular Middle Atlas and the areas surrounding it, the condition of water resources has become very critical over the past few decades. This situation results in a worrying decline in the groundwater level (Middle Atlas Lias aquifer, Fez Meknes aquifer), a sharp drop in the flow rates of springs and streams, and a remarkable variation in the surface area of lakes. The highlighting of the water resources situation is illustrated through the analysis of data measured by the Sebou Hydraulic Basin Agency in the Tabular Middle Atlas and its environs, piezometric measurements carried out in the Guigou depression, and the detection of changes in the surface area of Aoua lake using Landsat satellite images over the period from September 1984 to September 2022.

4.1. The piezometric level of the Tabular Middle Atlas and its environs

In the Tabular Middle Atlas, the piezometric level of groundwater varies depending on hydrogeological characteristics and altitudes. Observing a piezometric map realized by the Sebou Hydraulic Basin Agency (ABHS, 2010) reveals a remarkable difference in piezometric levels between low and high altitudes. The closest levels to the ground are located in the Afourgagh and Laanoucer depressions and the contact areas between the Tabular Middle Atlas and the Fez-Meknes aquifer. The deepest groundwater levels are found in the Imouzzer-Aoua and Guigou depressions. In the Tabular Middle Atlas, groundwater levels are declining. In the lack of accurate data on the groundwater levels, we based our analysis on precise indicators collected directly in the field. We used data on well depth to illustrate the concerning situation of water resources. Surveys conducted by Chrif El Idrissi, (2019) in the Imouzzer depression and by Qadem, (2015) in the Guigou depression indicate that wells are subject to deepening operations to meet water needs, particularly for agricultural irrigation. In the Imouzzer depression, farmers have deepened their wells, with 33% of them adding between 15 m and 20 m in depth after the initial digging. In the Guigou depression, the added depth exceeds 30 m, and most farmers have added less than 15 m. Thus, the authors demonstrate that well-deepening operations have significantly increased since 2000.

The piezometric measurements conducted by the ABHS (figure 3) between 1982 and 2017 indicate a significant decline in the Fez-Meknes aquifer over the past three decades. It decreased from approximately 10 m in 1982 to 40 m in 1998, with a relatively slow rate of decline during this period. From 2000 onwards, the level of the Fez-Meknes aquifer experienced a rapid downward trend, dropping from around 40 m to over 100 m deep by 2017. The piezometric level of the aquifer reflects the alarming condition of water resources in the vicinities of the Tabular Middle Atlas. Over 35 years, the aquifer has transitioned from 10 m to over 100 m, with an evolution rate of approximately 2.5 m per year.

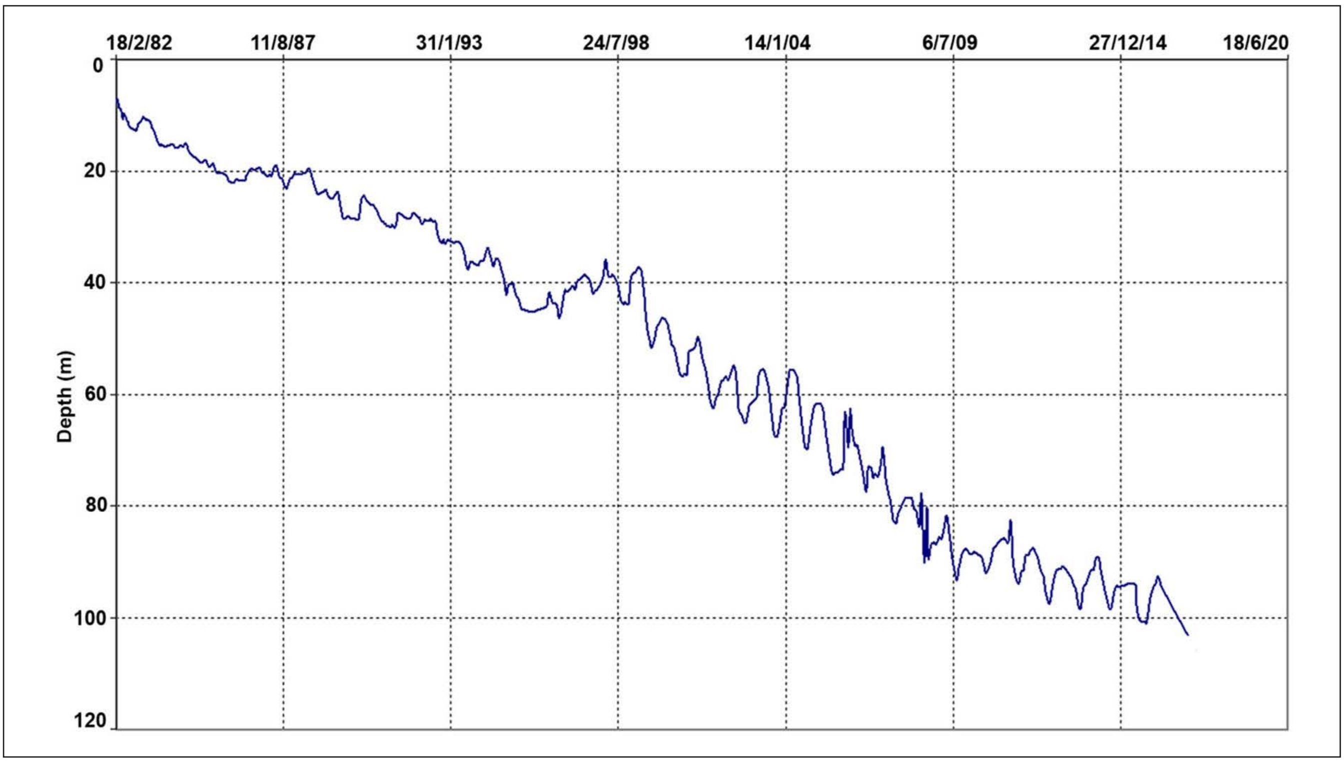

Figure 3. Evolution of the piezometric level in the Fez Meknes aquifer between 1982 and 2017. Source: own elaboration based on Sebou Hydraulic Basin Agency, Data accessed, January 31, 2024.

4.2. The piezometric level of the Guigou depression

At national and international scales, groundwater resources are experiencing a worrying decline (Brunner *et al*., 2021; Bahir *et al.,* 2021). Generally, there is consensus on the alarming current situation and concerning future threats. In this context, the investigation of groundwater resources has become paramount. Overall, the study of aquifers relies on both direct and indirect methods depending on the study's context, data availability, and tools (El Assaoui *et al*., 2021). In this study, the highlighting of the groundwater resource situation in the Guigou depression is based on piezometric measurements and interviews conducted with local populations regarding the current and past state of the aquifer. Collecting data directly from the field allowed us to overcome the issue of groundwater measurement availability and to demonstrate the alarming situation of the aquifer in the Guigou depression.

The responses obtained from interviews with farmers indicate the alarming decline of the Guigou aquifer since the 1980s. The deepening of wells serves as a precise indicator of the aquifer's decline. The depth of a well in 1984 was 6 m, and it increased to 89 m in 2020 (fieldwork data). Additionally, surveys conducted by Qadem, (2015) show that wells in the Guigou depression undergo deepening operations after initial excavation. Although the deepening of wells began in the 1990s (El-Bouhali, 2023), it experienced a notable increase between 2000 and 2010. During ten years (2000 to 2010), approximately 70% of respondents deepened their wells (Qadem, 2015) to reach the deeper aquifer level. The Guigou depression currently features multiple basins for collecting water pumped from the aquifer, as many wells have become incapable of supplying a pump for a sufficient duration for irrigation. Thus, in areas of depression distinguished by a deep piezometric level, farmers use another technique to ensure crop irrigation. This involves transporting water from locations where the piezometric level is shallower. These changes in irrigation techniques have allowed farmers to adapt to the decline of the water table and ensure crop irrigation in the Guigou depression.

The piezometric measurements conducted in the Guigou depression in March 2020 are presented in figures 4 and 5. The spatial distribution of the measured wells shows that the piezometric level varies depending on the locations, based on topographic and lithological characteristics, ranging from 7 m (minimum value) to 68 m (maximum value). Wells with levels close to the ground ([< 15 m]) represent 12% of the measured wells and are located in Ait Khabach. Along the Guigou Wadi, the piezometric level varies between 15 m and 30 m, constituting 48% of the measured wells and dominating the study area. The deepest piezometric levels ([30 - 45 m] and [> 45 m]), exceeding 30 m, account for approximately 30% of the measured wells and are mainly located on the left bank of the Guigou Wadi. Although the water table level in the Guigou depression was very close to the ground during the 1980s (El-Bouhali, 2023), it has become profound in recent years. The continuous decline in the water table level has led to the emergence of abandoned wells in several areas of the depression (representing approximately 10% of the measured wells). The appearance of abandoned wells is linked to the critically low water table and the insufficient economic capabilities of farmers to deepen the wells. The Guigou depression is just one example of groundwater degradation in the Middle Atlas. Studies conducted across Morocco also indicate a trend of dipping groundwater levels (El Assaoui *et al.,* 2015; Bahir *et al*., 2021). The consequences of declining groundwater levels include the drying up of lakes and the alarming decrease in spring and Wadi flows.

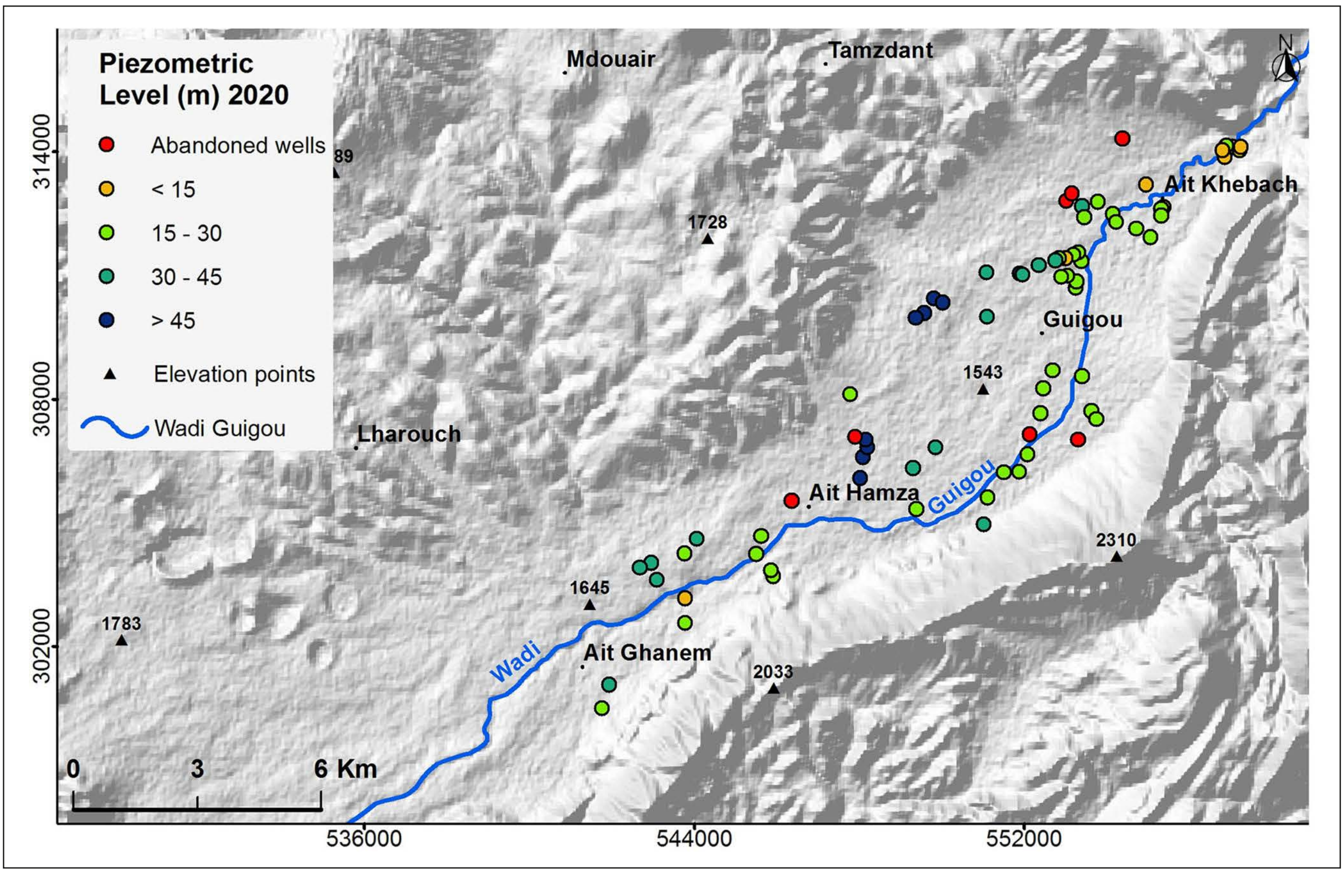

Figure 4. Distribution of the piezometric level in the Guigou depression (measurements conducted using a piezometric probe in March 2020). Source: own elaboration based on piezometric measurements conducted in the Guigou Depression in March 2020.

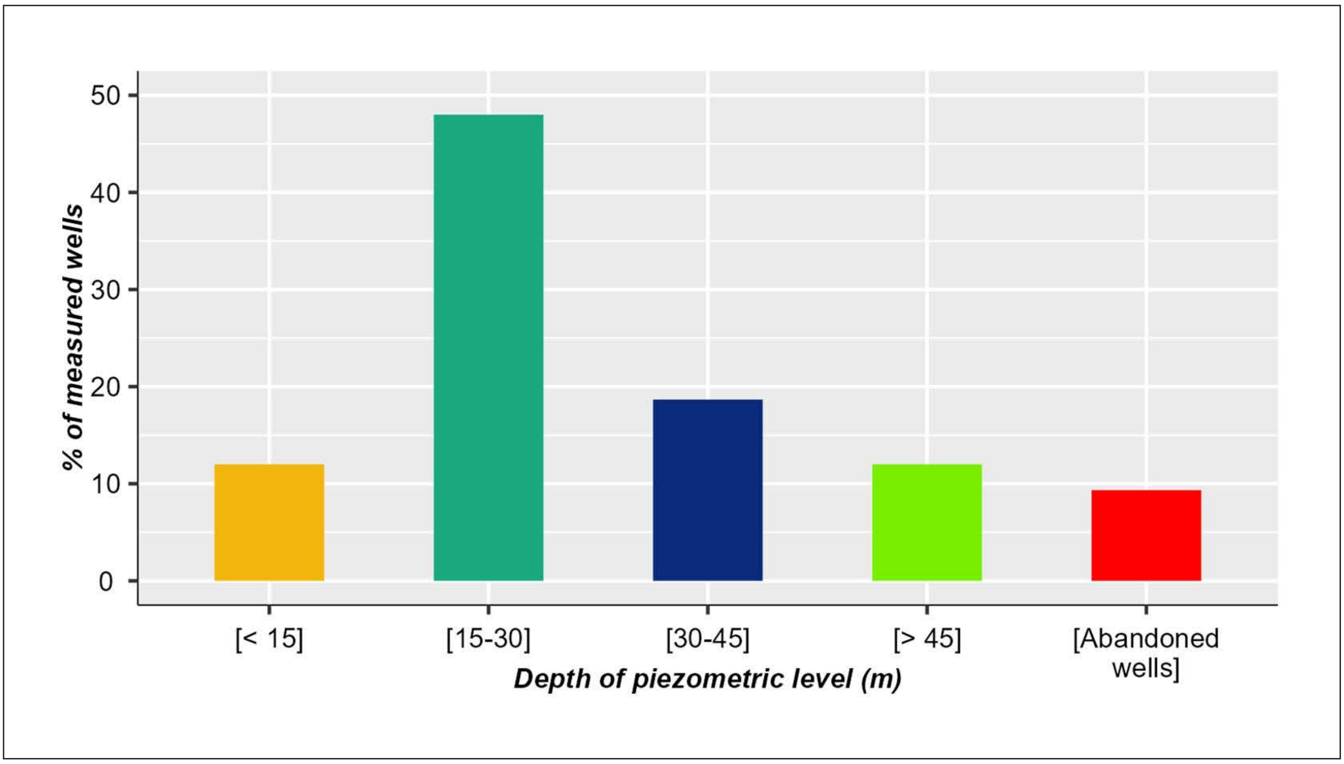

Figure 5. Piezometric level classes (m) in the Guigou depression in March 2020. Source: own elaboration based on piezometric measurements conducted in the Guigou Depression in March 2020.

4.3. Changes in the water surface area of Aoua lake

Ecosystems dependent on groundwater, particularly lakes, have experienced a notable decrease in water surface area and ecological diversity (Krogulec, 2018; Erostate *et al*., 2020). The most adverse aspects of lake degradation are evident in the gradual shrinking of their surfaces. With the increasing effects of climate change (reduced rainfall, drought severity, rising temperatures) and anthropogenic pressure (changes in land use patterns), these systems are receiving significant attention (Huntington *et al*., 2016). Over the past decades, lakes located in the Tabular Middle Atlas (Aoua, Ifrah, Afourgagh, Iffer, Hachelaf, and Sidi Mimoun) have experienced significant regression, but the rate of change varies depending on the hydrogeological characteristics of each lake and the extent of exploitation. In this strategic sector of Morocco, known as the "water tower of Morocco," lake levels have fluctuated dramatically, showing a downward trend and, in some cases, complete drying in recent years (El-Bouhali, 2023).

The monitoring of the water surface area in Aoua lake from September 1984 to September 2022 using Landsat satellite images shows that it recorded remarkable variations. During the study period, the lake transitioned from nearly filled to drying out over a long period. Figure 6 depicts the water surface area of Aoua lake over more than three decades. From September 1984 to September 1999, the lake experienced significant changes, with the surface area varying between 76 hectares in 1987 and 12 hectares in 1999. Over 16 years, the water surface area of Aoua lake remained above 10 hectares. From 2000 to 2008, the lake experienced drying periods, notably from 2000 to 2002 and 2007 to 2008. During this period, the water surface area in Aoua lake increased significantly, ranging from 7 hectares in 2003 to 31 hectares in 2004. Although Aoua lake was dry in 2008, it quickly expanded to reach an area of 77 hectares in 2009 and 98 hectares in 2010. This phase was followed by a gradual shrinkage of the Aoua lake water surface area until 2016 (19 hectares). From 2017 to 2022, this lake experienced worrying drying, the most severe during the study period. This situation indicates that in recent years, the hydrological deficit of the lake has increased alarmingly. It represents a long-term drying from september 2018 to September 2022. Thus, the water surface area monitoring demonstrates that Aoua lake exhibits rapid fluctuations. From one year to the next, the lake experienced evident changes (2008 - 2009, 2015 - 2016). This involves rapid extension and shrinkage of the water's surface area. The transition from drying up to nearly filled and vice versa occurs very quickly. In the Middle Atlas region, the degradation of lakes and the decline of wetlands reflect the highly critical situation of water resources under the influence of unfavorable climatic conditions and increasing anthropogenic pressure.

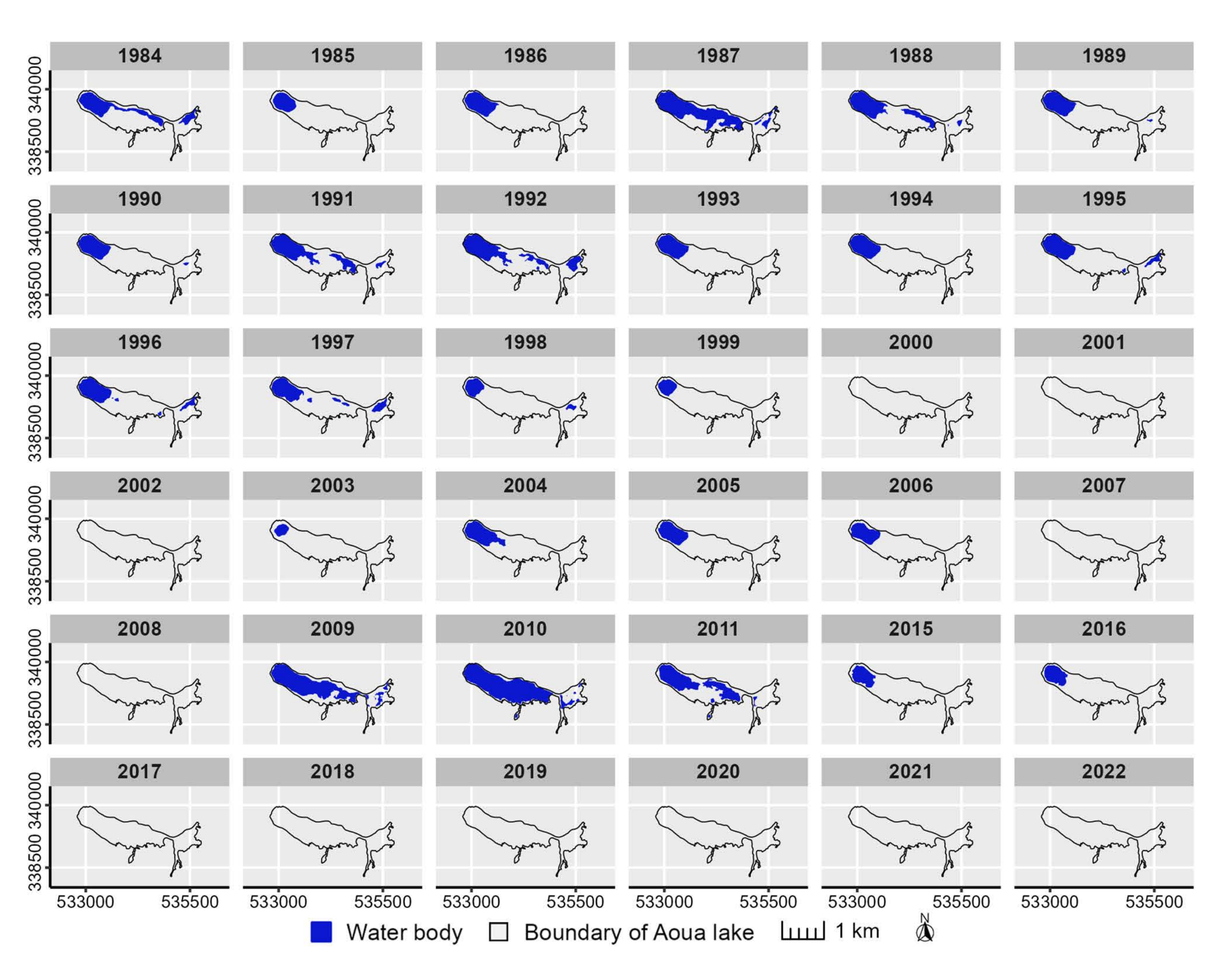

Figure 6. Changes in the water surface area of Aoua lake from September 1984 to September 2022. Source: own elaboration on based processing Landsat TM, OLI, and OLI-2 satellite images.

5. DISCUSSION

The Middle Atlas and its surroundings provide a typical example of the quantitative degradation of surface and groundwater resources. Results obtained from the analysis of official data, fieldwork, and processing of Landsat satellite images indicate that water stress has reached an advanced stage. Changes in water resources offer significant indicators of climatic conditions and anthropogenic pressure. Decreasing rainfall, rising temperatures, and the gradual extension of irrigated agricultural areas in the depressions of the Tabular Middle Atlas have significantly impacted water resources. Alongside the extension of irrigated areas, the demand for irrigation water increases, especially during the summer, exerting intense pressure on groundwater aquifers. The intensification of irrigation and the continuous growth in extraction volumes in the context of rainfall deficits have widely contributed to the disruption of the hydrological regime in the study area.

In several regions of Morocco, water resources have undergone significant variations. Bahir *et al.* (2021) demonstrated that the Essaouira aquifer experienced variable declines ranging from 5 m to 17 m depending on aquifer characteristics from 1976 to 2019. In the Berrechid aquifer, El Assaoui *et al.* (2015) indicated a concerning situation between 1980 and 2008, with declines reaching 20 m in some areas. In 2024, the Ministry of Equipment and Water (MEE) reported that several aquifers underwent notable declines between September 2022 and August 2023. The highest descent was observed in the Tadla aquifer (-5 m), followed by the Beni Amir and Sous aquifers (-4 m) and the Chtouka aquifer (-5 m). The critical state of water resources compelled responsible authorities to launch an emergency program to ensure water needs at the national scale (MEE, 2024). The evolution of piezometric levels in aquifers and surface water resources is closely linked to climate changes and exploitation levels. To better understand the driving factors contributing to the degradation of water resources in the study area, we analyzed climate and land use.

5.1. Effect of climate on water resources

The modifications in climatic parameters (precipitation and temperature) can have detrimental effects on water resources. In Morocco, the precipitation deficit has led to a severe climatic drought since the 1980s (Esper *et al*., 2007; Stour & Agoumi, 2008). To assess hydrological drought in the study area, we computed the Standardized Precipitation Index (SPI) over 24 months for four climatic stations (Ifrane, Ain Bittit, Ait Khabach and Azzaba). The results (figure 7) indicate that the period from 1980 to 2017 experienced several drought periods across all stations. Negative SPI values indicate drought, while positive anomalies define wet conditions. The SPI-24 values also illustrate a similar pattern of drought variability, albeit with variations in severity. The succession of drought periods has led to hydrological drought in the Tabular Middle Atlas and its borders. The decline in groundwater levels and the drying of lakes reflect the severity of drought over the last decades. The observed precipitation deficit since the 1980s has significantly impacted groundwater levels. The correlation between precipitation data and piezometric level by Qadem *et al.* (2020) indicates a robust relationship between the two variables, with an R^2 greater than 0.9 for both stations (Fez and Ifrane) correlated with three piezometers located in the Fez Meknes aquifer. The level of agreement between variables suggests that decreased precipitation contributes to the quantitative degradation of groundwater resources, resulting in negative consequences for surface water resources such as lakes, wadis, springs, etc.

The comparison between the water surface area of Aoua lake and the SPI 24-month at the Ifrane station from 1984 to 2022 (figure 8) has shown the impacts of drought on water resources. From September 1990 to September 1999, the water surface area of Aoua lake experienced remarkable fluctuations. Between 2000 and 2008, the lake reached a critical level, with periods of drying up (2000 to 2002 and 2007 to 2008). This situation coincided with periods of long-term drought. The return of wet conditions from 2009 to 2015 contributed to the increase in the water surface area of Aoua lake (98 ha in 2010). From 2016 to 2022, the SPI-24 indicates the return of a severe drought period that contributed to the long-term drying up of the lake (6 years). Although until 1999, the drought periods were relatively long, Aoua lake did not completely dry up. From 2000 to 2022, its experienced periods of drying up. This situation can be explained by the recurrence of drought and the increasing pressure on groundwater to ensure irrigation of irrigated agricultural surfaces throughout the Imouzzer-Aoua depressions.

In parallel with the decrease in precipitation over a long period, temperatures have shown a marked increase. Annual temperature data measured by the National Oceanic and Atmospheric Administration (NOAA) suggest an evident rise in positive temperature anomalies from the late 1970s to the early 1980s (NOAA, 2022). Precisely, the series from 1910 to 2021 consists of two principal periods. The first (1910 - 1976) is characterized by the dominance of negative anomalies, while the second exhibits positive anomalies. This shift in temperature trend and the positive anomalies remain consistent throughout the second period, with a notable temperature increase in recent years. This uniformity of negative anomalies reflects a global warming trend. Official reports from the IPCC (Intergovernmental Panel on Climate Change) and NOAA have emphasized this warming (IPCC, 2018; NOAA, 2022).

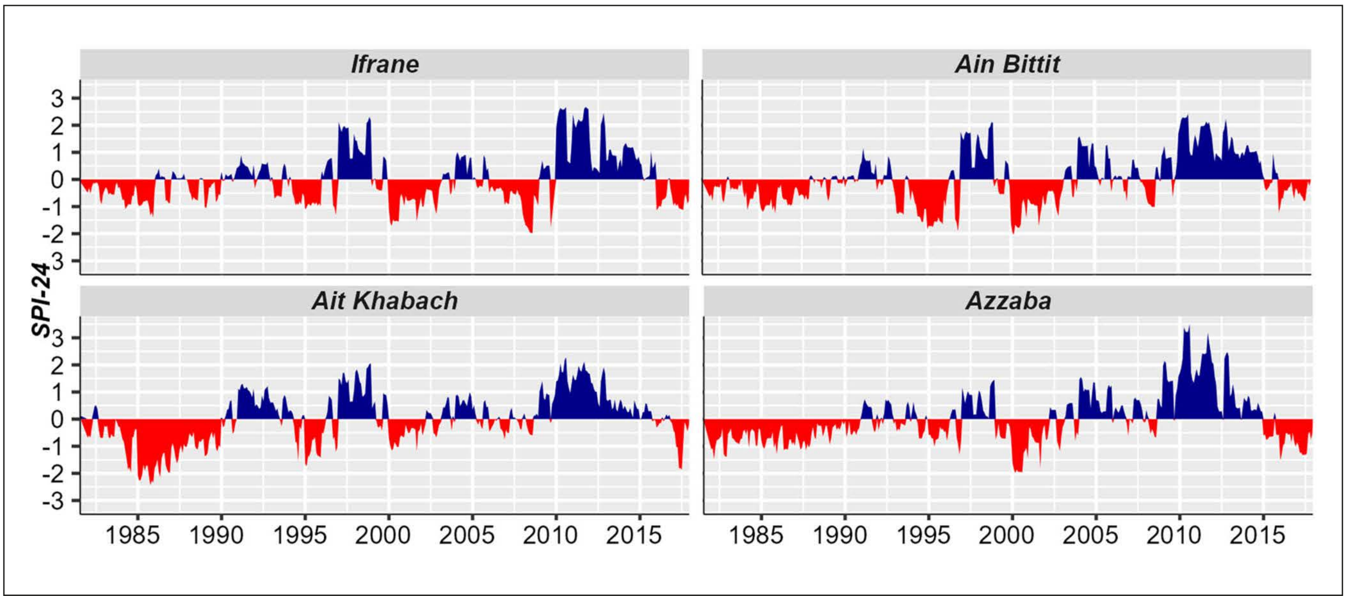

Figure 7. SPI at 24 months for Ifrane, Ain Bittit, Ait Khabach, and Azzaba stations over the period 1980 - 2017. Source: own elaboration based on processing of rainfall data derived from the Sebou Hydraulic Basin Agency.

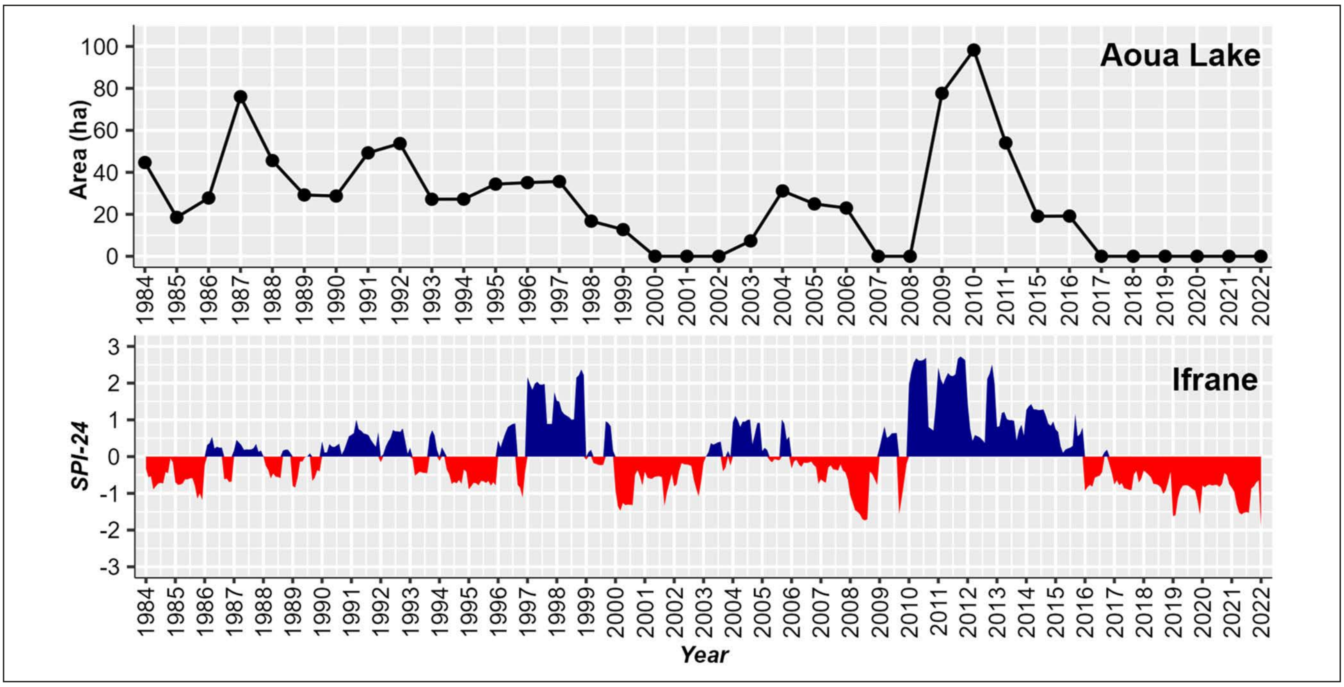

Figure 8. Comparison between the lake water area and the 24-month SPI at the Ifrane station between 1984 and 2022. Source: own elaboration based on processing of rainfall data derived from the Sebou Hydraulic Basin Agency and Landsat TM, OLI, and OLI-2 satellite images.

5.2. Effect of land use changes on water resources

Land use is classified by the Global Climate Observing System (GCOS) program among essential climate variables (GCOS, 2016). Over the past decades, changes in climatic parameters have contributed to disrupting agricultural systems traditionally reliant on precipitation and have promoted the evolution of irrigated crops. In this study, tracking the evolution of irrigated areas in the Tabular Middle Atlas depressions occupies a significant place, as they represent both the expression of agricultural development in this long-neglected natural region and factors of pressure on water resources. Pasturelands and traditional land use practices have characterized the Middle Atlas (Jennan, 1986). Since the 1990s, hope for local development has emerged through initiatives and a new appreciation of the region's potential by local actors (Tag, 1996). Currently, the Middle Atlas witnesses notable transformations in land use practices. These transformations are evident in the progressive evolution of irrigated agricultural areas at the expense of pasturelands and rainfed croplands in the severe drought context that has exerted significant pressure on water resources, thus amplifying the hydrological deficit.

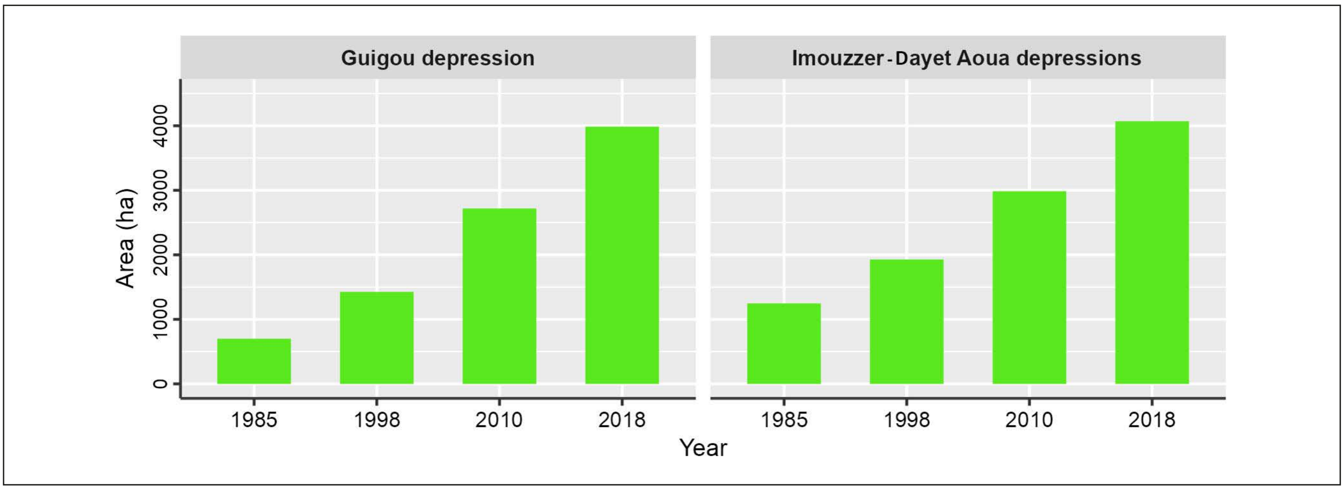

Figure 9. Evolution of irrigated areas (ha) in two sectors of the Tabular Middle Atlas from 1985 to 2018. Source: own elaboration based on processing Landsat TM and OLI satellite images.

Table 3. Evolution of irrigated areas in Imouzzer-Aoua and Guigou depressions (ha) from 1985 to 2018.

	Irrigated Areas (ha)				Evolution of irrigated Areas		
Depressions	1985	1998	2010	2018	1985 -2018 (ha)	Mean /year (ha)	Evolution rate 1985 - 2018 (%)
Imouzzer- Aoua	1 247	1 927	2 985	4 070	2 824	86	327
Guigou	699	1 425	2 718	3 987	3 288	100	570

Source: Processing of Landsat TM and OLI satellite images (August 1985, 1998, 2010 and 2018).

The obtained results from the Landsat satellite image processing in two sectors of the Tabular Middle Atlas (table 3 and figure 9) show a remarkable increase in irrigated areas between 1985 and 2018. Over three decades, irrigated areas multiplied by more than five in the Guigou depression (570%) and more than three in the Imouzzer-Aoua depressions (327%). The rate of change in both areas varied between 86 ha and 100 ha in the Imouzzer-Aoua and Guigou depressions, respectively. While both zones experienced a significant increase in irrigated areas between 1985 and 1998, the rate of change became higher between 1998 and 2018. This increase in irrigated areas coincided with periods of long-term drought. The multiplication of irrigated areas on average across all depressions is primarily explained by successive government interventions (subsidies to farmers under the Green Morocco plan), the availability of water resources, and farmers recourse to irrigation to address the problem of declining yields from rainfed crops, which are highly vulnerable to climate variability (El-Bouhali, 2023). The progressive evolution of agricultural practices based on irrigation in the Tabular Middle Atlas has led to profound landscape, economic, and social transformations. Furthermore, the extension of irrigated areas has accelerated the hydrological deficit, resulting in the continuous decline of groundwater levels. The continuous decline of groundwater levels has gradually led to adjustments in the hydro-agricultural system to cope with the water deficit. Above-ground reservoirs have emerged, marking

 e-ISSN: 2340-2776 | doi: https://dx.doi.org/10.12795/rea.2024.i48.10

the latest phase of this evolution. These reservoirs, supplied by water from wells of varying depths, ensure irrigation over an extended period.

6. CONCLUSION

Water resources, the dynamics of irrigated areas, and changes in climatic parameters occupy a significant role in scientific research. Studies conducted in this context are numerous, and the results obtained in different countries show that the disturbance of one element directly or indirectly influences others. The findings suggest a remarkable decrease in precipitation and a trend towards rising temperatures. In parallel with these worrying climate conditions, land use practices are undergoing radical transformations in many parts of the world. This primarily affects replacing traditional land use systems with modern ones, particularly agriculture. The development of agricultural practices is reflected in a considerable extension of irrigated areas over the last decades at the expense of rainfed crops, forests, and pasturelands. This phase has coincided with long periods of drought, resulting in significant pressure on water resources and leading to concerning hydrological deficits.

The analysis of hydrological data shows that water resources in the Tabular Middle Atlas and its vicinities have been subject to remarkable quantitative degradation in recent decades. This degradation primarily lies in the decline of groundwater levels and the drying up of lakes. In the Fez-Meknes aquifer, measurements conducted by the Sebou Hydraulic Basin Agency indicate an alarming drop in the water table. Over three decades, the piezometric level has descended from a few meters in 1980 to over 100 meters in 2017. A comparison between the current and past situation of the Guigou aquifer reveals a remarkable decrease in the piezometric level. Interviews with local populations and field measurements suggest that until 1980, the piezometric level was below 10 meters. Currently, it has become more than 45 meters in several places in the depression. The spatiotemporal monitoring of the water surface area of Aoua lake from September 1984 to September 2022 illustrates a significant shrinkage with prolonged drying. These observations reflect the concerning state of water resources in a strategic sector of the Moroccan mountains.

The critical situation of water resources in the study area is due to both natural and anthropogenic factors. Analysis of precipitation using the Standardized Precipitation Index shows a recurrence of drought periods of varying severity since the 1980s. Concurrently, with prolonged droughts, agricultural practices have undergone significant modifications. These changes are observed in several depressions, characterized by the progressive degradation of traditional land management elements and the continuous growth of modern land use practices. The satellite image processing results indicate a progressive increase in irrigated areas within the studied depressions (Guigou depression and Imouzzer-Aoua depressions) at the expense of pasturelands and rainfed croplands. Over three decades, the area of irrigated crops has multiplied by more than four on average in the two studied sectors. The successive changes in land use practices in the Middle Atlas Tabular region and the increased severity of drought affecting Morocco since the 1980s have exerted immense pressure on water resources.

The hydrological deficit observed in the study area has led to successive changes in the hydro-agricultural system as a form of adaptation to the continuous quantitative degradation of water resources. The latest phase of irrigation system development observed in the field is the emergence of water collection basins from groundwater, as in several locations within the depressions, wells have become incapable of supplying the pump for irrigation for a sufficient duration. The landscape and environmental changes in the Tabular Middle Atlas have adversely impacted local ecosystems, natural resources, and human activities. Finally, understanding the complex interactions between climate, land use practices, and water resources is crucial for developing sustainable water and local ecosystem management strategies in the Tabular Middle Atlas. Strategies considering local population needs and ensuring sustainable water management.

Acknowledgments

The authors are grateful to the U.S. Geological Survey (USGS) for providing the Landsat TM, OLI and OLI-2 satellite images. The authors also thank the Sebou Hydraulic Basin Agency (ABHS) for providing precipitation data. We acknowledge and express gratitude to all individuals who participated in the realization of the fieldwork (piezometric measurements) during challenging periods.

Responsible reporting and conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. All authors contributed to the study and approved the final manuscript. Abdelaziz EL-BOUHALI: Data curation, Conceptualization, Methodology, Software, Investigation, Data analysis, Writing – original draft. Mhamed AMYAY: Methodology, Supervision, Conceptualization, Writing – review & editing, Validation. Khadija EL OUAZANI ECH-CHAHDI: Data curation, Data analysis, Writing - Review & editing.

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