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Remote sensing monitoring of irrigated areas from 1972 to 2018 in the Guigou Plain, Middle Atlas, Morocco

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Abstract: The cartography and quantification of irrigated fields in the context of decreasing rainfall constitute a key element for water resources management. Therefore, in this context, the use of remote sensing methods applied to Landsat-type images with a high spatial resolution for monitoring the changes in land use in general and irrigated crops, in particular, is highly relevant. This paper aims to present a method for mapping spatial and temporal changes in irrigated parcels in the Guigou Plain, located in the central Middle Atlas, based on Landsat images and fieldwork. For the years 1985, 1998, 2010 and 2018, the use of a supervised classification method based on the principle of machine learning, fed by precise field surveys, has made it possible to highlight a significant extension of irrigated areas to the expense of pastureland and rainfed crops. Over the entire period under consideration, the results obtained with good precision (98.5% overall accuracy) showed that the area under irrigated crops has increased from approximately 699 ha to 3988 ha, i.e. an increase of 570%. The corollary of this increase is strong pressure on the water resource, especially groundwater. This information on the total extension of irrigated plots can be taken as a reference in the perspective of reasoned management of water resources in the sector.

Keywords: irrigated crops, land use, Middle Atlas, Morocco, remote sensing

INTRODUCTION

Irrigation has always played an important role in the development of human societies by promoting agricultural production and enhancing food security. During the 20th century, the area under irrigation increased from 63 million ha to 306 million ha worldwide [Siebert *et al.* 2015]. Irrigation accounts for more than 70% of the fresh water withdrawn by human activities, so this withdrawal induces the greatest imbalance in the hydrological cycle at different spatial scales [Wada, Bierkens 2014]. Although irrigation practices affect food production and water resources management, detailed knowledge of irrigation is still lacking. Indeed, while the use of remote sensing techniques has resulted in several irrigation mapping products being available at the global and regional scale, GMIA 5.0 [Siebert *et al.* 2005], MIRCA2000 [Portmann *et al.* 2010], GRIPC [Salmon *et al.* 2015] with a maximum resolution of 250 m, explicit and precise information on the spatial occurrence of irrigation is not available at the fine scale, making irrigation the missing variable for a comprehensive understanding of the dynamics of the hydrological cycle in agricultural areas.

Remote sensing methods based on spatially and temporally continuous data have emerged as a powerful and efficient tool for producing land cover maps and monitoring irrigated land in many locations around the world under various environmental conditions [Thenkabail *et al.* 2005; Xie, Lark 2021]. In recent years, the use of satellite image time series to map land cover with the high spatial resolution has been facilitated by the open access to Landsat, Sentinel and SPOT satellite archives [Chance *et al.* 2018; Czekajlo *et al.* 2021; Maselli *et al.* 2020]. Indeed, a review of the international literature shows a considerable number of studies that are based on the use of satellite image time series at

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local, regional and continental scales [Belgiu, Csillik 2018; Bhatnagar *et al.* 2020; Bian *et al.* 2020; Bretreger *et al.* 2020; Chaves *et al.* 2020; Maselli *et al.* 2020; Pervez *et al.* 2014]. The use of these data has been accompanied by the development of numerous algorithms for processing and extracting information from images (Support Vector Machine, Random Forest, Maximum Likelihood, etc.) [Ahmadi *et al.* 2020; Htitiou *et al.* 2019; Pelletier *et al.* 2016; Rana, Venkata Suryanarayana 2020; Rodriguez-Galiano *et al.* 2012], but all of them exploit the spectral difference between irrigated and non-irrigated areas [Bégué *et al.* 2018]. However, most of the remote sensing works using these high spatial resolution images result in a global land cover aiming at the study of large landscape transformations, but few explicitly include irrigation as a distinct class [Ozdogan *et al.* 2010; Xie, Lark 2021]. Indeed, the difficulty in identifying irrigated areas is due to the diversity in the size of irrigated fields and their dispersed distribution, as well as the fact that the different nature of plantations within areas and climatic factors determine different irrigation dates during the year [Tack *et al.* 2017].

This paper presents a methodology for high spatial resolution mapping and quantifies the evolution of irrigated areas based on fieldwork and Landsat TM (Thematic Mapper) and OLI (Operational Land Imager) satellite images in the Guigou Plain, in the central Middle Atlas, Morocco. This part of Morocco, which was traditionally a land of breeding where transhumance was perpetuated by local breeders and neighbouring regions until recently [Amyay *et al.* 2000; Badidi 1995; El Jihad 2016; Tag 1996], has been characterised, since the end of the last century, by a dynamic of land occupation and use in general and of irrigated areas in particular [El-Bouhali *et al.* 2021a]. The extension of agricultural practices based on irrigation in the context of decreasing rainfall has a strong influence on water resources, particularly underground [El-Bouhali *et al.* 2021b]. In order to assess the environmental impacts of the extension of irrigated areas and to formulate strategies for the sustainable use of limited water resources, it is essential to know the precise location of irrigated agriculture and its evolution over time. This information on the spatio-temporal dynamics of irrigated agriculture for over more than three decades (33 y) is extracted using a supervised classification method based on the principle of machine learning.

MATERIALS AND METHODS

STUDY AREA

The area considered for this study is located in the Guigou Plain (765 km^2) within the Haut-Sebou watershed which is part of the Middle Atlas Causse. This area is part of the administrative provinces of Boulemane and Ifrane (Fig. 1).

The terrain is mainly composed of Lias limestone covered by basaltic flows [Bentayeb, Leclerc 1977; Charrière 1990] with a tabular structure, more faulted than folded [Martin 1981; Zeryouhi 1977], facilitating the infiltration of water and the existence of large karstic aquifers [Bentayeb, Leclerc 1977; Zeryouhi 1977]. Surface flows are scarce [Gamez *et al.* 2000]

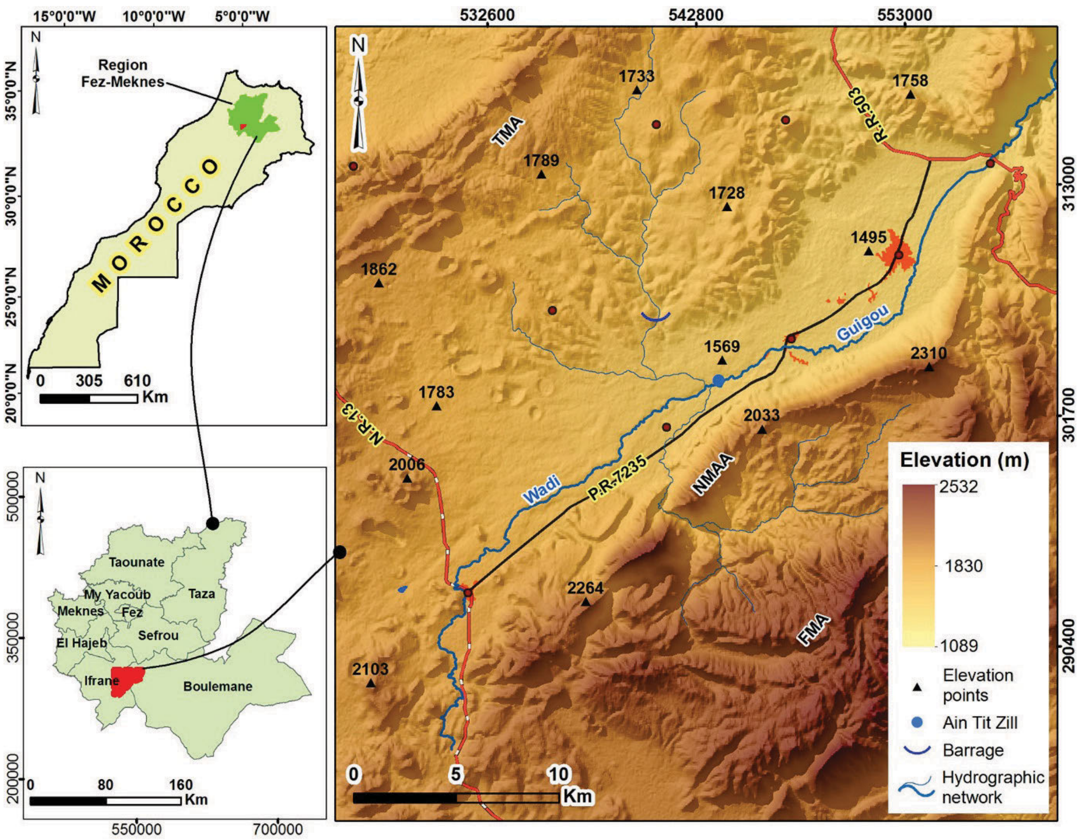

Fig. 1. Location of the study area; North Middle Atlas Accident (NMAA) – the passage between the Tabular Middle Atlas (TMA) unit and the folded Middle Atlas (FMA) unit, source: own elaboration

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and often related to hydro-karstic emergences that feed the wadis [Akdim *et al.* 2011]. The Wadi Guigou is the main watercourse in the area. Supplied by the spring Aberchane, it flows over eruptive rocks and crosses the large Guigou Plain, a water transfer and consumption area, to Aït Khabbach, where there is a hydrometric gauge [Qadem 2015]. Altitudes in the study area range from 1495 m in the Guigou depression to 2310 m at the level of the North Middle Atlas accident (NMAA). The climate is semi-arid, with hot, dry summers and cold, rainy or snowy winters [Akdim *et al.* 2011]. From 1970 to 2017, the climatic station of Aït Khabbach recorded 357 mm of average annual rainfall (Sebou Hydraulic Basin Agency).

The Guigou Plain is therefore characterised by substantial aquifer reserves [Amrani, Hinaje 2014] but the potential of surface water resources is relatively scarce due to low rainfall, bedrock permeability, anisotropy and depth of aquifers. These hydrogeological characteristics govern the organisation of landscape and human land use.

DATA AND METHODS

Diachronic studies of landscapes are commonly carried out using aerial photographs and satellite images with temporal, spatial and spectral resolutions that are suitable for monitoring land use and land cover changes, and associated processes. In recent years, these approaches have benefited from remote sensing databases enrichment and their availability. The approach used in this study consists of several steps and is based on the joint use of multi-date satellite images (Tab. 1) and fieldwork. Two periods are processed and analysed differently: 1972–2018 and 1985–2018.

The images acquired from 1972 to 2018 make it possible to assess the rate of change in the environment and the evolution of irrigated areas. For the selected period, the six Corona satellite images, acquired during a mission in 1972, are used as reference documents. With a spatial resolution of 1.2 m but too complex to be processed by image classification methods, they are considered for this study because they allow an overview of the main land use and occupancy units before the national plans for the agricultural development of the territories started to be implemented. The images of the study area are mosaicked and the analysis of the general organisation of the land cover is done by photo-interpretation.

The acquisition dates selected make it possible to understand the rhythms of modification of the environment and the evolution of the irrigated surfaces according to climatic or political factors. The year 1985 reflects the irrigation situation after the long period of drought which affected Morocco at the beginning of the 1980s. The year 1998 is situated in the period of the beginning of State intervention for the development of agriculture and the generalisation of modern production techniques in mountainous areas. With the aim of managing social and economic imbalances between regions, the first interventions in the field of agriculture in Morocco were selective. In 2008, the State launched the Green Morocco Plan to correct the errors of the first interventions. The 2010 image, therefore, includes the first effects of this plan. The 2018 mapping shows the

Table 1. Satellite data used

Satellite	Date	Path	Row	Source	Spatial resolution (m)
		photographic film			
Corona KH-4B	26 May 1976	DS1101-2138DA021b		USGS	1.2
	26 May 1976	DS1101-2138DA021c		USGS	1.2
	26 May 1976	DS1101-2138DA022b		USGS	1.2
	26 May 1976	DS1101-2138DA022c		USGS	1.2
	26 May 1976	DS1101-2138DA023b		USGS	1.2
	26 May 1976	DS1101-2138DA023c		USGS	1.2
Landsat TM 4-5	17 May 1985	201	037	USGS	30
	14 Aug 1985	200	037	USGS	30
	12 Apr 1998	200	037	USGS	30
	02 Aug 1998	200	037	USGS	30
	15 May 2010	200	037	USGS	30
	03 Aug 2010	200	037	USGS	30
Landsat 8 OLI	19 Apr 2018	200	037	USGS	30
	09 Aug 2018	200	037	USGS	30
Sentinel-2	13 Jul 2018	T30	SUB	ESA	10
	13 Jul 2018	T30	SUC	ESA	10
	13 Jul 2018	T30	STC	ESA	10
	13 Jul 2018	T30	STB	ESA	10

Source: own elaboration based on United States Geological Survey (USGS), European Space Agency (ESA).

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current situation of land use and land cover. The selection of dates is followed by the determination of the most favourable months for the study of irrigated areas and the nomenclature used for image classifications. The sectors visited and the surveys of farmers made it possible to establish a list of crops grown in the region, to separate them into two main land-use classes: irrigated (potato, onion, carrot, alfalfa, corn) and rainfed (barley, wheat, oats), and to draw up a precise agricultural calendar.

The combination of fieldwork knowledge and visual examination of the Sentinel-2 colour composition (July 2018) led to the definition of landscape groups that highlights the contrasts in the surface and land use in the Guigou Plain (Fig. 2). At this period of the year, due to the chlorophyll activity of irrigated crops and the senescence or harvest of rainfed crops, there was a clear spectral separability of these different components. All irrigated crops showed specific and homogeneous responses, reflecting active vegetation. The basaltic and calcareous wastelands used for grazing, forests, and habitats also contrast clearly and complete the final nomenclature retained for the classification of the images.

In preparation for the diachronic analysis, geometric and radiometric corrections are applied to Landsat TM and OLI images. The image classification and validation process (Fig. 3) followed a strict procedure based on the locating of representative field and ground data sampling. On the agricultural territory, 100 control points per class and land use surveys (learning data) were carried out during the three field campaigns in 2018 on about 100 plots per land use class.

Many authors [MAXWELL, SYLVESTER 2012; PERVEZ *et al.* 2014; SAADI *et al.* 2015; ZHENG *et al.* 2015] have used the normalised difference vegetation index (*NDVI*) to distinguish irrigated crops from other land use classes. As the spectral signatures of different surfaces can be confusing at a given time of the year, authors also often use time series for a diachronic approach [DUTRIEUX *et al.*

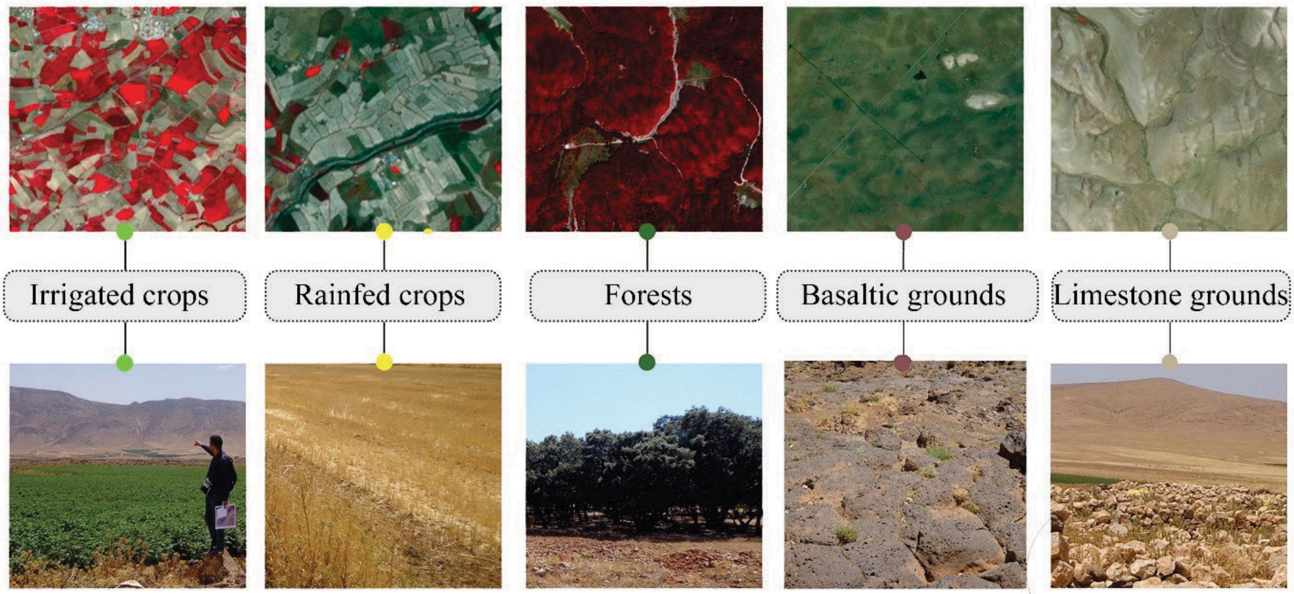

Fig. 2. Field correspondence – Sentinel-2 image, August 2018 status; source: own elaboration based on Sentinel-2 image and fieldwork

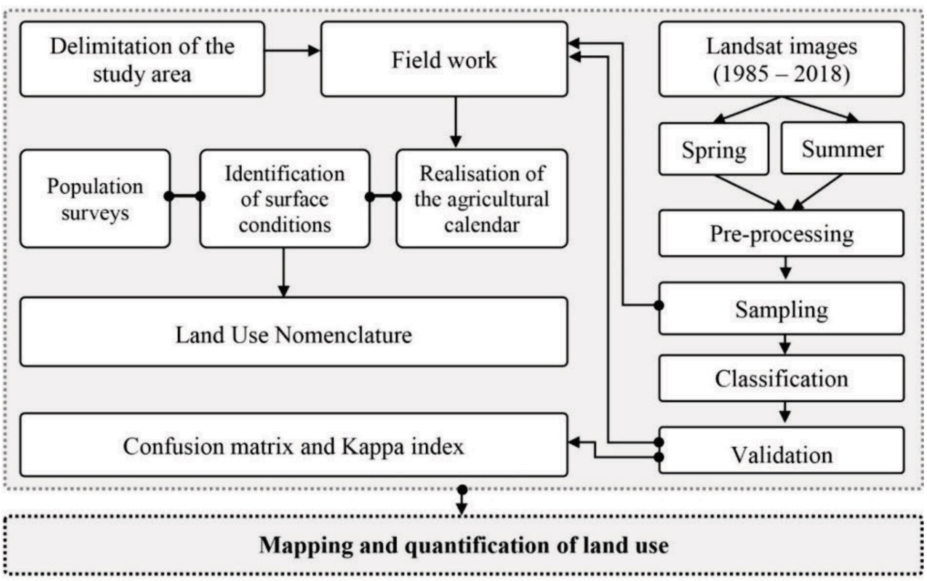

Fig. 3. Scheme of classification and validation process; source: own elaboration

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2016; Jianya *et al.* 2008; Kumar Sharma *et al.* 2018]; this allows to remove the spectral confusions between vegetation formations during certain seasons. To discriminate irrigated crop areas from other land use patterns, satellite images here were classified using the maximum likelihood method, which is a supervised method based on the principle of "machine learning". All channels of each image were used, except for the Corona images and the thermal channel for the Landsat data. The classification accuracy of the 2018 image is computed from a confusion matrix, a usual remote sensing method [Blatchford *et al.* 2019; Congalton 1991; Congalton *et al.* 1983; Foody 2002] where reference data are fieldwork data acquired at the same time. Land use maps by date (1985, 1998, 2010 and 2018) are thus produced and the areas are calculated for each class. The irrigation quantification maps were overlaid to specialise the areas of change during this period.

This methodology could be applied to images from other years to detail the increase in irrigated areas, on the condition that the images used are synchronous with the irrigation period, which may be slightly different from one year to another depending on climatic conditions. This methodology is therefore reproducible, although the results obtained depend on the researchers' level of analysis and mastery of processing methods.

RESULTS AND DISCUSSION

CLASSIFICATION RESULTS

From 1972 to 2018: An expanding agricultural area

The comparative visual analysis of the Corona (1972) and Sentinel-2 (2018) data showed substantial spatiotemporal changes in land use in the study area over the last decades (Fig. 4). The different types of lands that are composing the territory are clearly identified in the images by their specific colour and reveal a significant development of the land used for agriculture over the period under consideration. These areas with a high positive trend in temporal evolution are the continuation of a strip of land, cultivated in 1972, bordering the Wadi Guigou and extending towards the grazing lands throughout the depression.

In 1972, economic activity in the Guigou Plain was still largely based on transhumance [Jennan 1986]. During this period, the population concentration in the depression was low, with the exception of small settlements occupying the valley and producing cereals (maize, barley, wheat) under extensive irrigation from a traditional network derived from the Guigou Wadi or its springs [Loubignac 1938], but the plain is mainly covered by vast expanses of bare land used for grazing. In 2018, the Sentinel image identifies the main components of the territory. It contrasts several distinct land areas, including irrigated areas, bare land and habitat.

The process of land use changes can be illustrated in two municipalities crossed by the Guigou Wadi: Timahdite and Guigou. The Corona and Sentinel-2 image extracts (Fig. 5) show that over the period from 1972 to 2018, these areas have undergone significant urban sprawl at the expense of agricultural land, reflecting the increase in population over this period. According to the General Population and Housing Census (GPHC), the study area has seen a very significant increase in population from 1994 to 2014 (Tab. 2).

From 1985 to 2018: Irrigation deployment

The overall accuracy of 98.5% showed a good performance in the classification of the Landsat 8 image of 09.08.2018. This accuracy is very satisfactory for all classes (Tab. 3) and is explained by good spectral separability at the time of shooting. The basaltic land, forest and irrigated crop classes are perfectly classified (100%). Slight confusions are to be mentioned for limestone land (96%), habitats (98%) and rainfed crops (97%) classes. The major errors of both omission and commission, meanwhile, are marginal and arise from limestone soils that may interfere with the rainfed crop, habitat and basaltic land classes. These results demonstrated that August is an appropriate month for distinguishing irrigated crop areas.

Figure 6 shows the land use maps for the years 1985, 1998, 2010 and 2018, i.e. over a period of 33 y. The spatial and temporal changes in land use over this period are very apparent. For the four dates, all the cultivated areas are limited to a strip of land along the Wadi Guigou. In 1985, the cultivated areas discontinuously occupied the Guigou depression and shared it with the basaltic terrain. In subsequent years, this bare land was gradually converted to cultivated land. At the same time, there was a significant expansion of irrigated crops in all directions of the depression. In 2018, overall, rainfed crops were mostly on the

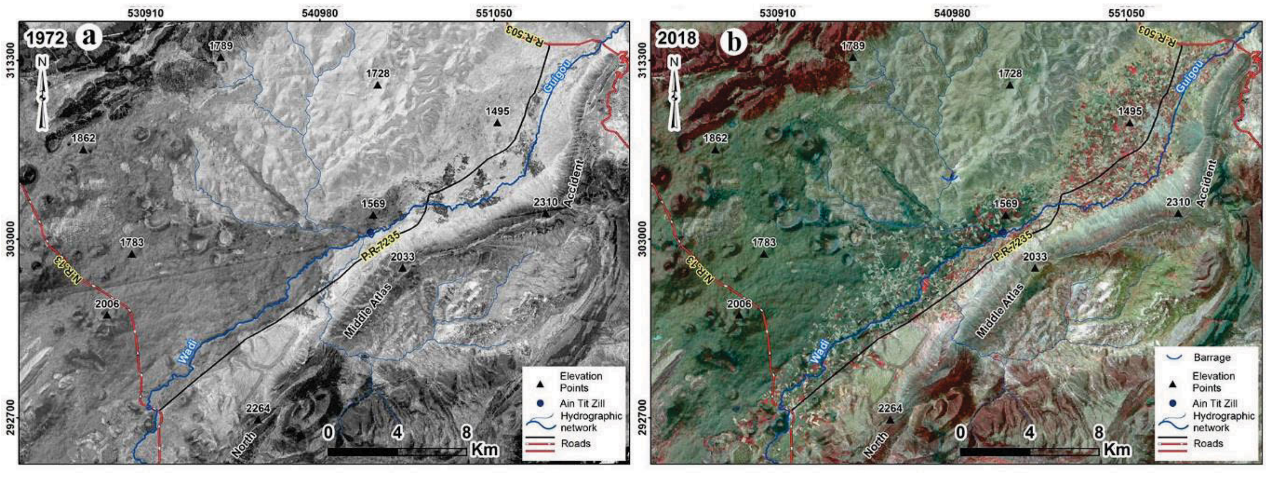

Fig. 4. Study area: a) Corona image, 1972; b) Sentinel-2 image, 2018; source: own elaboration based on United States Geological Survey and European Space Agency

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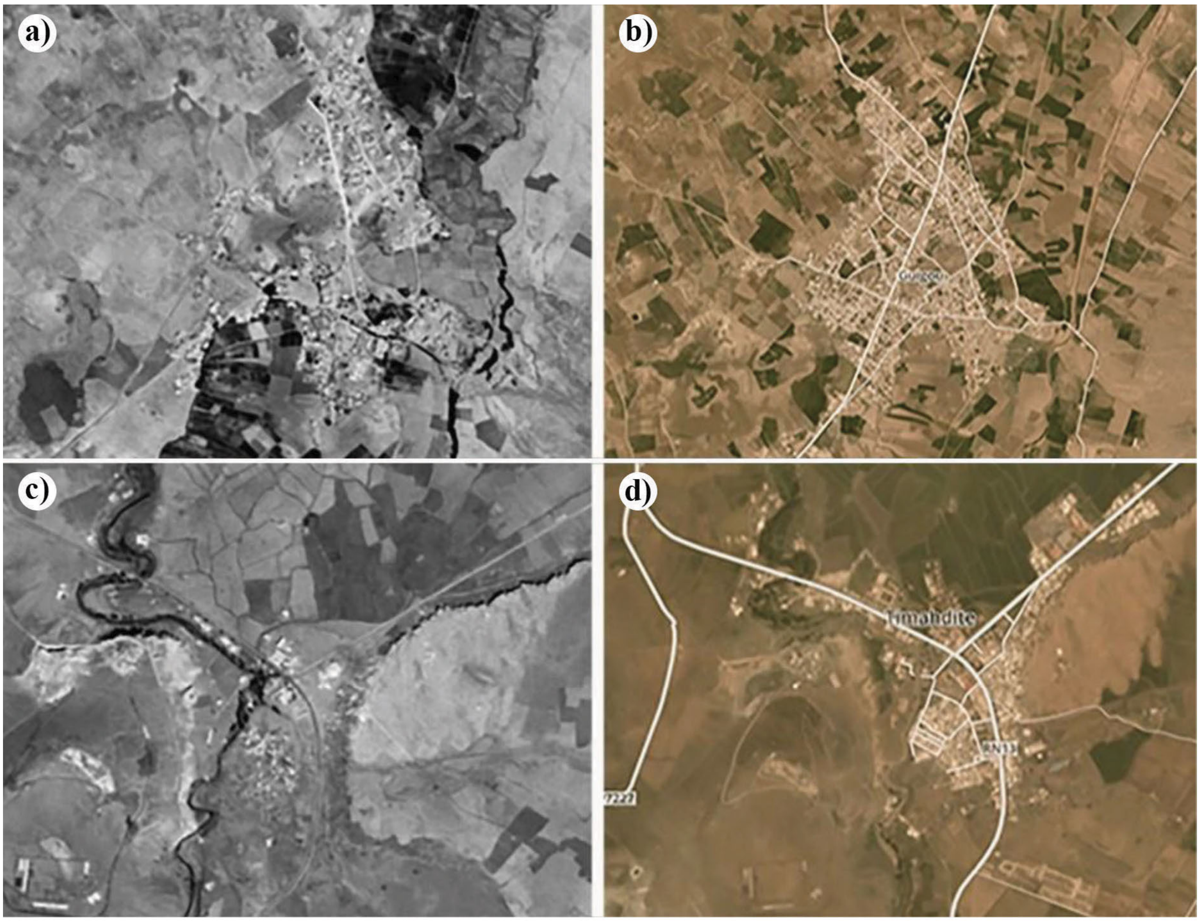

Fig. 5. Evolution of the urban centres from 1972 to 2018: a) Guigou, 1972; b) Guigou, 2018; c) Timahdite, 1972; d) Timahdite, 2018; source: United States Geological Survey

Table 2. Evolution of the population in Guigou and Timahdite from 1994 to 2014

Commune	1994	2004	2014
Guigou	16,249	19,035	21,607
Timahdite	8,585	10,080	10,945

Source: High Commission for Planning.

periphery of irrigated crops. These observations showed, on the one hand, the continuous expansion of irrigated areas to the detriment of basaltic and calcareous soils and, on the other hand, a concentration of this process mainly in the Guigou sector.

Table 4 shows that the area of cultivated lands, both rainfed and irrigated, increased significantly, from 7,243 ha to 9,622 ha, between 1985 and 2018. Within this category, irrigated crops increased from 699 ha (less than 1% of the area) in 1985 to 3,987 ha (5.2% of the area) in 2018, an increase of more than

Table 3. Confusion matrix of the classification of the Landsat 8 image of 09.08.2018

Class	Irrigated crops	Rainfed crops	Forests	Habitats	Basaltic grounds	Limestone grounds	Total
	%						
Irrigated crops	100	0	0	0	0	0	**100**
Rainfed crops	0	97	0	1	2	0	**100**
Forests	0	0	100	0	0	0	**100**
Habitats	0	1	0	98	0	1	**100**
Basaltic grounds	0	0	0	0	100	0	**100**
Limestone grounds	0	2	0	1	1	96	**100**
Total	**100**	**100**	**100**	**100**	**103**	**97**	–

Source: own study.

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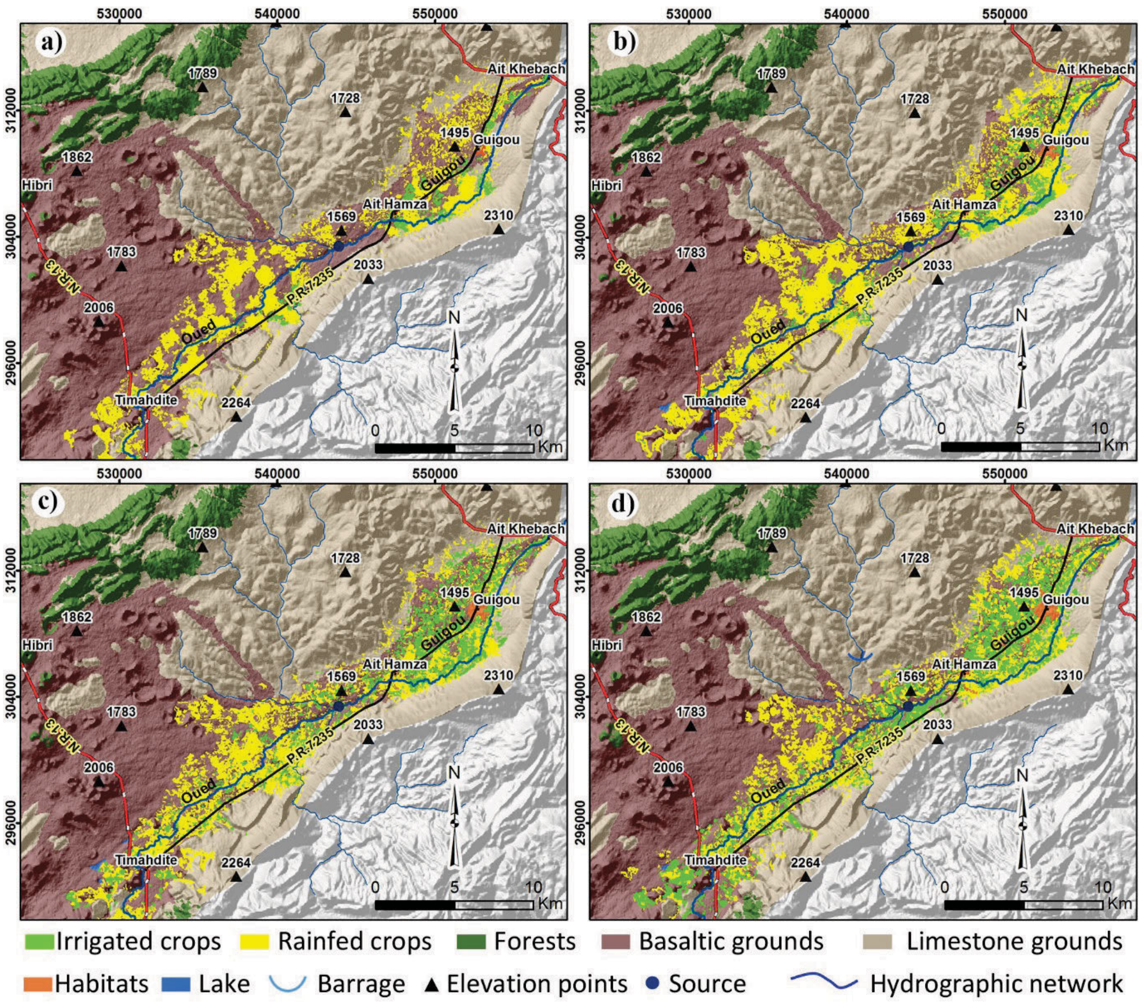

Fig. 6. Land use map: a) 1985, b) 1998, c) 2019, d) 2018; source: Landsat TM and OLI images

Table 4. Land use from 1985 to 2018

Class	Surface in							
	1985		1998		2010		2018	
	ha	%	ha	%	ha	%	ha	%
Irrigated crops	699.0	0.9	1,425.1	1.9	2,717.8	3.6	3,987.3	5.2
Rainfed crops	6,544.2	8.5	7,871.9	10.3	6,690.9	8.7	5,635.5	7.4
Forests	6,364.9	8.3	6,419.9	8.4	6,466.8	8.4	6,890.1	9.0
Basaltic grounds	26,749.0	34.9	25,022.7	32.7	24,926.2	32.6	24,506.0	32.0
Limestone grounds	36,155.2	47.2	35,652.0	46.6	35,518.7	46.4	35,178.0	46.0
Habitats	35.8	0.0	134.6	0.2	187.0	0.2	328.6	0.4

Source: own study.

3,288 ha. Rainfed crops, with 6,544 ha in 1985 (8.6%), were slightly decreasing in spatial coverage with 5,635 ha (7.4%) in 2018. The data suggest a continuous but minimal increase in forest formations with 6,365 ha in 1985 and 6,890 ha in 2018, or 9% of the total area. Basaltic and calcareous outcrops dominated the study area: more than a third of the surface is composed of basaltic soils and almost half – of calcareous soils. However, these areas continuously reduced over the period studied. Basaltic land decreased from 26,749 ha in 1985 to 25,023 ha in 1998, 24,926 ha in 2010 and 24,506 ha in 2018, i.e. there is a loss of 2,243 ha between 1985 and 2018. A regression of 977 ha is observed for limestone terrains over the same period. At the territory level and over all the dates studied, the habitat class is the lowest represented with 36 ha (0.05%) in 1985 and 329 ha (0.43%) in 2018. But this class has the largest expansion, with an almost tenfold area increase from 1985 to 2018. Here again, this positive dynamism can be explained by the significant expansion of the Guigou municipality on the basaltic terrain. Overall, the decline between 1985 and 2018 in rainfed crops, basaltic and limestone

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terrains is paralleled by an expansion in irrigated crops and settlement.

The spatialisation of irrigated areas from 1985 to 2018 shows a large expansion of irrigated crops in the Guigou depression (Fig. 7). The quantification of this dynamism (Tab. 5) highlights the development of these crops with more than 3,200 ha over 33 y (about 100 ha·y^{-1}). In contrast, rainfed crops and grazing land (both calcareous and basaltic bare terrains) showed a continuous regression of their surface, respectively by 908 ha and 3240 ha.

INTERPRETATION

In this study, the monitoring of land use area was carried out by combining satellite images and fieldwork data. The results obtained from the time series analysis show that the study area has experienced a dynamic characterised by an expansion of cultivated areas, an intensification of irrigation and the regression of traditional land use practices. Once this overview has been completed, it is worthwhile to consider the factors causing these

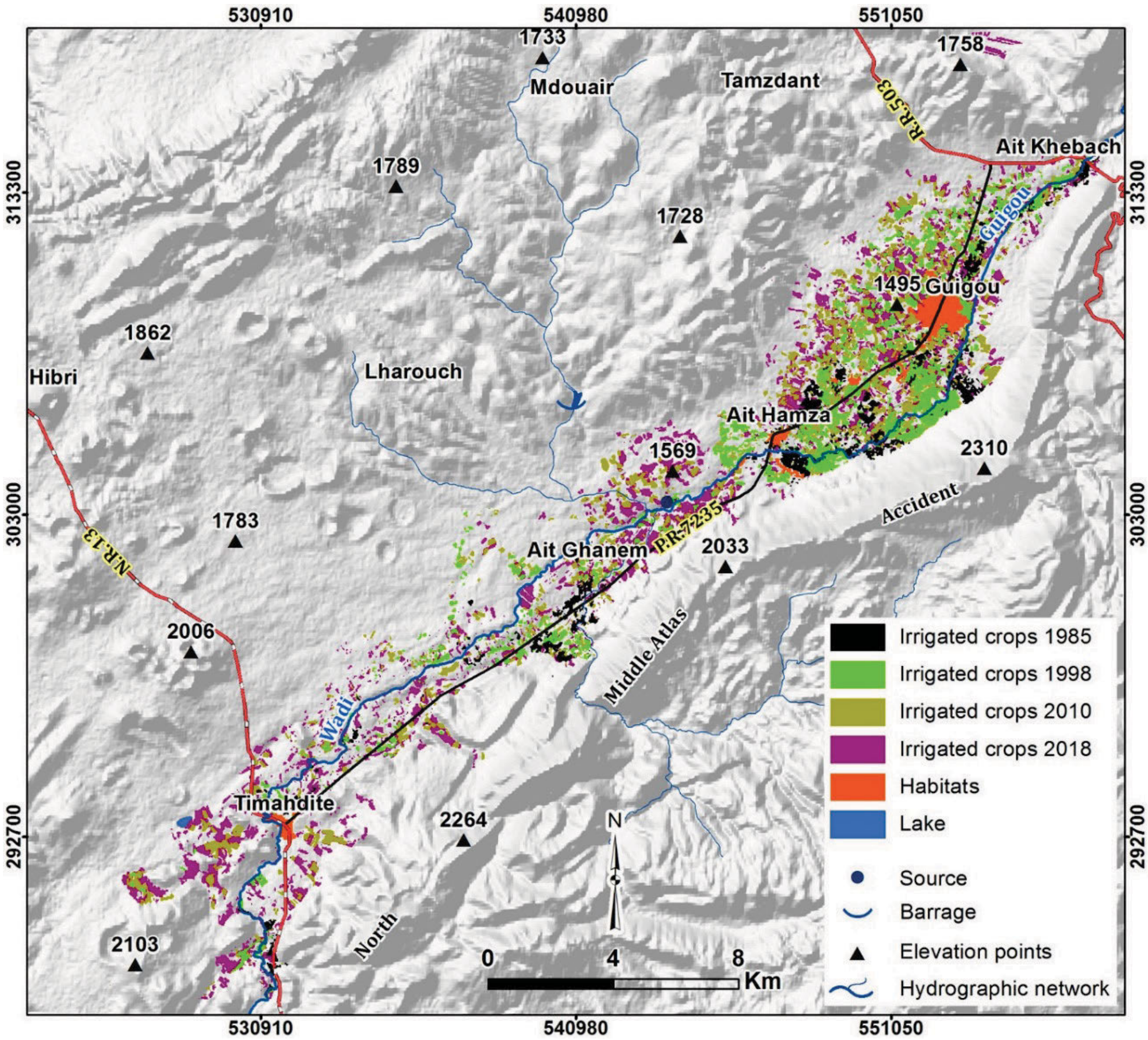

Fig. 7. Evolution of irrigated crop areas from 1985 to 2018; source: own study

Table 5. Evolution of land use (ha) from 1985 to 2018 by period

Classes	1985–1998	1998–2010	2010–2018	1985–2018
Irrigated crops	726	1293	1270	3288
Rainfed crops	1328	–1181	–1055	–909
Forests	55	47	423	525
Basaltic grounds	–1726	–97	–420	–2243
Limestone grounds	–503	–133	–341	–977
Habitats	99	52	142	293

Source: own study.

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changes in order to determine the decisive periods in the transformation of land use in this sector.

From the 1960s onwards, due to the socio-economic problems that Morocco experienced, three plans were successively introduced: the 1960–1964 Five-Year Plan, the 1965–1967 Three-Year Plan and the 1968–1972 Five-Year Plan, with the founding of the National Irrigation Office (Fr. Office National d'Irrigation – ONI) in 1960 and the Rural Modernisation Office (Fr. Office National de Modernisation Rurale – ONMR) in 1961, which were substituted by the Agricultural Development Office (Fr. Office de Mise en Valeur Agricole – OMVA). The Moroccan government was thus trying to concentrate technical and financial measures to have a more effective action in the agricultural sector, the main sector of the Moroccan economy [Akesbi 2006]. But this economy remains highly dependent on climatic hazards and the "traditional sector", which regroups the majority of farmers, shows a very complex structure. In fact, political choices were selective and agricultural investment measures essentially promoted large-scale hydraulics, using a policy of dams (1966–1985) which mainly benefited medium and large farms in the large-scale irrigation schemes. Except for a few irrigated spots or valleys, Middle Atlas does not benefit from these measures and remains the typical example of these low-populated territories, largely undeveloped and facing a significant rural exodus. Jennan [1986] reported that from 1971 to 1982, the demographic growth of the Middle Atlas did not exceed 1.2%, and some municipalities saw their population decrease. Even though irrigated crops are beginning to spread along Wadi Guigou and near springs, local people still use traditional techniques for sharing and managing water (customary law, water turns) and the yield of crops is low. Until 1985, the region was primarily regarded as a breeding area, but populations gradually moved from a pastoral society to a fixed community based on grazing land and water resources. This led to the emergence of the first nuclei of sedentarisation.

During the decade (1980–1990), the significant rainfall and hydrological droughts (drying up of springs, drying up of lakes, etc.) that occurred in Morocco caused serious impacts on agricultural production [Barakat, Handoufe 1997; Labouesse 1986; Stour, Agoumi 2008], and particularly disturbed the parts of the agricultural system based on rainfall (decrease in land yield, degradation of pasture lands). This situation leads the public authorities to engage in programs to combat drought within a global vision of rural development and the deployment of new agricultural production systems, less sensitive to climatic hazards. Priority is then given to rural areas that have not been the object of significant public investments in the past in order to correct the imbalances between rainfed and irrigated areas. Thus, demographic growth, forced sedentarisation of the populations and the crisis of transhumance will lead the rural sectors of the Middle Atlas towards a pluri-agricultural activity. After the primacy of extensive cereal cropping, irrigation systems were redesigned with the drilling of wells and the introduction of motor-driven pumps to extract groundwater [El-Bouhali *et al.* 2021a; Jennan 1986]. This was the starting point for the expansion and intensification of potato crops. In this government policies context, a process of evolution took place in the municipalities. The Guigou Plain has seen a significant expansion in the irrigated crops area, from 699 ha in 1985 to 1,425 ha in 1998, while the rainfed crops area increased from 6,554 ha to 7,871 ha. These changes in the agricultural areas are promoted by various initiatives related to an appreciation of the potential of the region by the local actors [Tag 1996] and lead to a declining breeding land (both bare limestone and basalt land). Urban centres such as Timahdite and Guigou experienced a demographic boom.

Government interventions took over between 1998 and 2010 in order to improve the population's standard of living and encourage sedentarisation. In the sector, since 2006, the contribution of resources has focused mainly on hydraulic developments with drilling and construction of irrigation canals as part of the Green Morocco Plan; this has resulted in an increase of 1,293 ha of irrigated land surface area. The years 2011–2016 are marked by an intensification of government subsidies, which increased from 179 in 2011 to 265 in 2016 with a peak of 371 in 2015 [Ministère ... 2017], and the entry of external investors from Er-Rachidia, Doukala, Missour and other provinces. This boosts the irrigation of the land, which surface area has increased by 1,270 ha. The conversion of basaltic terrains and the drilling of new wells and boreholes increased in number. The Sehb El Marga dam was built and a diverse range of irrigation techniques was developed (Photo 1). Population growth continues with the expansion of the urban centres of Guigou and Timahdite.

The territory of irrigated crops increased from 2,717 ha in 2010 to 3,987 ha in 2018. This increase was mostly at the expense of land used for rainfed crops or pasture. The will of the population and the subsidies of the Government are reflected in the shaping of an agrarian landscape based on irrigated market gardening: potatoes, onions, and carrots with other types of crops (maize, zucchinis, alfalfa, etc.) occupying a very limited area (Photo 2). This new way of farming replaces the traditional rainfed system of agriculture.

With the same methodology we have already noticed an increase of 350% in irrigated areas over the period 1985–2018 in the sectors located further north in the Central Middle Atlas [El-Bouhali *et al.* 2021a, El-Bouhali *et al.* 2021b]. Here, the increase is 600% in the same period. It is therefore obvious that on the whole of the Central Middle Atlas the pressure on water resources has increased considerably in the last few decades.

In the context of a decrease in precipitation noted since the end of the 1970s, the increase in irrigated surfaces could only be achieved through technical evolutions of the hydro-agricultural system, of which three main phases can be distinguished. The first phase was characterised by a small extension of irrigated areas around a traditional network of seguias fed directly from dams on the Wadi Guigou or via springs [Jennan 1986; Loubignac 1938]. The second phase of hydro-agricultural development in the Guigou Plain began with the drought that affected Morocco in the 1980s. The lack of surface runoff during the summer forced farmers to rely secondarily on groundwater. This stage was marked by the intensification of wells and the introduction of gas-powered motor pumps to draw water from the aquifer during the entire irrigation period. More recently, wells have been over-drilled and replacement basins or reserves have been built to cope with the hydrological deficit, which has led to an alarming drop in the groundwater table. This situation of groundwater resources in the Guigou Plain leads us to question the sustainability of irrigated crops in the years to come.

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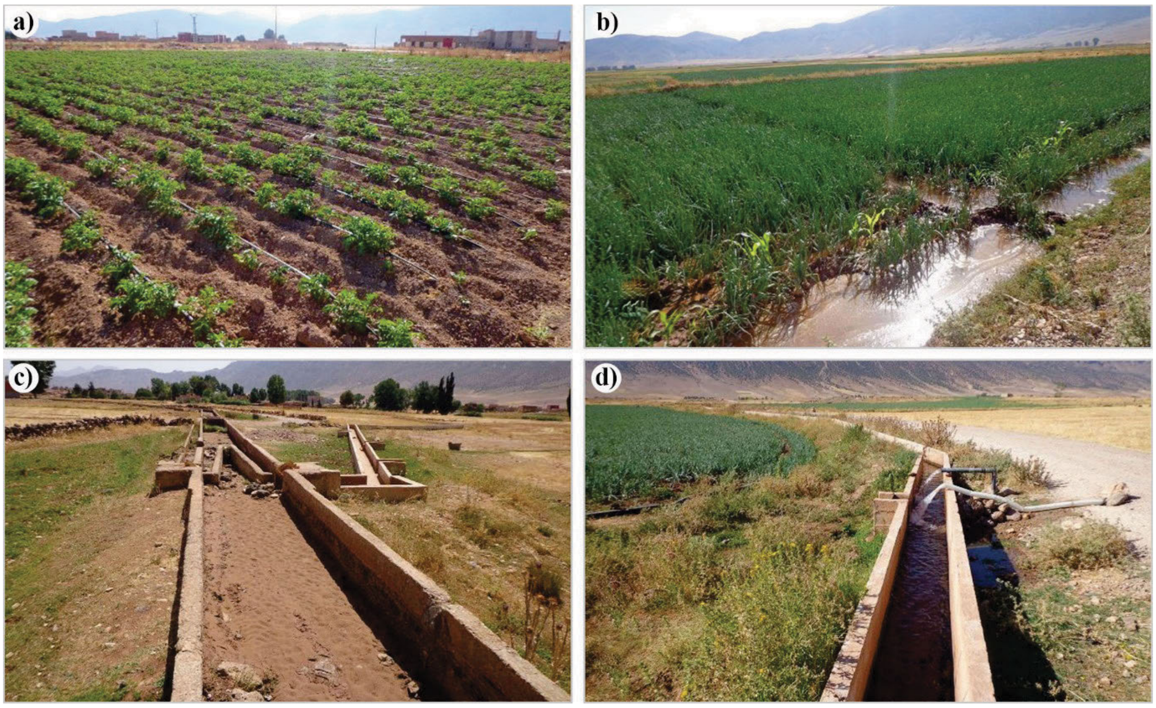

Photo. 1. Dominant irrigation techniques in the Guigou depression in August 2018: a) drip irrigation, b) row irrigation, c) irrigation by canals, d) irrigation by pumping to the canals (phot. *A. El-Bouhali*)

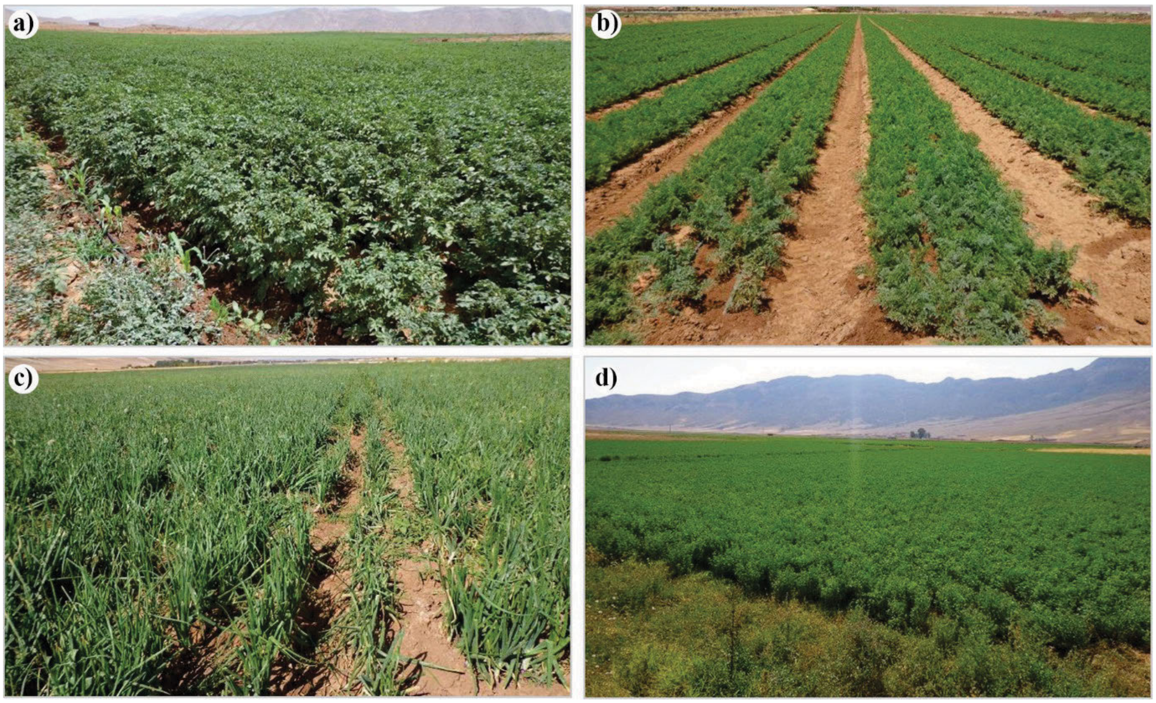

Photo. 2. Diversity of irrigated crops in the Guigou depression in August 2018: a) potatoes in the Guigou depression, b) carrots in Timahdite, c) onions in the Guigou depression, d) alfalfa in the Guigou depression (phot. *A. El-Bouhali*)

CONCLUSIONS

This study addresses a need for scientific knowledge on the extension of irrigated areas, which is crucial for the study and evaluation of irrigation dynamics, water use and associated socio-economic and environmental impacts. For this purpose, we used a supervised classification method on four series of Landsat images corresponding to the key years either from the point of view of agricultural policy or climatic conditions. The irrigation maps obtained highlight the spatiotemporal evolution of irrigated agricultural areas in the Guigou Plain in the central Middle Atlas with an overall accuracy of 98.5%. In three decades the surface area of irrigated plots has increased from 699 ha to 3,987 ha. This average growth rate of 100 $ha \cdot y^{-1}$ has led to collective lands with a pastoral vocation being made cultivable. This transformation is linked to a combination of natural factors, such as periods of

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drought and the availability of underground water in particular, and social factors, such as demographic growth, the opening up of mountain populations, the voluntarist policies of the State, and the development and generalisation of water exploitation and irrigation techniques. In a time of few years, the Guigou Plain has become one of the most important irrigated areas of the Middle Atlas and is representative of the recent mutations of the land use in the Moroccan mountain areas. While this has helped to settle the population in this mountainous area and improve their standard of living, the strong pressure on groundwater resources through the excessive and uncontrolled pumping that this generates involves crucial environmental issues. As a result, state intervention has become necessary to ensure the sustainable development of crops and water resources. In this sense, the mapping of irrigated plots is an essential document for a relevant intervention of the State, which is necessary for the preservation of agriculture and water resources. However, improvements are possible to make this mapping more dynamic, on an annual scale, for example.

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