

# The Dynamics of Irrigated Agriculture Using Geographic Information Systems and Google Earth in the Tafrata Plain (Northeast Morocco)

Smail Bouguelba<sup>1\*</sup>, Mohamed El kallouchi<sup>2</sup>

<sup>1</sup>Department of Geography, Geographic Information Technology and Space Management Team, Faculty of Arts and Humanities, Mohamed 1st University, Oujda, Morocco.

\*Corresponding author: [smail.bouguelba@ump.ac.ma](mailto:smail.bouguelba@ump.ac.ma)

## Article history:

Received: 11 December 2025

Accepted: 19 March 2026

Published: 30 June 2026

## Keywords:

Irrigated agriculture, Irrigated dynamics, Agricultural expansion, Remote sensing, Sustainable water.

## Abstract

Irrigation plays a fundamental role in sustaining agricultural production in arid and semi-arid regions where rainfall remains insufficient and irregular. This study aims to analyse the spatial and temporal dynamics of irrigated areas over the last three decades. The methodological approach is based on the use of the Normalized Difference Vegetation Index (NDVI) derived from satellite imagery for the years 1992, 2012, and 2022, combined with Google Earth images, and supported by field verification to ensure the accuracy of the results. The analysis reveals a significant expansion of irrigated agricultural areas in the plain. Irrigated land increased by approximately 2,282 hectares, with an average annual expansion rate of about 394 hectares. Between 2012 and 2022, irrigated agricultural areas reached 10,977 hectares, reflecting a marked acceleration in agricultural development during the last decade. The results also indicate a notable increase in fruit tree plantations between 2006 and 2023, the number of agricultural holdings dedicated to fruit trees increased from 4,765 to 5,578, representing a growth of about 17.1%. Olive-related exploitations accounted for more than 95% of the total. Spatial analysis highlights a clear concentration of irrigated farms near surface water resources, groundwater reserves, and fertile soils. These dynamics reflect profound socio-spatial transformations driven largely by recurrent drought conditions, and leading to a transition from traditional agriculture systems toward modern irrigated agriculture, this transformation has also intensified pressure on groundwater resources, particularly through the increasing drilling of wells, raising important challenges for sustainable water management and regional agricultural sustainability.

<https://dx.doi.org/10.52951/dasj.26180106>

This article is open-access under the CC BY 4.0 license (<http://creativecommons.org/licenses/by/4.0/>).

## Introduction

Irrigated agriculture, which covers roughly 20 % of the world's cultivated land, is responsible for producing more than 40 % of the global food supply (FAO, 2021). Irrigated agriculture plays an important role in meeting and achieving global food security. However, agriculture is the largest consumer of water worldwide, with groundwater providing an estimated 40% of global irrigation (Zipper *et al.*, 2024). Twenty-five per-cent of the world's land area supports global food production (FAO, 2021). Climate change has led to a decline in agricultural production worldwide, especially in dry and semi-dry areas. As a result, there has been increased interest in irrigation systems to adapt to the effects of climate change. Agriculture irrigation, being one of the most crucial elements of the agricultural sector, helps to provide food security, economic development, and environmental stability on a global scale

(Ali *et al.*, 2025). Water resources are becoming increasingly crucial in supporting food production, particularly in the context of climate change, urbanization, and population growth (Ghimire *et al.*, 2025). Groundwater irrigation plays an important role in sustainable agricultural development by providing a protective shield during droughts and dry spells, as well as intensifying and diversifying the cropping system (Saha *et al.*, 2020). Irrigation is important for agricultural production and is often decisive for this, especially in arid and semi-arid areas, where precipitation is insufficient. The benefits of irrigation include increased productivity and the dissociation of constraints, ensuring greater resistance to extreme weather events (Bendini *et al.*, 2023).

There has been an increased reliance on irrigated agriculture in recent decades, contributing to the gradual expansion of irrigated land in most countries (Velpuri *et al.*, 2009), especially in dry and semi-arid regions where agriculture is adversely affected by climate change. This situation has imposed significant challenges on the limited water resources in these areas due to rising demand. The growth of the global population, combined with agricultural activities, rapid urban expansion, and climate change, has intensified pressure on food production due to high demand and water scarcity (Amiri *et al.*, 2025). The excessive use of irrigation water in the Mediterranean region has led to the degradation of freshwater resources through the depletion of groundwater layers. Several European directives indicate that estimating the area of irrigated land in each watershed is a fundamental step toward the sustainable management of natural resources (Alexandridis *et al.*, 2008). At the local level, the scarcity and degradation of water resources in Morocco, caused by climate change, have reached alarming levels (Cheikhaoui *et al.*, 2024). Sustainable management of irrigation systems using robust and holistic tools and software is necessary to improve water use efficiency and productivity (Bwambale *et al.*, 2019). The necessity of effective management of irrigation and agricultural water has emerged to ensure the continuity of farming activities. Especially since the availability of water in the future will be negatively affected by changes in temperature and rainfall (Purnamasari *et al.*, 2025). One of the fundamental requirements for informed management and decision-making is access to up-to-date and regionally detailed information about irrigated agricultural lands. This necessitates monitoring the development of irrigated agriculture, which is of great importance despite the scarcity of scientific studies on this subject, creating a significant knowledge gap (Mcallister *et al.*, 2015).

The United Nations Sustainable Development Goals emphasize the need for sustainable water and agricultural management to achieve food security and optimal land use. This requires accurate global data on irrigated areas to support water cycle analysis and crop modelling. Accurate data on the changes of irrigated agricultural areas is crucial for identifying different socio-economic drivers which can be utilized towards effective planning and management of irrigation systems, advances in remote sensing have enabled the development of innovative approaches for monitoring irrigated landscapes, allowing for high-precision mapping of their spatial extent and distribution, this has significantly improved the reliability of irrigation-related datasets within defined administrative units (Dari *et al.*, 2022; Ozdogan *et al.*, 2010). In this context, vegetation indices have emerged as effective quantitative tools for detecting and characterizing irrigated areas, among which the Normalized Difference Vegetation Index (NDVI) remains one of the most extensively applied metrics (Ambika *et al.*, 2016).

Modern technologies have great potential for developing methods to monitor irrigated areas. However, mapping irrigated regions remains a challenge due to the complexity and diversity of irrigation methods and crops. Nevertheless, the use of remote sensing and Geographic Information Systems (GIS) remains among the most effective modern tools for studying the dynamics of agricultural lands and describing their characteristics as well as for

analysing the relationship between land use and land cover change (LUCC) and water resources. Remote Sensing and Geographical Information System (RS-GIS) technologies have been widely used to study Land Use and Land Cover Change (LUCC), at different scales (Meier *et al.*, 2018).

The evolution of geospatial technology allows users to collect spatial data and use it for analysis, modelling, simulation, and geo-visualization (Singh *et al.*, 2010). Nevertheless, identifying Irrigated regions remains difficult in land use classification, and existing global datasets show considerable discrepancies. While remote sensing methods are commonly employed to map agricultural land overall, there are very few studies that concentrate specifically on irrigated farming. Remote sensing enables the creation of precise spatial maps of irrigated lands, providing a more comprehensive understanding of changes in land use. GIS can be used to accurately map irrigated areas, which are vital in achieving precision in irrigation. Data is acquired from satellites like Landsat to detect irrigated areas. Spectral patterns of the data are analysed to classify irrigated and non-irrigated areas, and spatial-temporal variations of irrigation can be assessed (Moisa *et al.*, 2022).

The Normalized Difference Vegetation Index (NDVI) represents one of the most robust spectral metrics for characterizing and quantifying vegetation dynamics (Ghimire *et al.*, 2025), owing to its high sensitivity to variations in plant density and Vigor, which makes it superior to many other vegetation indices developed for similar purposes, effectively capturing green biomass and exhibiting a strong correlation with the moisture levels available to vegetation (Huang *et al.*, 2021). Irrigated crops typically exhibit higher NDVI values, especially during the growing season, due to increased soil moisture availability from irrigation (Pervez and Brown, 2010). Therefore, NDVI images from three different years were analysed to assess inter-annual changes and distinguish irrigated lands from non-irrigated areas based on vegetation density. This study aims to draw and analyse the spatial and temporal dynamics of irrigated agricultural areas to support the improvement of water planning for irrigation, the development of the irrigated agriculture sector using the unified plant cover index (NDVI) derived from satellites and conduct land coverage classification based on Thresholding classification and field verification.

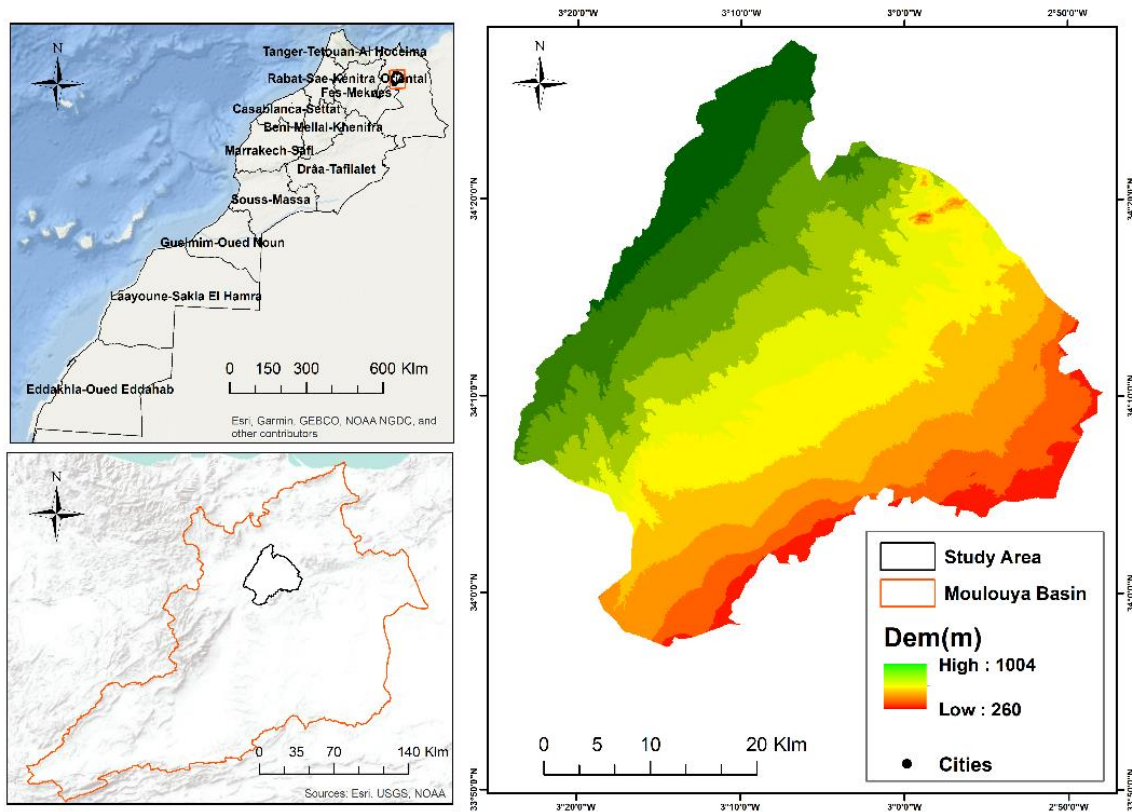
## Materials and Methods

### Study Area

A group of Moroccan farming areas is witnessing an important agricultural, irrigated dynamic, including the Tafрата plain in northeast Morocco, which has experienced major shifts related to its local characteristics. Irrigated areas in the Plain have not been widely formed except in recent decades, as the dynamics of the irrigated agricultural scene have remained relatively limited for long. Irrigated agriculture is considered an important economic activity in the study area, where irrigated agriculture tends to intensify. It is mainly composed of major agricultural crops: Clover, vegetables, and olive Trees. Grain is considered a rain-dependent winter crop, grown in early December and harvested at the end of May. As for clover, it is irrigated for summer crops.

The study area is located in eastern Morocco (34°20'–34°50' N and 3°20'–2°50' W). The Tafрата Plain covers approximately 1,650 km<sup>2</sup> and represents an important agricultural unit in the region. The plain is located on the right bank of the Moulouya River, between the cities of Guerçif and Oued Za, and it is considered one of the most important basin plains in the Guerçif area (Figure 1). It extends eastward toward mountain Oulad Amr and the valley El Abid basin, bounded to the south by the Debdou Massif and mountain Sidi Lahcen, to the southwest by the Maârouf Plain, and to the north by the Moulouya River. The study area belongs to the semi-arid regions that have undergone significant irrigated agricultural

development. However, spatial maps describing the dynamics of irrigated agriculture are lacking, which limits our understanding of its characteristics, trends, and impacts on the regional agricultural structure. Therefore, the main objective of this work is to map the evolution of irrigated areas using satellite imagery and geospatial agricultural crops: Clover, vegetables, and olive Trees. Grain is considered a rain-dependent winter crop, grown in early December and harvested at the end of May. As for clover, it is irrigated for summer crops.



**Figure 1. Location map of the study area**

Olive, vegetables, and clover productivity are a basic part of the local economy. Surface water is not exploited much, and the only source of fresh water for irrigation is subterranean water. Many privately owned wells and boreholes were drilled in the second decade of the 21<sup>st</sup> century. Since then, water extraction has increased significantly because of the expansion of irrigated areas and the use of modern irrigation systems. The Tafrata Plain is administratively composed of four rural communes belonging to the Oriental Region of Morocco: Houara Oulad Rahou and Lmrija, which are part of the Guerçif Province, and Gteter and Sidi Ali Belkacem, which fall under the administrative jurisdiction of the Taourirt Province.

## Methods

The methodology employed in this study relied on Geographic Information Systems (GIS), utilizing ArcGIS software to produce spatial maps that highlighted and identified spatial distributions and tracked the sequence of development of irrigated areas in the Tafrata Plain. That required use of remote sensing technology to process and interpret satellite images (Landsat), which provided critical data on changes in agricultural land use. The expansion of irrigated areas in the Tafrata Plain, the study area located in northeastern Morocco, has occurred and is expected to continue according to three main aspects: the planned irrigated areas by the sectors responsible for the agricultural sector; private initiatives by local farmers;

and individual private investments coming from out-side the plain. This agricultural transformation has been accompanied by substantial progress in the integration of advanced agricultural technologies and innovative frameworks for water resource governance, resulting in profound shifts within irrigation infrastructures and management paradigms. These evolutions emphasize the pivotal function of sustainable water management practices, which secure the hydrological requirements of crops while preserving ecological balance and resilience. The strategic importance of water resources in agricultural systems is increasingly evident, particularly in safeguarding global food security amid the compounding defies of climate variability, demographic expansion, and escalating anthropogenic pressures on natural capital. Google Earth was used as a reference dataset to validate the classification results and to compare the delineated irrigated areas with NDVI-derived maps. It was also employed to map irrigated agricultural zones and to analyze the spatial patterns of fruit tree cultivation in the study area. This integration allows for more accurate assessment of irrigated land and understanding of the spatial variations of agricultural exploitation, which enhances the ability to provide water and agricultural resources more efficiently and sustainably.

In order to look at the development of agricultural areas and their impact on the field and society, the study adopted a complementary approach that combines qualitative and quantitative approaches through integrating multi-source data, including observations and field visits, forms, remote sensing data, previous reports and studies, with a view to revealing changes and trends in agricultural land development in the study area. In terms of spatial data, the study methodology focused on the use of old and modern satellite images (Landsat 5TM, Landsat 7 and Landsat 8) for the years (1992, 2012, 2022), in addition to satellite images, remote sensing indicators, change detection algorithms, along with spatial analysis using geographic information systems (GIS). These images are of pre-processing and correction processes, which allowed the obtaining of correct and geographically clear images with high accuracy. As for the extraction of irrigated land, it was mainly based on the Unified Land Cover Index (NDVI) where this index was used to distinguish between irrigated and non-irrigated areas and determine their areas and locations. Landsat 5 TM imagery (1992) provided Bands 1–5 and 7 with a spatial resolution of  $30 \times 30$  m. For 2012, Landsat 7 ETM+ data were utilized, including Bands 1–5 and 7 at  $30 \times 30$  m, after applying the scan line corrector (SLC)-off gap-filling procedure. Finally, Landsat 8 OLI/TIRS imagery (2022) supplied Bands 2–7 with a spatial resolution of  $30 \times 30$  m. Radio-metric calibration and normalization procedures were applied to ensure consistent and reliable multi-temporal analysis of vegetation cover.

The classification of irrigated, non-irrigated, and other land types using the Normalized Difference Vegetation Index (NDVI) relies on distinct ranges that reflect vegetation health and moisture levels. Typically, NDVI values range from  $-1$  to  $+1$  (Ahmed *et al.*, 2024), with higher values indicating denser and healthier vegetation, often associated with irrigated areas, while lower values suggest sparse vegetation or non-vegetated surfaces (Bwambale *et al.*, 2022). Data analysis includes the following:

### **1. Initial processing of images**

- Radiation correction: To remove the effect of the atmosphere and lighting.
- Engineering correction: To match the image with the correct geographic coordinates (Geo-referenced).

### **2. Calculate the NDVI index**

The Normalized Difference Vegetation Index (NDVI) -based assessment of vegetation activity in the study area, including classification and mapping, was performed using ArcGIS version 10.8. This index is often used in research related to regional and global vegetation

assessments (Xue and Su, 2017). NDVI is calculated based on reflectance in the near-infrared (NIR) and red (RED) bands using the following equation:

$$NDVI = (NIR - RED) / (NIR + RED) \text{ Where:}$$

NDVI is the Normalized Difference Vegetation Index.

NIR is the reflectance in the near-infrared band.

RED is the reflectance in the red band (Rouse *et al.*, 1974).

The resulting NDVI image shows values between  $-1$  and  $+1$ .

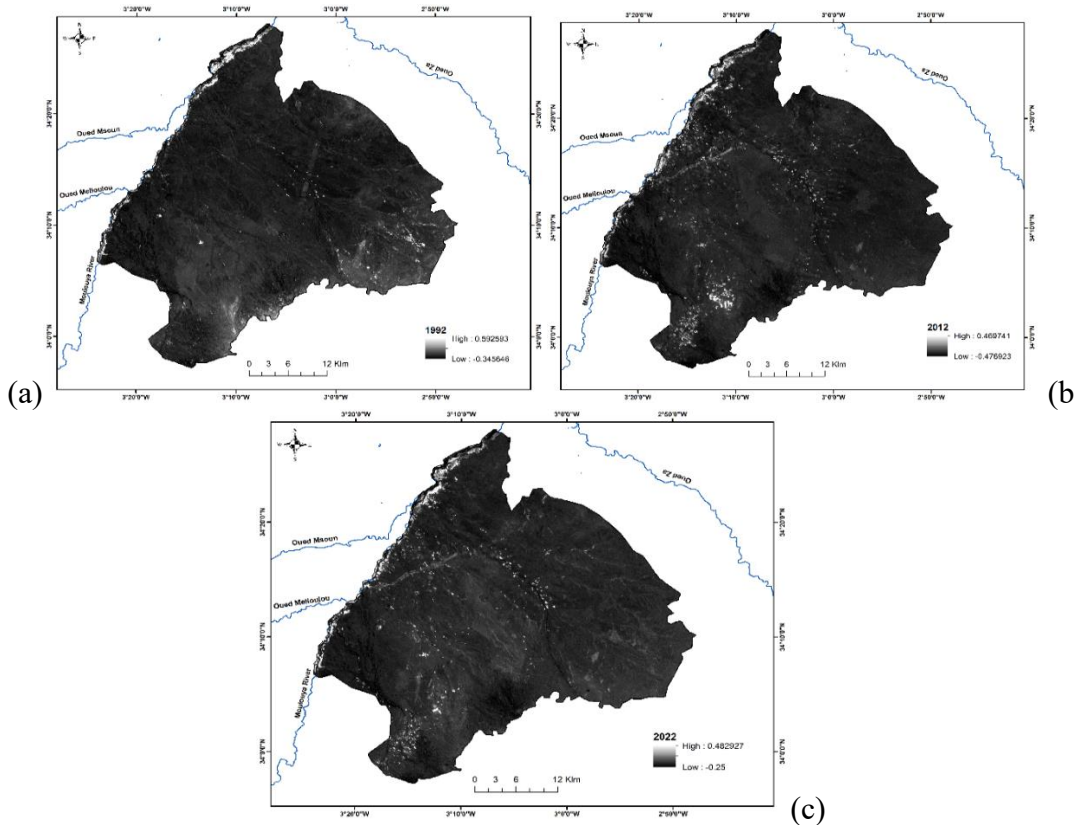


Figure 2. Satellite images of the study area in 1992 (a), 2012 (b) and 2022 (c)

### 3. Analysis of NDVI values

NDVI is used directly to determine land surface emissivity (Ali *et al.*, 2025b). Multi seasonal information of vegetation is used to obtain seasonal growth information of the crops, accurate results are achieved (Somayajula *et al.*, 2022). This indicator represents a basic element for determining the characteristics of the plant cover and the distribution of irrigated crops, which contributes to assessing the temporal expansion of irrigated lands in the study area. The NDVI was calculated using 3 Landsat satellite images captured at specific times to provide more precise and representative insights into the changes in irrigated areas over a period of 30 years. The images were chosen from August, the driest month, when only groundwater-irrigated fields remain visibly green. In the case of the Guercif Plain, which includes the Tafрата Plain, the dry climate and sparse vegetation make agricultural activity rely primarily on irrigated crops, while the very limited rain-fed agriculture helped distinguish NDVI values corresponding to irrigated and non-irrigated areas.

- Land with dense vegetation (mostly irrigated) appears at high values: 0.4 to 0.8.
- Dryland or unplanted lands have low or negative values.

#### **4. Land classification**

A group of methods were used, such as:

- Irrigated land is characterized by consistently high NDVI values.
- Uncultivated land exhibits low or variable NDVI values.

A group of methods was used, such as thresholding, where a specific NDVI threshold was set to differentiate between watchers and non-watchers, focusing on irrigated agricultural areas and detecting natural cover. In the Tafrata plain, irrigated lands and tree crops, mainly olive trees, had NDVI values from 0.15 to 0.48. These values identify low-density agriculture or moderate reforestation in semi-arid settings. Ground truthing was employed to verify accuracy by matching extracted areas with field data. Additionally, Google Earth was used as a verification tool to assess the accuracy of the extracted rainfed land from the industrial satellite imagery. This platform allowed the visualization of areas with high NDVI values through available aerial photographs, which facilitated the distinction between irrigated agricultural lands and natural vegetation cover. It also enabled the verification of precision maps produced during the presentation of results and the use of historical imagery to compare the temporal evolution of irrigated agricultural lands, thereby confirming the reliability of the derived data.

After identifying the irrigated land on the map, its area was calculated and distributed over time. ArcGIS was then used to convert classified maps from Raster to Vector, enabling calculation of the total area for each land cover category. Google Earth images from 2006 and 2023 were used to monitor the local development of irrigated agriculture, especially trees. These images helped determine the distribution of agricultural forms in the plain. This methodology enabled the identification of nature and characteristics of agricultural dynamics. It also allowed for the calculation of the volume of changes in irrigated agricultural exploitation and the identification of the factors influencing these changes, including their pathways and directions

### **Results and Discussion**

#### **Expansion Dynamics of Irrigated Areas in Tafrata plain**

The available data did not permit sufficient monitoring of agricultural development in the Tafrata Plain in eastern Morocco during the colonial period. However, some sources provided a general view of this agricultural dynamic, as the shifts associated with the rainfed agricultural system constituted the first signs of giving up large-scale grazing. This development came at the beginning of the adoption of agriculture in the semi-nomadic stage, which was based on the duality of agricultural activity (rainfed and pastoral agriculture), agricultural activity in the field at the beginning was confined to the cultivation of grain, both wheat and barley, during the late 19th century. The study utilized and analyzed agricultural land maps for the years 1992, 2012, and 2022 to assess changes in land use and agricultural practices over time. By interpreting satellite imagery and thematic maps, the research allowed for the identification of spatial patterns, trends in irrigation and cultivation, and the evolution of farm management strategies. This approach provided a comprehensive understanding of the dynamics of agricultural exploitation in the study area, enabling the derivation of the following key conclusions:

The area used for agriculture in the Tafrata Plain in 1992 reached 5,606 hectares, representing a very small proportion of the total area of the plain, which covers approximately 1,650 km<sup>2</sup> (165,000 hectares). It reflects the hegemony of the traditional pasture on the plain to the extent of this period through the spread of large and important areas of grasslands. It is a clear indication of the slowness of the degree of transformation and the movement of human exploitation of the field and its scaling from traditional grazing to agriculture, both traditional

and modern. In the Plain floodplain, agriculture was mainly small-scale, focused on self-sufficiency and cattle fodder. A grazing-agricultural system dominated, with producers practicing rainfed agriculture, cultivating wheat and barley, and grazing livestock. Another group of farmers, forming a minority, relied on exploiting surface water, practicing a mixed cultivation system of olive trees and fodder crops. This group includes certain families from the Gteter village cluster, as well as the Houara group of Oulad Rahou, who benefit from irrigation. Agricultural activity also extends to small and limited plots, particularly in transitional zones between the plain and surrounding areas, where farming has expanded at the expense of natural vegetation and forest cover (Bouguelba, 2024). The official agricultural census of 1996 helped to clarify the extent of agricultural exploitation, distinguishing between rainfed and irrigated practices.

**Table 1. Distribution of Agricultural Holdings of Tafrata Plain**

Commune	Farms	Sau (ha)	Parcels	Irrigated (ha)	Non-irrigated (ha)
<b>Gteter</b>	2001	33398	4959	1613	31785
<b>Houara oulad raho</b>	2126	26003	7736	4757	21246
<b>Lmrija</b>	1380	12520	8184	1094	11426
<b>Sidi ali belkassem</b>	1266	13433	6999	681	12752

Table 1 (Official Moroccan Agricultural Census, 1996) illustrates the variation in the size of arable land and the extent of agricultural exploitation among the village groups in the Tafrata Plain. Regarding rainfed agricultural areas, which constitute a significant portion of the cultivated land across the villages; there are notable differences between them. The Gteter, rural community holds the largest rainfed area, totaling 31,785 hectares (94.5% of its arable land), followed by the Houara group in Awlad Rahho with 21,246 hectares (81.7%). In the Sidi Ali Bel Quassem rural community, rainfed plots covered 12,752 hectares (95%), while in the Lmrija rural community, rainfed agriculture accounted for 91.3% of the exploited land in 1996. Statistical figures 1 indicate that until the 1990s the Tafrata Plain largely relied on rainfed agricultural practices, which are dependent on climatic conditions. This reliance contributed to low agricultural productivity. The situation can be attributed to limited support from the relevant sectors for farmers, insufficient private resources, high costs of land preparation, and the expenses associated with water pumping, which was primarily powered by gasoline.

**Table 2. Temporal Evolution of Cultivated Area and Annual Growth Rate in Hectares in Tafrata Plain (1992–2022)**

Time Period	Area (ha)	Added Area (ha)	Duration (years)	Annual Area Growth Rate (ha/year)
<b>1992</b>	5601	–	–	–
<b>1992-2012</b>	7883	2282	20	394,15
<b>2012-2022</b>	10977	3094	10	309,4

The agricultural areas added to the region constituted a significant proportion during the period (1992-2012), as shown in Table 2 (Analysis results of satellite images from 1992, 2012, and 2022), and clearly demonstrated the extent of agricultural dynamism, with irrigated areas expanding by 2,282 hectares over a period of 20 years, at an average rate of 394.15 hectares per year. The irrigated agricultural area in the Tafrata plain increased to 10,977 hectares between 2012 and 2022, and the rate of increase in agricultural area doubled compared to the first period. In just 10 years, the annual rate of increase reached 309.4

hectares, due to the availability of financial resources linked to the remittances of emigrants abroad and investors in the plain. Between 2012 and 2022, the annual rate increased significantly, mainly due to the influx of European foreign currency brought in by expatriates and invested in agriculture, in addition to the support and assistance associated with the Green Morocco Plan.

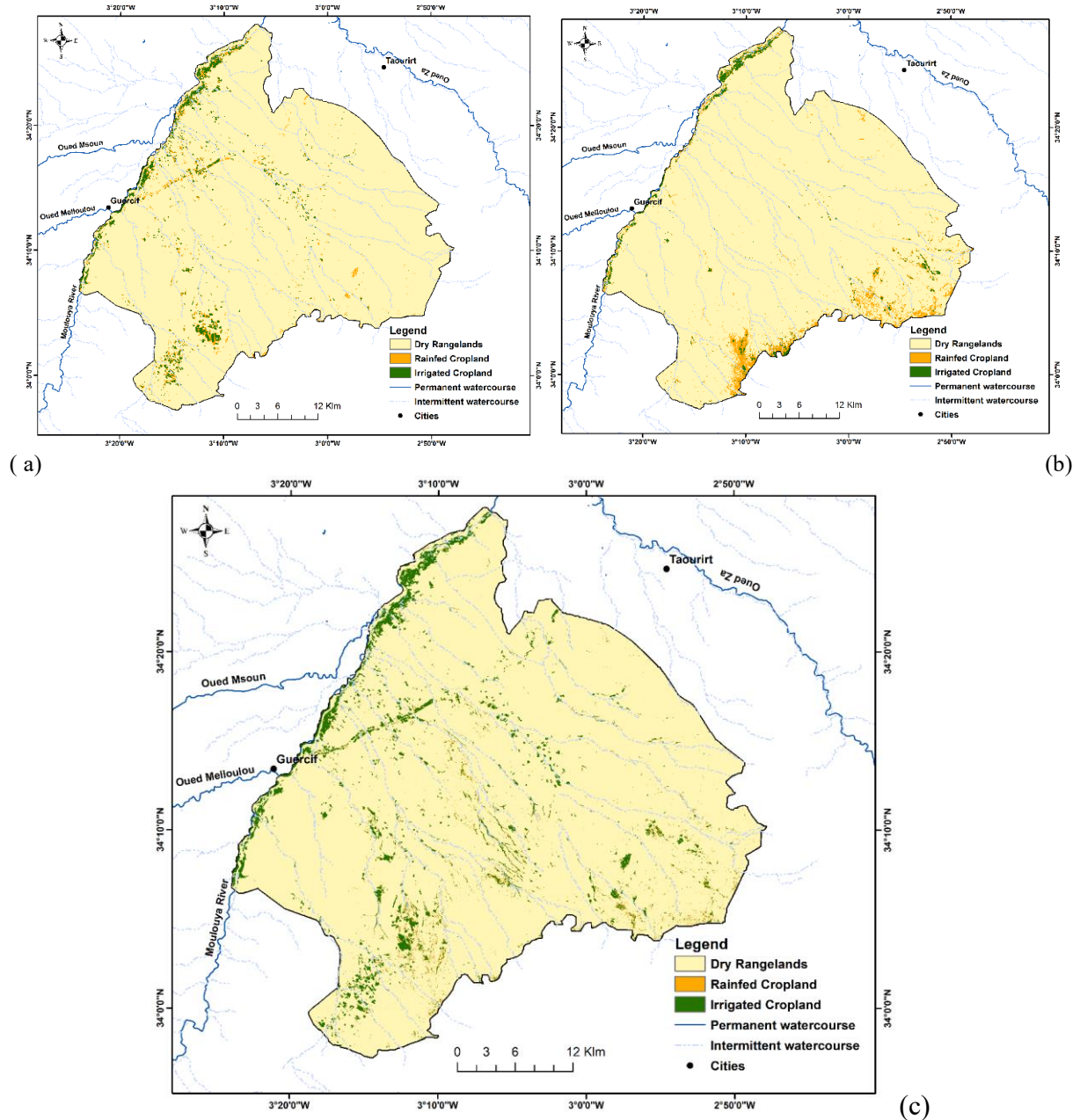
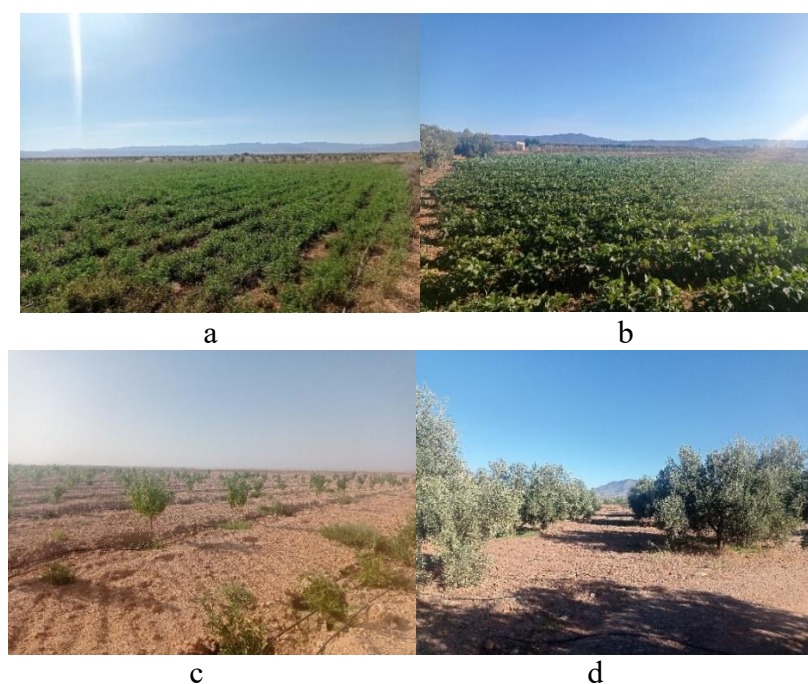


Figure 3. Temporal evolution of irrigated areas in 1992 (a), 2012 (b) and 2022 (c)

The expansion of irrigated agriculture in the Tafrata Plain reflects a profound spatial transformation, accompanied by a sharp decline in steppe vegetation exceeding 50% between 1992 and 2022 (Bouguelba, 2025). This shift is primarily driven by recurrent droughts and the conversion of rangelands into cultivated areas, leading to a weakening of traditional pastoral systems and a transition toward more controlled and water-efficient production models. This dynamic is particularly evident in the communes of Houara Oulad Rahhou, Lmrija, and central Gteter, as well as in the southwestern and southeastern sectors of the plain. The growth of irrigated cropland has largely occurred at the expense of rainfed agriculture, especially near former irrigated zones and along ephemeral river corridors.

Medium-sized farms are mainly concentrated along watercourses within localized irrigation schemes, particularly those associated with the Moulouya River, with their recent expansion closely linked to the proliferation of wells and boreholes. A total of 1,246 groundwater abstraction structures has been recorded (Agence de Bassin Hydraulique Moulouya, 2017). Displaying a heterogeneous yet functionally coherent spatial pattern, strongly connected to olive-oriented farming systems. Localized irrigation constitutes the dominant technique, covering 54% of the sampled irrigated areas (Field, 2022), and stands as a clear indicator of agricultural modernization and the ongoing intensification of irrigated land use in the study area.



**Figure 4 (A–D). Photographic documentation of irrigated agriculture and olive plantations in the Tafrata Plain (2022)**

Field observations conducted in 2022 (Figure 4A–D) confirm the distribution patterns of irrigated lands mapped via NDVI and Google Earth, illustrating the spatial organization of irrigated farms and olive tree plantations, showing medium- and large-sized farms concentrated along watercourses and floodplains.

### Dynamics of Irrigated Tree-Cropped Areas

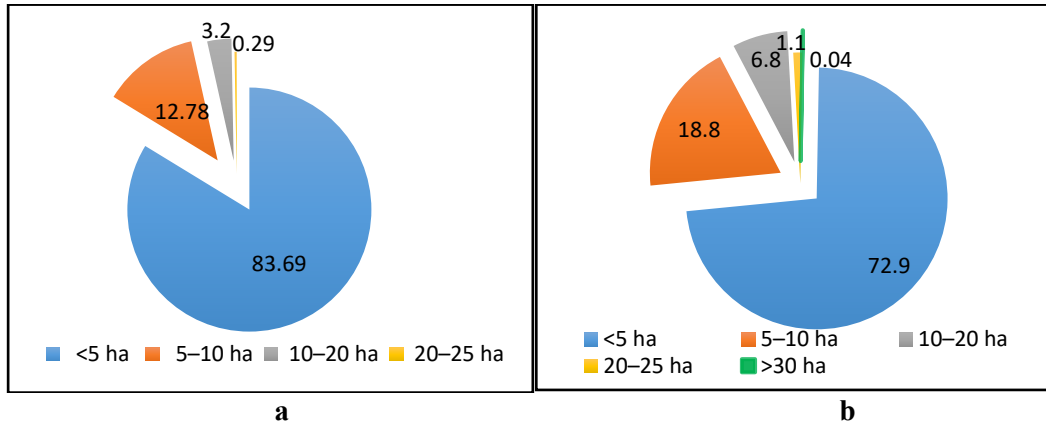
In 2006, the number of agricultural holdings dedicated to tree plantations in the region reached 4,765, covering a total area of 13,195.46 hectares. These holdings were unevenly distributed both spatially and in terms of size categories. A significant proportion of farms (3,988 holdings, 83.69% of the total) were smaller than 5 hectares.

**Table 3. Evolution of Fruit Tree Farm Size Categories in the Tafrata Plain between 2006 and 2023**

Year	<5 ha	5–10 ha	10–20 ha	20–25 ha	30–40 ha	>40 ha
2006	3988	609	154	14		
2023	1030	382	63	16	16	16

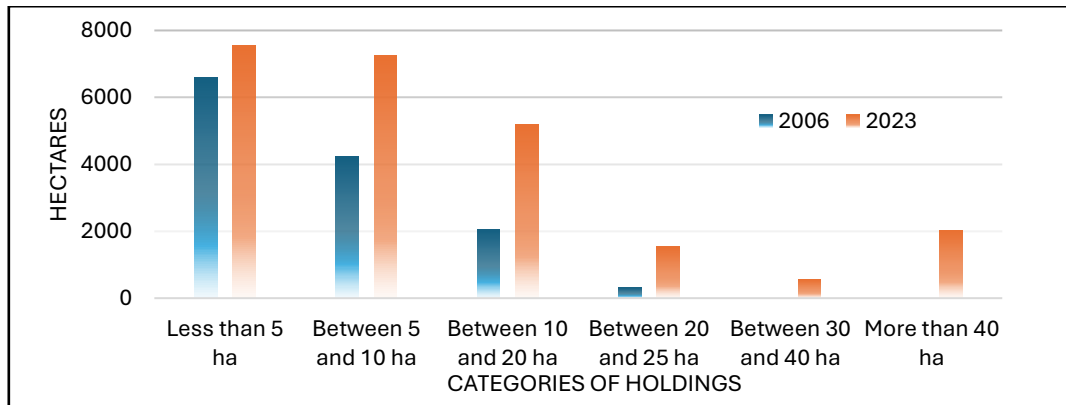
This was followed by farms ranging between 5 and 10 hectares, which accounted for 609 holdings (12.78%). As farm size increased, both the number of holdings and the total cultivated area decreased: 154 farms (3.23%) fell within the 10–20 hectares range, while the

category of 20–25 hectares comprised only 14 holdings (0.29%), representing the largest individual farm size but the smallest number of holdings.



**Figure 5 (a 2006–b 2023). comparative Percentage Distribution of Fruit Tree Farm Size Categories in the Taffeta Plain (2006 and 2023)**

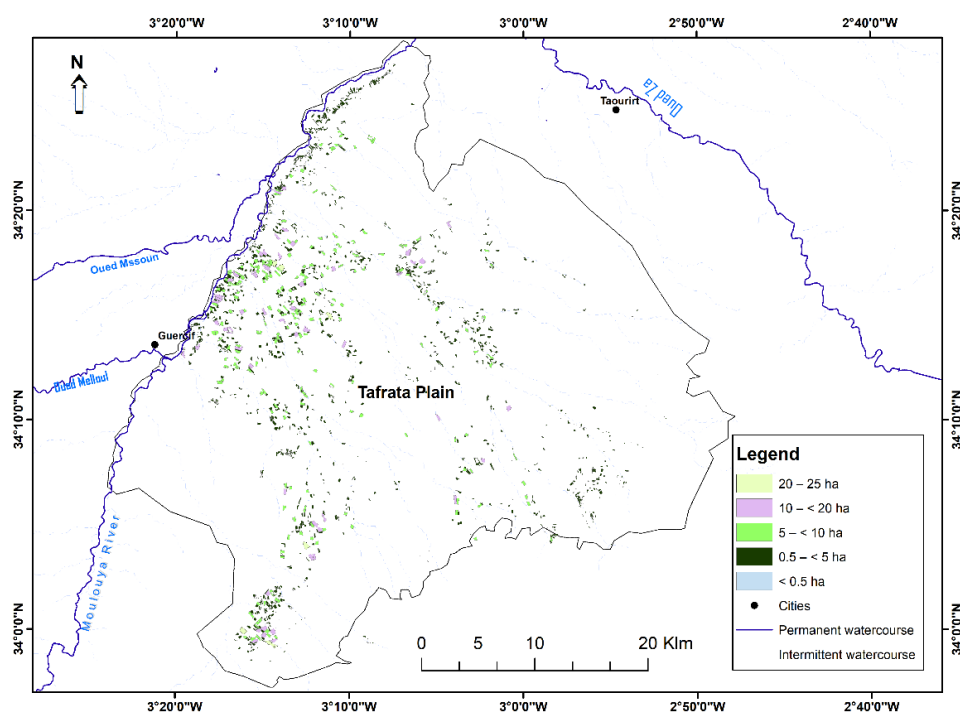
These holdings dedicated to fruit trees experienced significant development between 2006 and 2023 (Figure 6), showing a positive trend both in terms of the number of holdings and their cultivated areas. The size of agricultural exploitation is linked to its profitability and the techniques and methods used to exploit it. Thus, in 2023, the total number of holdings in the study area reached 5,578 fruit tree farms, which represents a significant proportion in terms of number, with small farms of less than 5 hectares accounting for 4,071 farms, or 72.9%. Next in importance is medium-sized farms, ranging from 5 to 10 hectares, with 1,030 farms, or 18.4%. Farms in the 10–20-hectare category numbered 382, or 6.8%. While large fruit tree farms in the Tafrata plain, with an area exceeding 30 hectares, accounted for 0.04% of farms, which is a small percentage of the total number of farms associated with fruit trees.



**Figure 6. Evolution of the distribution of agricultural holding size classes of fruit tree plantations in the Tafrata Plain between 2006 and 2023**

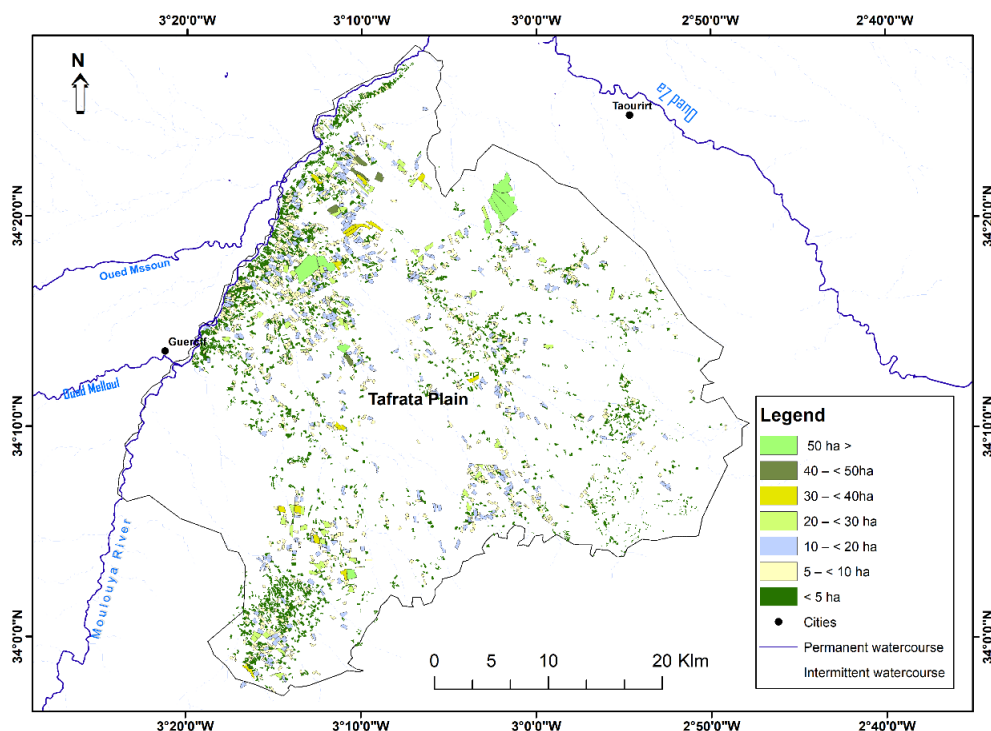
In 2006, the area used for fruit trees in the Tafrata plain covered a significant area in the category of holdings of less than 5 hectares. The largest area is represented by 6,585.63 hectares, followed by the class of agricultural holdings farm-size class of 5–10 hectares, with an area of 4,245.49 hectares. While the category between 10 and 20 hectares recorded an area of 2,040.62 hectares, indicating the dominance of medium-sized farms associated with fruit trees. Meanwhthe, large farms in the plain were very weak in 2006, with the category between 20 and 25 hectares, which is the largest agricultural exploitation category to date, accounted for only 323.72 hectares, while the total area of fruit trees in the region in 2023 was

approximately 24,131 hectares, with varying proportions according to exploitation categories, where The category of less than 5 hectares accounted for a significant proportion of 7,557 hectares, followed in importance by the category of agricultural holdings between 5 and 10 hectares, with 1,030 holdings covering 7,240 hectares, while the category with a size ranging between 10 and 20 hectares covered a significant area of 5,193 hectares. The category between 20 and 30 hectares covers 1,537 hectares, while large agricultural holdings exceeding 30 hectares cover 2,604 hectares, despite their small number compared to the total number of holdings. To clarify the picture further, it was necessary to determine the total area for each category. The post-Green Morocco Plan period saw significant expansion in agricultural holdings (Bouguelba, 2024) .This was especially true for holdings involved in afforestation. There was an increase in medium-sized holdings and the emergence of large holdings over 25 hectares, which did not exist in the plain before 2006. Areas increased for holdings in every size category: less than 5 hectares, between 5 and 10 hectares, between 10 and 20 hectares, and between 20 and 30 hectares.



**Figure 7. Distribution of the size of irrigated agricultural holdings devoted to tree plantations in the Tafraata Plain, 2006**

In 2006, there were a total of 4,765 agricultural holdings dedicated to plantations, distributed unevenly across categories of land area not exceeding 25 hectares. There are a concentration and predominance of farms with an area of less than 5 hectares and between 5 and 10 hectares, with farms of less than 5 hectares representing 9.49% of the total area under cultivation and those between 5 and 10 hectares representing 32.1%. On the other hand, there is a noticeable dispersion in the category of 10 ha and above. This group covers 18% of the agricultural area of farms. Farms between 10 and 20 cover only 15% of the agricultural area used for afforestation. The largest farms, between 20 and 25 hectares, constitute a very small percentage and are distributed unevenly across the plain. This situation has consequences on many levels due to the relationship between farm size and the use of mechanization, and productivity. It also leads to spatial disparities in agricultural exploitation, with negative social and economic effects. In general, the period between 2006 and 2023 saw significant changes in the categories and areas of exploitation.



**Figure 8. Distribution of the size of irrigated agricultural holdings devoted to tree plantations in the Tafrata Plain, 2023**

The total number of holdings and agricultural exploitations linked to fruit trees in 2023 was approximately 5,578. Olive-related exploitations accounted for more than 95% (Field, 2022). The distribution of the size of agricultural exploitations in the plain varies for many reasons. Their density is concentrated along the national road linking Guercif and Taourirt, particularly in the section linked to the commune of Houara Oulad Rahou, and along the Moulouya River in the rural communes of Gteter and Houara Oulad Rouhou. Some of these exploitations benefit from river water, as well as the proximity of groundwater and the presence of alluvial soil compared to other farms. In connection with these factors, the floodplain of Oued Athlagh is a large area of agricultural exploitation associated with olive trees. The plains surrounding the center of Lamrija and along the road leading to the city of Guercif are also areas of tree cultivation. The remaining areas experience little or no cultivation. The geographical distribution of agricultural exploitation, as illustrated Figure 4, reveals that holdings of less than 5 hectares are widely dispersed across the plain. The next most significant category, comprising holdings between 5 and 10 hectares, is present throughout most of the plane but at a lower density. In contrast, holdings between 10 and 20 hectares are more sporadically distributed. The largest categories of exploitation are represented as extensive agricultural areas scattered across the region.

Soils in the study area exhibit considerable variability, dominant soils share similar characteristics due to scarce rainfall, and the long-term absence of vegetative cover, resulting in poor horizons and low organic matter content (Seghir *et al.*, 2019). The plain dominated by Calcimines soils (50.60%), followed by weakly developed fluvial soils (30.98%) and weakly developed eroded soils (18.42%). Sandy loam textures predominate (55%), but the organic matter content is notably low (61%), limiting water retention capacity (Oubdil *et al.*, 2025). The high permeability of fluvial soils facilitates groundwater recharge and enhances irrigation potential, whereas Calcimines soils offer moderate water storage, and eroded mineral-rich soils require engineered retention measures to optimize water availability. Consequently, areas with well-developed alluvial soils along riverbanks and slopes support larger, more

intensive exploitations due to their superior fertility and water retention capacity. In contrast, the central parts of the plain consist of native, calcareous, and raw mineral soils, which are shallow, alkaline, and have low water-holding capacity. These soils, formed under harsh natural conditions with low organic matter, low rainfall, and high temperatures, constrain agricultural expansion and limit the size of farms. The presence of stones due to calcareous crust breakdown further reduces soil fertility. These less developed soils support smaller and less intensive exploitations. The floodplain of Oued Athlagh, characterized by fine alluvial deposits transported from surrounding highlands and valleys, represents a particularly favorable area for agricultural intensification. Similarly, the plains near Lmrija along the road to Guercif benefit from transported silt soils, which, combined with accessibility and proximity to water sources, facilitate tree crop expansion and larger farm sizes.

## Discussion

The chosen methodology and access to historical images with varying spatial accuracy enabled us to map and monitor irrigated agricultural land in the Tafrata plain, northeastern Morocco. This spatial analysis, using remote sensing and geographic information systems, provides key insights into the development and impact of irrigation on the region's agricultural sector. Agricultural activity in the study area has experienced a remarkable increase over recent decades, both through the expansion of cultivated land and the modernization and mechanization of the sector. In addition, agricultural specialization has become more pronounced, particularly with the widespread cultivation of olive trees across vast areas of the plain. This expansion reflects the dynamism of irrigated agriculture and its spatial concentration along the floodplains of several valleys and agricultural zones dependent on groundwater resources.

Stage one (1992-2012) saw the agricultural sector recover from the droughts of the 1980s, as evidenced by Analysis of annual rainfall at Taourirt (1931–2019) shows low, irregular, and intense precipitation, with frequent droughts. Notably, 1977–1990 and 1997–2001 experienced severe droughts, with annual totals below 200 mm and 110 mm (Agence de Bassin Hydraulique Moulouya, 2017). Agricultural activities were redistributed to adapt to new environmental conditions, leading to a concentration of farming in specific areas, these shifts changed rural land use and limited further agricultural expansion. Currently, irrigated agriculture represents the dominant farming system in Morocco's Molouya Basin, of which the Tafrata Plain forms a part; however, farmers who depend on rainfed cultivation face major challenges due to aridity and climatic variability (Bouberria, 2023).

The second stage (2012- 2022): This stage was linked to the emergence of Green Morocco Plan, which created an opportunity to support the agricultural sector in the plain and helped address the ongoing structural recession in the field. It also increased the income of local migrants and encouraged them to invest in the agricultural sector. The agricultural situation in the Tafrata Plain has changed significantly since 2012, with the introduction of irrigated farming that relies on the exploitation of groundwater resources. The availability of substantial groundwater reserves has provided fundamental support for this type of agriculture. In addition, the local topography facilitates the use and expansion of localized irrigation techniques. The nature of land tenure (collective lands) has enabled investment in large plots, enhancing productivity and agricultural yields, particularly as land rights holders seek to benefit from the rental income of agricultural lands despite the challenges associated with this practice. Furthermore, a stable population concentrated in scattered hamlets contributes to diversifying adaptive farming strategies in response to drought risks. The dynamic development of irrigated agriculture during this period was also linked to the creation of the hydro-agricultural project in the Tafrata plain in 2013, which involved the establishment of irrigated farming using water from the Hassan II dam on agricultural land belonging to the Sajaa tribe in the rural commune of Gteter. This project is part of the Green

Morocco Plan, which aims to strengthen the agricultural infrastructure in the Taourirt region by preparing 1,330 hectares, with 665 hectares allocated to olive cultivation and another 665 hectares to vegetable cultivation (ORMVAM, 2011).

The Tafrata Plain experienced a significant decline in pastoral activity in favor of rainfed and irrigated agricultural practices (Bouguelba, 2025). Olive cultivation in the region has been adopted as a new form of irrigated agriculture, which farmers have specialized in since 2012, when they equipped their land with localized irrigation technology, taking advantage of the support provided under the Green Morocco Plan. However, olive cultivation in the region dates back to an earlier period as part of irrigation management from the Moulouya River, with a limited number of farms overlooking the riverbank, both in the rural commune of Gteter and the commune of Houara Oulad Rahou. The aim of specializing in olive cultivation in the plain is to improve production levels and reduce land degradation, particularly with the decline in groundwater resources and the use of localized irrigation. It also constitutes a means of adapting to the climatic characteristics of scarce surface water, creating a positive socio-economic climate by increasing farmers' incomes and creating permanent or seasonal local employment opportunities, which are among the main objectives of agricultural specialization in olive cultivation in the plain. Land degradation represents a key determinant of land-use change and irrigated agricultural expansion in the Tafrata Plain. The area has experienced sustained vegetation decline and soil degradation, primarily driven by overgrazing, wood extraction, and recurrent droughts (Mouadili, 2021).

Third period (after 2022): This phase was marked by a significant increase in irrigated agricultural land, compared to signs of a decline in groundwater levels. The aquifer has experienced a gradual decline since 1995, from 15–16.5 m to approximately 17–18.8 m between 2000 and 2015, with a relative stabilization at low levels (Agence de Bassin Hydraulique Moulouya, 2017). After 2022, the expansion of irrigated agricultural land was accompanied by further indicators of groundwater depletion, including falling well levels, increased borehole density, higher daily pumping rates, and reduced natural recharge, prompting the adoption of measures such as surface irrigation to mitigate water stress. This necessitated the implementation of certain measures, such as: The widespread use of Localized drip irrigation in the plains before reaching a water crisis, which was the first step in containing this disruption. This phase was also marked by the introduction of new crops and plantations, which were among the options farmers targeted to ensure continued high agricultural yields and productivity while diversifying sources of agricultural income. In addition, increasing the area of irrigated land was one of the trends among farmers.

The positive development in irrigated agricultural areas hides deep regional disparities; some local communities have seen significant changes and intensive use of arable land, such as the rural communities of Houara Oulad Rahou and Lamrija, due to the spread of relatively fertile soil and the availability of groundwater, which has contributed to the spread of large agricultural holdings. While agricultural exploitation remained relatively weak in both the community of Sidi Ali Belkacem and a significant part of the rural community of Gteter, due to several factors, the most important of which are: the widespread use of small agricultural holdings, the depth of groundwater (Sidi Ali Belkacem), the prevalence of soil unsuitable for agriculture in some areas, and the problem of collective land ownership.

The most important feature of the plain in terms of agricultural exploitation is the specialization in olive cultivation, in addition to the cultivation of vegetables, fodder, cereals, and legumes, and the spread of various subsistence crops alongside tree plantations such as fruit trees and almonds, albeit to a lesser extent. The noticeable increase in agricultural land has been mainly linked to the dynamism of irrigated agriculture in recent decades, associated with afforestation, especially olive cultivation, which has been reflected in the overall development of agriculture in the area. Fodder crops have expanded, driven by their close link

to livestock breeding in stables. These transformations have resulted in increased productivity for certain crops, while others have experienced a decline. Another major aspect of this evolution concerns the control and acquisition of fertile land, which has promoted agricultural expansion - evidenced by land sales to external investors and the growing use of new technologies such as tube wells and drip irrigation systems. Changes in farming practices and land exploitation patterns have been accompanied by developments in farmers' incomes and the emergence of a new spatial agricultural model. The current agricultural dynamics have opened new prospects for the development of the sector and reshaped the agricultural landscape. These ongoing transformations continue to exert significant impacts on agricultural development in the plain, as well as on its economic, social, and environmental dimensions.

Irrigated agriculture in the study area has created a diverse landscape, with afforestation as the dominant land use. Adjacent plots are used for vegetables, legumes, fodder, and fallow land. The geometric layout of these plots, based on precise calculations, demonstrates the area's modernization through advanced agricultural techniques, which have required significant financial investment from farmers. Water has remained the main factor controlling the dynamics and transformations associated with the pastoral and agricultural landscape of the study area. The transition from nomadic pastoralism to a combination of nomadism and seasonal agriculture as a form of seasonal stability was due to the decline in water resources. Nature and colonial intervention then forced the population to settle permanently and combine traditional and modern farming. Thus, the status of water resources has become extremely important for agricultural development in the plains, and this importance is mainly linked to groundwater or dams available in the geographical area, which highlights the problem of the sustainability of agricultural activity due to intense pressure on the underground water table.

## **Conclusions**

The findings reveal a substantial and continuous expansion of irrigated agriculture since the early 1990s. Rainfall analysis at the Taourirt station (1931–2019) indicates strong inter-annual variability and recurrent droughts, with more than half of the recorded years below the long-term average. Severe drought episodes, particularly between 1977–1990 and 1997–2001, intensified water scarcity and accelerated reliance on irrigation and groundwater abstraction. This agricultural expansion reflects a profound territorial transformation, including a decline of steppe vegetation exceeding 50% between 1992 and 2022 and the conversion of rangelands and rainfed areas into irrigated cropland. Medium-sized farms are mainly concentrated along watercourses especially those connected to the Moulouya River and within the floodplain of Oued Athlagh, as well as near Lamrija and along the Guercif Taourirt corridor. Overall, the study demonstrates that the expansion of irrigated agriculture in the Tafrata Plain results from the combined influence of recurrent drought, groundwater availability, soil suitability, and agricultural modernization. Furthermore, the quantitative analysis reveals a rapid spatial expansion, while irrigation has strengthened agricultural productivity; its long-term sustainability remains critically dependent on balanced groundwater management under persistent climatic stress. The following recommendations are proposed. Integrate climate variability into agricultural planning and regulate and control groundwater abstraction to ensure aquifer sustainability. Align agricultural development with water resource carrying capacity and Promote water-efficient irrigation systems. Establish continuous geospatial monitoring of irrigated land expansion.

## **Acknowledgments**

The authors acknowledge the Department of Geography, Geographic Information Technology and Space Management Team, Faculty of Arts and Humanities, Mohamed 1st University, Morocco, for their support in completing this study.

### Conflicts of Interest

The authors declare that they have no conflicts of interest regarding the content of this article, the authors have read and approved the manuscript and agree with its submission to the journal.

### Funding Declaration

This research received no external funding.

### Author Contribution

S. Bouguelba proposed the research problem and carried out operations related to geographic information systems and supervised the findings of work. M. El kallouchi verified the analytical methods and investigated on the bibliographic side. Both authors discussed the results and contributed to the final manuscript.

### References

- Alexandridis, T. K., Zalidis, G. C., and Silleos, N. G. (2008). Mapping irrigated areas in Mediterranean basins using low-cost satellite Earth Observation. *Computers and Electronics in Agriculture*, 64(2), 93-103. <https://doi.org/10.1016/j.compag.2008.04.001>
- Ali, A., Hussain, B., Hissan, R.U., Al Aiban, K.M., Radulescu, M., and Magazzino, C. (2025a). Examining the landscape transformation and temperature dynamics in Pakistan. *Scientific Reports*, 15(1), 1-16. <https://doi.org/10.1038/s41598-024-80323-3>
- Ali, A., Jat Baloch, M. Y., Naveed, M., Nigar, A., Almalki, A. S., Rasool, A. G., and Arafat, A. A., (2025b). Advanced satellite-based remote sensing and data analytics for precision water resource management and agricultural optimization. *Scientific Reports*, 15(1), 1-17. <https://doi.org/10.1038/s41598-025-13167-0>
- Amiri, M., Bouguelba, S., Sbair, A., Ghzal, M., Qadem, Z., and Salem, A. (2025). Identification of suitable sites for rainwater harvesting using AHP and GIS in the Middle and High Moulouya Basin, Morocco. *E3S Web of Conferences*, 607, 1-9. <https://doi.org/10.1051/e3sconf/202560702001>
- Ambika, A. K., Wardlow, B., and Mishra, V. (2016). Remotely sensed high resolution irrigated area mapping in India for 2000 to 2015. *Scientific Data*, 3(1), 1-14. <https://doi.org/10.1038/sdata.2016.118>
- Ahmed, M. H., Mahdi, Z. S., Al-Jiboori, M. H., and Mahmood, D. A. (2024). Interannual variations of normalized vegetation index and potential evapotranspiration and their relationship in the Baghdad area. *Open Agriculture*, 9(1), 1-13. <https://doi.org/10.1515/opag-2022-0386>
- Agence de Bassin Hydraulique Moulouya. (2017). *Study on groundwater modeling of the Guercif aquifer*. Oujda, Morocco.
- Bendini, H. N., Fonseca, L. M. G., Bertolini, C. A., Mariano, R. F., Fernandes Filho, A. S., Fontenelle, T. H., and Ferreira, D. A. C. (2023). Irrigated agriculture mapping in a semi-arid region in Brazil based on the use of Sentinel-2 data and random forest algorithm. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, 48, 33–39. <https://doi.org/10.5194/isprs-archives-XLVIII-M-1-2023-33-2023>
- Bouberria, A.(2023). The use of remote sensing and GIS in studying the dynamics of irrigated space in Guercif Plain (Morocco). *Iraqi Journal of Science*, 64(4), 2060–2069. <https://doi.org/10.24996/ij.s.2023.64.4.40>

- Bouguelba, S. (2024). *Socio-spatial transformations in the Tafrata plain: From traditional pastoralism to irrigated agriculture (Northeast Morocco)*, PhD Thesis in Geography, Faculty of Arts and Humanities, Mohammed I University - Oujda - 394 p (Unpublished).
- Bouguelba, S. (2025). Degradation of vegetation cover and decline in rangeland productivity within the Eastern Moroccan steppe region: The Tafrata Plain in the Guercif Basin as a case study. *Arabian Journal of Scientific Research* 6(2), 1-12. <https://doi.org/10.5339/ajsr.2025.7>
- Bwambale, E., Home, P., Raude, J., and Wanyama, J. (2019). Development of a water allocation model for equitable water distribution at Doho Rice Irrigation Scheme, Uganda. *Hydrology*, 7(4), 62-69. <https://doi.org/10.11648/j.hyd.20190704.12>
- Bwambale, E., Naangmenyele, Z., Iradukunda, P., Agboka, K. M., Houessou-Dossou, E. A., Akansake, D. A., and Chikabvumbwa, S. R. (2022). Towards precision irrigation management: review of GIS, remote sensing and emerging technologies. *Cogent Engineering*, 9(1), 1-22. <https://doi.org/10.1080/23311916.2022.2100573>
- Cheikhaoui, Y., Sadiki, M., Allouza, M., Chakiri, S., and Bouabdli, A. (2024). Estimation of irrigation water requirements in the Gharb-irrigated perimeter (north-western Morocco). *Water Supply*, 24(2), 436-452. <https://doi.org/10.2166/ws.2024.012>
- Dari, J., Brocca, L., Quintana-Seguí, P., Casadei, S., Escorihuela, M. J., Stefan, V., and Morbidelli, R. (2022). Double-scale analysis on the detectability of irrigation signals from remote sensing soil moisture over an area with complex topography in central Italy. *Advances in water resources*, 161, 104-130. <https://doi.org/10.1016/j.advwatres.2022.104130>
- FAO. (2021). *The state of the world's land and water resources for food and agriculture – Systems at breaking point*. Synthesis report, 2021. Rome. <https://doi.org/10.4060/cb7654en>
- Field F. (2022). *Field data collection form used in this study (Author's own dataset)*. Unpublished dataset.
- Ghimire, P., Karki, S., Pandey, V. P., and Pradhan, A. M. S. (2025). Mapping spatio-temporal dynamics of irrigated agriculture in Nepal using MODIS NDVI and statistical data with Google Earth Engine: A step towards improved irrigation planning. *International Journal of Applied Earth Observation and Geoinformation*, 136, 1-16. <https://doi.org/10.1016/j.jag.2024.104345>
- Huang, S., Tang, L., Hupy, J. P., Wang, Y., and Shao, G. (2021). A commentary review on the use of normalized difference vegetation index (NDVI) in the era of popular remote sensing. *Journal of Forestry Research*, 32(1), 1-6. <https://doi.org/10.1007/s11676-020-01155-1>
- Mcallister, A., Whitfield, D., and Abuzar, M. (2015). Mapping irrigated farmlands using vegetation and thermal thresholds derived from Landsat and ASTER data in an irrigation district of Australia. *Photogrammetric Engineering & Remote Sensing*, 81(3), 229-238. <https://doi.org/10.14358/PERS.81.3.229-238>
- Meier, J., Zabel, F., and Mauser, W. (2018). A global approach to estimate irrigated areas – a comparison between different data and statistics. *Hydrology and Earth System Sciences*, 22(2), 1119-1133. <https://doi.org/10.5194/hess-22-1119-2018>
- Moisa, M. B., Dejene, I. N., Hinkosa, L. B., and Gameda, D. O. (2022). Land use/land cover change analysis using geospatial techniques: A case of Geba Watershed, western Ethiopia. *SN Applied Sciences*, 4(6), 187. <https://doi.org/10.1007/s42452-022-05069-x>
- Mouadili, O. (2021). *Hydric erosion and environmental dynamics in the basins of Oued Tlaghe and Oued Al-Abed (Taourirt, Eastern Morocco)*: Geomatic approaches (Doctoral dissertation), Mohammed I University, Oujda, Morocco.

- Ozdogan, M., Yang, Y., Allez, G., and Cervantes, C. (2010). Remote Sensing of Irrigated Agriculture: Opportunities and Challenges. *Remote sensing*, 2(9), 2274-2304. <https://doi.org/10.3390/rs2092274>
- Oubdil, S., Souiri, S., Ajmani, S., Nazih, A., Mentag, R., Benradi, F., and El Jalil, M. H. (2025). Characterization and GIS mapping of the physicochemical quality of soils in the irrigated area of Tafrata (Eastern Morocco): Implications for sustainable agricultural management. *Geographies*, 5(4), 1-22. <https://doi.org/10.3390/geographies5040066>
- ORMVAM (Office Régional de Mise en Valeur Agricole de Moulouya). (2011). *Study on the development of a new irrigation perimeter of approximately 1,000 ha in the Tafrata Plain, Taourirt Province: Socio-economic evaluation study, Phase 5* (96 pp.). Oujda, Morocco.
- Purnamasari, D., Teuling, A. J., and Weerts, A. H. (2025). Identifying irrigated areas using land surface temperature and hydrological modelling: Application to the Rhine Basin. *Hydrology and Earth System Sciences*, 29(6), 1483-1503. <https://doi.org/10.5194/hess-29-1483-2025>
- Pervez, M. S., and Brown, J. F. (2010). Mapping irrigated lands at 250-m scale by merging MODIS data and national agricultural statistics. *Remote Sensing*, 2(10), 2388-2412. <https://doi.org/10.3390/rs2102388>
- Rouse, J. W., Haas, R. H., Schell, J. A., and Deering, D. W. (1974). Monitoring vegetation systems in the Great Plains with ERTS. In S. C. Freden, E. P. Mercanti, & M. A. Becker (Eds.), *Proceedings of the Third Earth Resources Technology Satellite Symposium* (Vol. 1, pp. 309–317). Washington, DC: NASA. <https://share.google/3EkConnJXLo5zkHmU>
- Saha, R., Mitran, T., Mukherjee, S., Das, I. C., and Kumar, K. V. (2020). *Groundwater management for irrigated agriculture through geospatial techniques*. In *Geospatial technologies for crops and soils* (pp. 455–488). Singapore: Springer Singapore. [https://doi.org/10.1007/978-981-15-6864-0\\_13](https://doi.org/10.1007/978-981-15-6864-0_13)
- Singh, S., Singh, C., and Mukherjee, S. (2010). Impact of land-use and land-cover change on groundwater quality in the Lower Shiwalik Hills: A remote sensing and GIS-based approach. *Open Geosciences*, 2(2), 124-131. <https://doi.org/10.2478/v10085-010-0003-x>
- Seghir, A., Mazoz, L., and Idrissi, A. J. (2019). Cartographie de sol dans la zone méridionale de la plaine de Tafrata au Maroc Centro-Oriental et évaluation de leur sensibilité à la désertification. *Moroccan Journal of Agricultural and Veterinary Sciences*, 7(2), 371-378. [https://agrimaroc.org/index.php/Actes\\_IAPH2/article/view/704](https://agrimaroc.org/index.php/Actes_IAPH2/article/view/704)
- Somayajula, V. K. A., Ghai, D., Kumar, S., Tripathi, S. L., Verma, C., Safirescu, C. O., and Mihaltan, T. C. (2022). Classification and validation of spatio-temporal changes in land use/land cover and land surface temperature of multitemporal images. *Sustainability*, 14(23), 1-35. <https://doi.org/10.3390/su142315677>
- Velpuri, N. M., Thenkabail, P. S., Gumma, M. K., Biradar, C., Dheeravath, V., Noojipady, P., and Yuanjie, L. (2009). Influence of resolution in irrigated area mapping and area estimation. *Photogrammetric Engineering & Remote Sensing*, 75(12), 1383–1395. <https://doi.org/10.14358/PERS.75.12.1383>
- Xue, J., and Su, B. (2017). Significant remote sensing vegetation indices: A review of developments and applications. *Journal of Sensors*, 2017(1), 1-17. <https://doi.org/10.1155/2017/1353691>
- Zipper, S., Kastens, J., Foster, T., Wilson, B. B., Melton, F., Grinstead, A., and Marston, L. T. (2024). Estimating irrigation water use from remotely sensed evapotranspiration data: Accuracy and uncertainties at field, water right, and regional scales. *Agricultural Water Management*, 303, 1-14. <https://doi.org/10.1016/j.agwat.2024.109036>