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Water Erosion Assessment and its Relation with Human Activities Case Study, Metlili Oasis, Southern Algeria

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ABSTRACT

Oases are fragile ecosystems that face many challenges threatening their sustainability. One of these challenges is water erosion, a phenomenon that is rapidly increasing worldwide and threatens the sustainability of ecosystems in general, and oases in particular. Our study focuses on assessing the rate of water erosion in one of Algeria's most important oases, Metlili Oasis. This assessment is based on integrating remote sensing (RS) and Geographic Information Systems (GIS) with the Erosion Potential Method (EPM) model. After identifying the erosion pattern, we attempt to determine the primary cause behind this development using the results of a field survey distributed to the oasis residents. The results indicate that human activities had a significant impact on the rate of erosion. The findings of this study can serve as an important tool for authorities in managing and protecting the natural resources of the Metlili Oasis by implementing developmental programs that protect the oasis system and ensure its sustainability. The study's recommendations include encouraging residents to engage in reforestation and increase vegetation cover with suitable crops, which will help protect the soil from water erosion. The study also highlights the importance of remote sensing technologies and GIS in studying natural phenomena, especially in areas where fieldwork is challenging.

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تقييم التعرية المائية وعلاقتها بالأنشطة البشرية دراسة حالة واحة متليلي، جنوب الجزائر

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الملخص

تعد الواحات من النظم البيئية الهشة التي تواجه العديد من التحديات التي تهدد استدامتها. أحد هذه التحديات هو التعرية المائية، وهي ظاهرة تتزايد بسرعة في جميع أنحاء العالم وتهدد استدامة النظم البيئية بشكل عام، والواحات بشكل خاص. تركز دراستنا على تقييم معدل التعرية المائية في واحدة من أهم الواحات الجزائرية، واحة متليلي. ويستند هذا التقييم على دمج الاستشعار عن بعد ونظام المعلومات الجغرافية (GIS) مع نموذج جهد التعرية (EPM). بعد تحديد نمط التآكل، حاولنا تحديد السبب الرئيس للتحكم في هذا التطور باستخدام نتائج استبيان ميداني تم توزيعه على سكان الواحة. أشارت النتائج إلى أن الأنشطة البشرية كان لها تأثير كبير على معدل التعرية. يمكن أن تكون نتائج هذه الدراسة أداة هامة للسلطات في إدارة وحماية الموارد الطبيعية لواحة متليلي، وذلك من خلال تنفيذ برامج تنموية تحمي النظام الواحاتي وتضمن استدامته. تشمل توصيات هذه الدراسة تشجيع السكان على إعادة التشجير وزيادة الغطاء النباتي بالمحاصيل المناسبة، مما يساهم في حماية التربة من التعرية المائية. كما تبرز الدراسة أهمية تقنيات الاستشعار عن بعد ونظم المعلومات الجغرافية في دراسة الظواهر الطبيعية، خاصة في المناطق التي يصعب فيها العمل الميداني.

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Introduction

Oases are complex and fragile agro-ecosystems characterized by dry climate, scarce rainfall, high temperatures, and evaporation. They are considered one of the most vulnerable and unique ecological systems in arid regions (A Pickett and Cadenasso, 1995; Zhang et al., 2021). These ecosystems are found in southern Algeria, which encompasses the largest area of the country. The Metlili Oasis, the study area, is regarded as one of the most important Algerian oases due to historical, demographic, natural, and geographical factors. It is situated in the northern part of the Algerian desert, within the Ghardaia province, and a large watershed. The geographical location of the Metlili Oasis exposes it to a high risk of erosion, driven by various factors including water and wind. This study focuses on water erosion, which is recognized as one of the primary causes of soil degradation worldwide (Karkouri, 2020).

Water erosion is a natural phenomenon and one of the major environmental challenges of modern times (Dragićević et al., 2010; Tošicá et al., 2012). It is defined as the upper soil layer erosion process resulting from the separation of soil particles due to rainfall and runoff. The resulting sediments are subsequently transported away (Efthimiou et al., 2016). Soil erosion, sediment transport, and sedimentation processes are primarily controlled by four main factors: soil erosion, climate, topography, and land use. Its severity can be aggravated by human activities such as agricultural practices and deforestation (Efthimiou et al., 2016).

Various models have been developed to estimate soil erosion. They can be classified into three main types: empirical, conceptual, and physical models (Merritt et al., 2003; Mirakhorlo and Rahimzadegan, 2018). The most commonly used models are: Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1965, 1978) Modified Universal Soil Loss Equation (MUSLE) (Erskine et al., 2002; Mati et al., 2000) Water Erosion Prediction Project (WEPP) (Millward and Mersey, 2001; Millward and Mersey, 1999; Raghunath, 2002) Revised Universal Soil Loss Equation (RUSLE) (Millward and Mersey, 2001; Millward and Mersey, 1999; Raghunath, 2002) Pacific Southwest Interagency Committee (PSIAC)(Clark and Hartwich, 2001; Heydarian, 1996; Nelson and Rasele, 1989; Tangestani, 2006), and Erosion Potential Method (EPM) (Ghobadi et al., 2014; Tangestani, 2006).

The Erosion Potential Method (EPM) was established and developed by Gavrilovic in 1962 and 1972 to measure and quantify total erosion and average annual sediment production. This model is based on experimental research conducted at a station in Serbia. The EPM approach has been widely adopted for soil erosion mapping in several regions around the world, including Iran (Ghobadi et al., 2012; Mirakhorlo and Rahimzadegan, 2018), Morocco (Chaaouan et al., 2013; Zahnoun et al., 2019), Saudi Arabia (Al-Ghamdi et al., 2012), Greece (Efthimiou et al., 2016), and Podgorica (Spalevic et al., 2015).

Satellite images have been widely used for erosion monitoring and investigation since Landsat-1 was launched in 1972 (Vrieling, 2006). In addition, Geographic Information System (GIS) is a useful, simple, and inexpensive tool to develop erosion models (Anache et al., 2016; Erdogan et al., 2007; Mirakhorlo and Rahimzadegan, 2018). Recently, an accurate GIS software with large features that enables to storage, extraction, and processing of information in the form of layers and tables, is available (Moradi et al., 2015).

The objective of this study is to evaluate and assess the extent of water erosion from 1984 to 2019 in Metlili Oasis. Moreover, the study attempts to explain the relation of this natural phenomenon with different human, social, and economic factors. Indeed, the results of this study highlighted a direct relationship between human activities and the erosion pattern over the last 35 years. Furthermore, this study proposes some necessary measures to prevent the disappearance of fragile ecosystems such as oases.

Study Area

The city of Metlili is located in the north-central region of Algeria, approximately 643 km from the capital city of Algeria. The municipality of Metlili covers an area of 7,300 km². Geographically, it is positioned between latitude coordinates 32°27' and 32°45' N and longitude coordinates 03°14' and 03°24' E (Fig. 1). According to the digital elevation model (DEM), the elevation of the study area ranges between 454 m and 622 m above sea level.

Metlili City is built on a hard, difficult-to-rebuild soil consisting of a series of rocky plateaus intersected by small wadis (ephemeral streams) that converge and flow into the Metlili valley, feeding the oasis.

The topography of Metlili is characterized by gentle slopes to the northwest, which increase towards the valley to the southeast. This topographic pattern is a result of erosion, which has created a complex hydrographic network throughout the plateau in all directions.

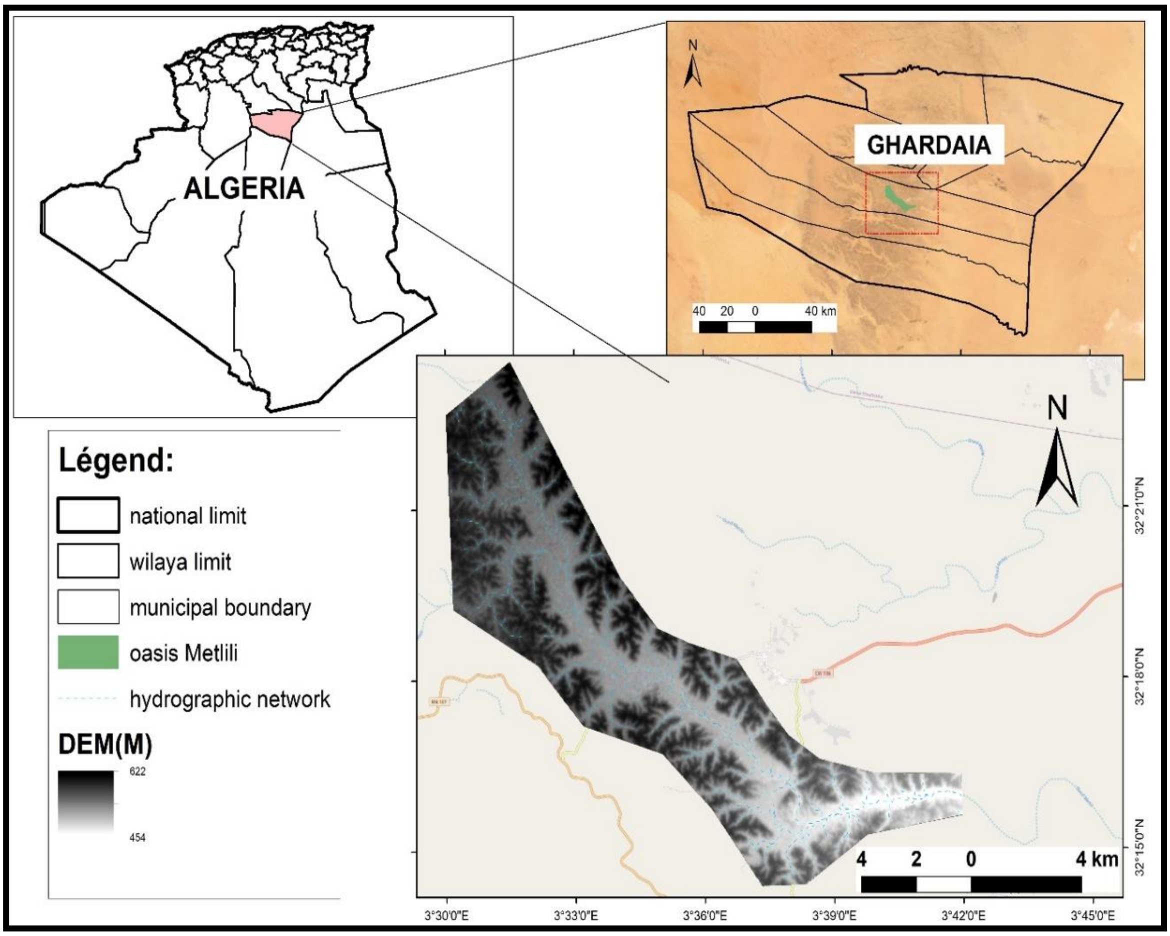

Fig. 1. Geographical location of the study area.

Materials and Methods

Data used

Several satellite images and a Digital Elevation Model (DEM) image are obtained from the US Geological Survey website (https://earthexplorer.usgs.gov/). The characteristics of these images are presented in Table 1. The study is also supported by aerial images from Google Earth Pro, field questionnaires, demographic statistics, and climate data collected from the Ghardaïa climatic station.

Table 1: Characteristics of the satellite images used.

Data type	Type	Acquisition data	Spatial resolution (m)	Source
Landsat5	TM	30/12/1984	30 m	USGS
Landsat5	TM	29/12/2001	30 m	USGS
Landsat8	OLI	23/12/2019	30 m	USGS
SRTM	DEM	2009	30 m	USGS

Methodology

1. Land use/land cover (LULC)

Land use/land cover is one of the important factors controlling water erosion (Ozsahin et al., 2018; Eskandari et al., 2022). This factor varies over time and needs to be accurately mapped to evaluate the erosion in any given area. LULC is mapped throughout the Metlili Oasis using the Normalized Difference Vegetation Index (NDVI) derived from Landsat 8 and Landsat 5 satellite images. This process is conducted in a GIS realm using the following formula:

$$NDVI = (NIR - Red)/(NIR + Red) \text{ ……... (1)}$$

Where: For Landsat 5, *NDVI* = (Band 4 - Band 3) / (Band 4 + Band 3); For Landsat 8, *NDVI* = (Band 5 - Band 4) / (Band 5 + Band 4); R

The range of NDVI values between 0 and 0.4 represents the vegetated areas in the study area. These results have been verified through field investigations and Google Earth imagery for different study years.

2. Erosion Potential Method (EPM)

The EPM model developed by Gavrilovic incorporates a combination of soil erosion factors, including rainfall, temperature, soil erosion susceptibility, soil protection coefficient, slope, and vegetation cover. To apply the Gavrilovic model, these various parameters must be mapped and integrated as inputs within a GIS realm. This GIS-based approach enables a quick and efficient assessment and estimation of soil losses. The Gavrilovic model is computed through a series of equations as follows:

$$W = T * h * \pi * \sqrt{z^3} \quad \text{……….. (2)}$$

Where: W is the annual erosion rate (m^3/km^2/year) divided into categories according to Table (2); T is the Thermal Coefficient; h is the average annual precipitation (mm); π (3.14); Z is the erosion rate; h is average annual precipitation (mm); T is Thermal Coefficient calculated by the following equation:

$$T \equiv (0.1\, to + 0.1)^{0.5} \quad \text{……….. (3)}$$

Where: *to* is the average annual temperature.

The annual rainfall rate and average temperature in the Metlili Oasis are given in Table 3.

Table 2: Soil erosion rate based on excavated soil volume. (source: Zachar, 1982)

Erosion	Excavated soil volume ($m^3.km^2. y^{-1}$)	Category
non-existent	<50	1
low	50-500	2
medium	501-1500	3
high	1501-5000	4
very high	5001-20000	5
severe	>20000	6

Table 3: Annual rainfall and temperature in the study area (source: Ghardaia meteorological station)

Year	to (c)	T	P (mm)
1984	20.8	1.47	80
2001	23.6	1.56	85
2019	22.8	1.54	70.60

The erosion rate (Z) is considered one of the most important components of the Gavrilovic model, computed by equation (4):

$$Z = Y * Xa * (\varphi * \sqrt{ja}\ ) \quad \text{……….. (4)}$$

Where: Y is Soil Erosion Sensitivity Coefficient, Xa is Soil Protection Coefficient, φ is erosion coefficient , *ja* is slope rate. They are defined and calculated as follows:

C-1 Soil Erosion Sensitivity Coefficient (Y):

It is calculated using a regression equation (Wischmeier and Smith, 1978):

$$Y = (0.00021 * (12 - OM)M^{1.14} + 3.25(S - 2) + 2.5(P - 3))/100\ ) * 1.58 \quad \text{…….. (5)}$$

Where: M is particle size factor = (% silt + % very fine sand) (100 -- % clay); OM is organic matter (%); S is soil structure code (very fine granular: 1; fine granular: 2; medium and coarse granular: 3; block or massive: 4); *P* = permeability class code (fast: 1; moderate to fast: 2; moderate: 3; slow to moderate: 4; slow: 5; very slow: 6).

The soil in the Metlili area belongs to the Quaternary period, originating from the erosion of the rocky layers formed during the secondary period. It is a sandy to alluvial clayey soil (Djili and Hamdi-Aïssa, 2018). Based on geological data, soil data, field surveys, and the classification developed by Gavrilovic, the soil erosion coefficient is estimated to be 1.

C-2 Soil Protection Coefficient (Xa):

It is in the Gavrilovic model is directly linked to the vegetation cover, which plays a crucial role in reducing erosion by protecting the soil and increasing its permeability. To adjust the soil protection coefficient values, the researchers used the Normalized Difference Vegetation Index (NDVI) obtained from Landsat satellite data and aligned the results with the previously established criteria.

C-3 Type and extent of erosion coefficient (φ):

The values of this coefficient depend on the watershed size. It can be used to determine and identify areas affected by erosion based on various field surveys of the watershed. The values can be obtained by combining the field results with high-resolution satellite images. However, if high-resolution satellite images are not available, the equation provided by Milevski (2008). It is used to compute this parameter from Landsat satellite images. The index is calculated as the square root of the spectral band (TM3) by the maximum value of radiation (φ_{MAX}). This equation provides the spatial distribution of areas subjected to erosion as a function of the percentage of radiation, which increases steadily with the erosion severity.

$$\varphi = \sqrt{Red/\varphi_{MAX}} \quad \text{........ (6)}$$

Where: For Landsat 5, Red Band 3; For Landsat 8, Red =Band 4; φ MAX is the value of the maximum radiation.

The extent of erosion coefficient (φ), Soil protection coefficient (Xa), and erosion rate (Z) are presented in Figure 2.

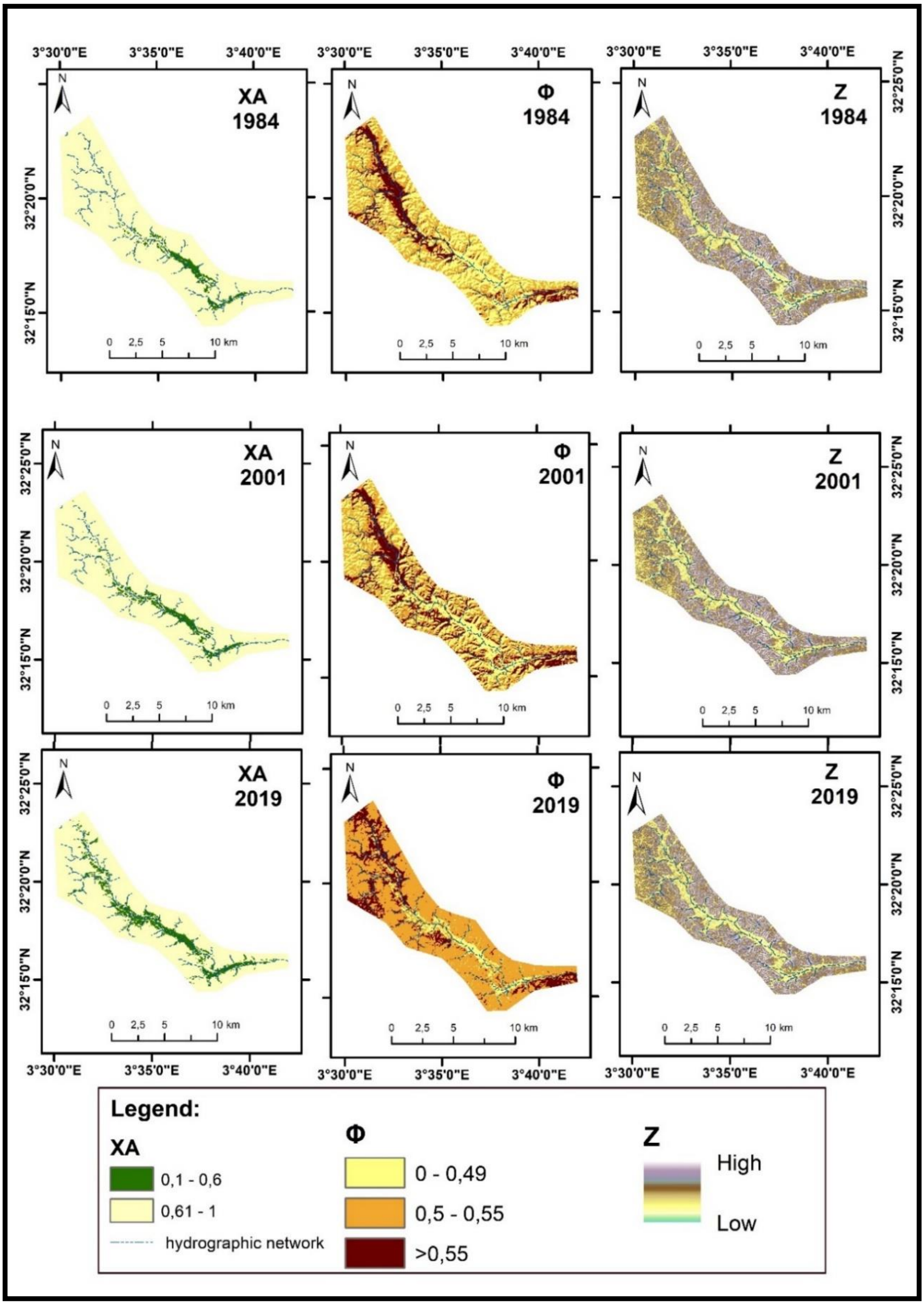

Fig. 2. Spatial distribution of Soil Protection Coefficient (Xa), Type and extent of erosion coefficient (φ), and Erosion rate (Z).

C-4 The slope rate (Ja)%:

It is a critical factor in the EPM. Increasing flow velocity due to slope action is a key driver of severe erosion. In this study, we extracted the slope values from a DEM within a GIS realm and mapped the slope throughout the study area as illustrated in Figure 3.

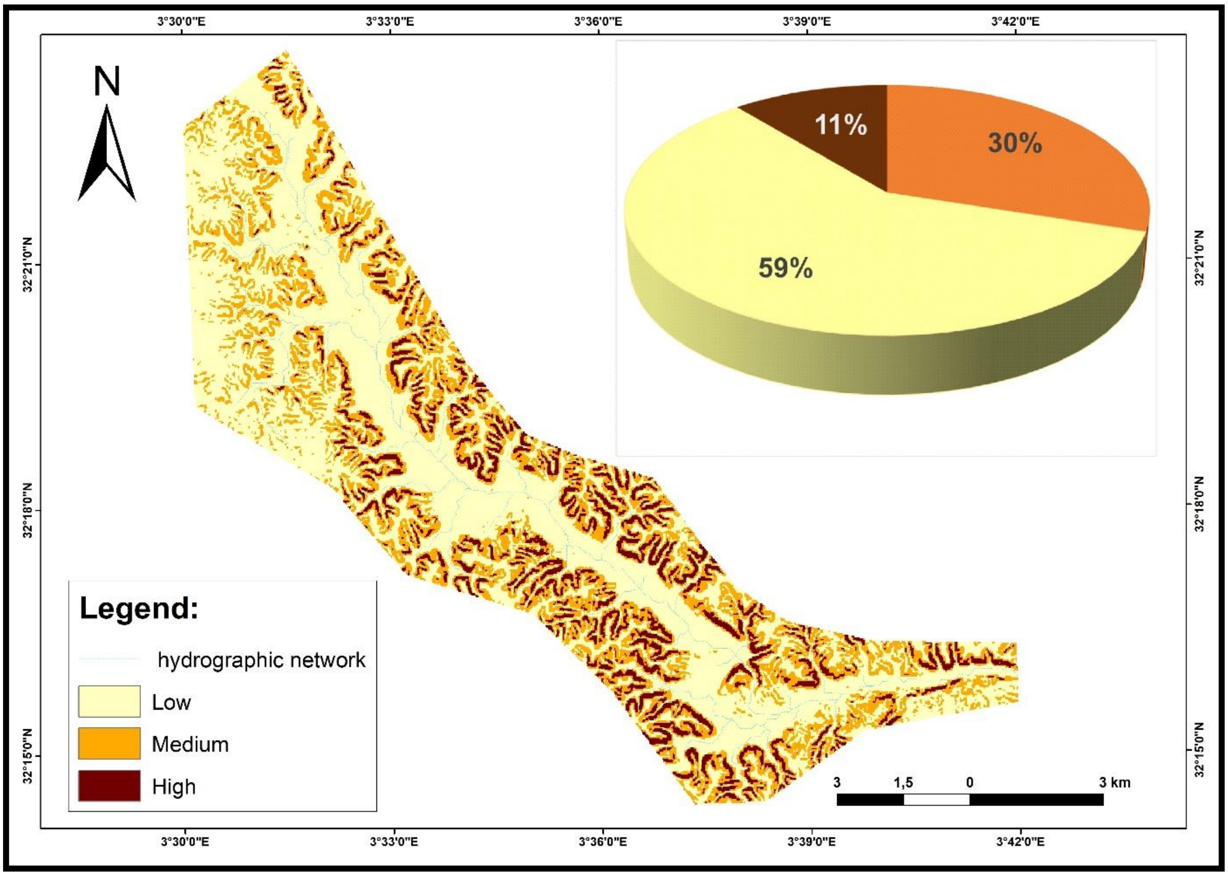

Fig. 3. Slope gradient map (Ja).

3. Field Questionnaire

To accurately interpret the EPM model results and highlight the main factors controlling the water erosion phenomenon in the study area, a questionnaire was prepared and distributed to 200 inhabitants aged between 20 to 60 years old. The answers were collected as tables and graphs and then statistically analyzed. The aim is to identify the main human activities that have directly impacted the oasis expansion and, subsequently, the water erosion patterns.

Results

From the LU/LC maps presented in Figure 4, the Metlili Oasis has expanded by 56.02% from 1984 to 2001 and by 53.62% from 2001 to 2019. This expansion is due to two main factors:

First, there has been an increase in the built-up area, which reached 134% in the first period (1984-2001) and 52% in the second period (2001-2019). This growth is the result of increased demand for housing and facilities, with housing increasing by 188.82% between 1984 and 2001, and 71.10% between 2001 and 2019, while facilities increased by 30.45% between 1984 and 2001, and 20.64% between 2001 and 2019.

Secondly, the area of palm plantations increased by 40.39% in the first period and by 53.86% in the second period. The overall growth of the oasis area is due to the expansion of palm groves in the periphery and the increase of built-up areas inside the oasis, as shown in Figure 4 and Table 4.

Table 4: Land use classes and their surface area.

	Vegetation (km^2)	Built-up area (km^2)	Bare soil (km^2)	Oasis (km^2)	Total area (km^2)
1984	9.135635	1.83016	82.875105	10.965795	93.8409
2001	12.82625	4.282669	76.731981	17.108919	93.8409
2019	17.74734	5.242123	70.851437	22.989463	93.8409

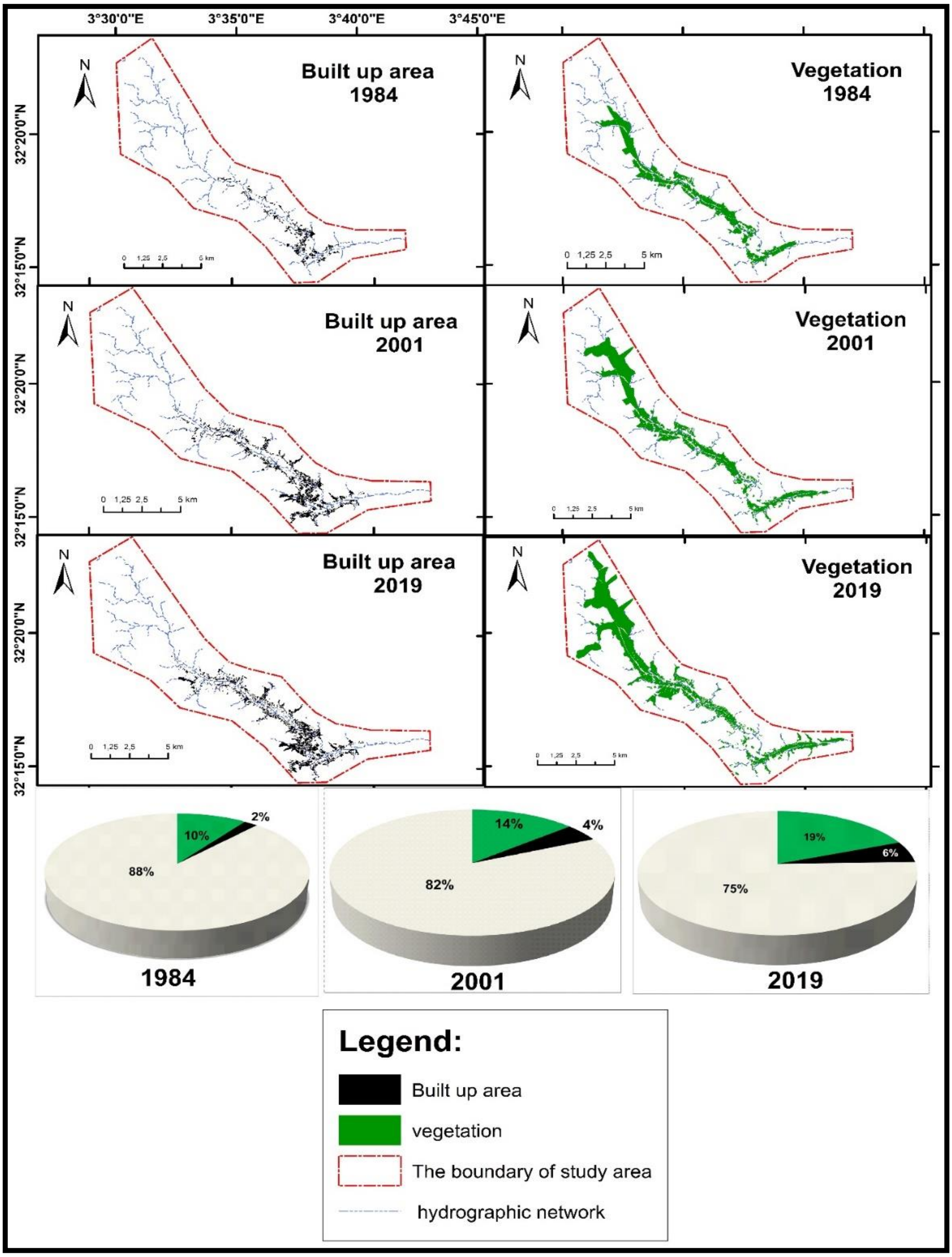

Fig. 4. Land use/Land cover classification in the study area from 1984 to 2019.

The erosion degrees are classified into three classes as shown in Table 5 and Figure 5. It is noted that areas subjected to severe erosion decreased from 1984 to 2001 by 56.8%, and then decreased by an additional 22.26% between 2001 and 2019.

Meanwhile, areas subjected to moderate erosion increased by 7.04% in the first period (1984-2001) and by 31.23% in the second period (2001-2019). Similarly, areas prone to low erosion also increased by 40.94% in the period 1984-2001 and by 57.45% in the period 2001-2019.

Table 5. Erosion rate and its respective surface area in Metlili oasis

Erosion rate	Surface area km^2 (1984)	Surface area km^2 (2001)	Surface area km^2 (2019)
Low	4.3299	6.1029	8.5905
Medium	32.5143	34.8039	44.9613
High	56.8026	52.74	40.095

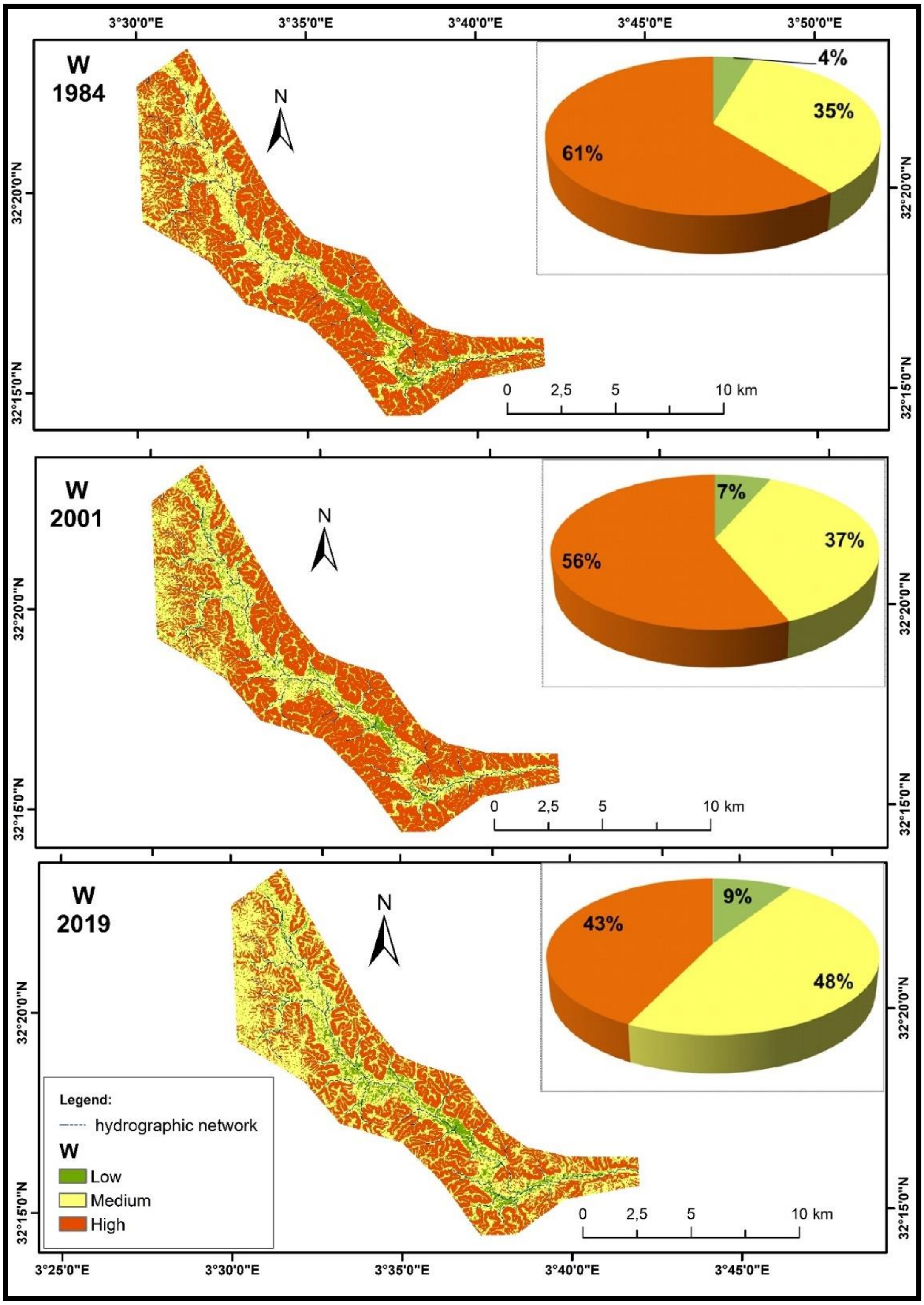

Fig. 5. Annual Erosion Rate (W).

Discussion

To understand the results obtained by the 35-year potential erosion model in the Metlili oasis, it is necessary to evaluate the factors that controlled the progression of this natural phenomenon. The climate is the most important factor in this process. Indeed, low precipitation or temperatures reduce erosion, whereas high temperatures or annual precipitation increase erosion rates. In addition to population growth, the social conditions of the oasis inhabitants and government policies to expand the region also influence the erosion rate. Indeed, Wischmeier and Smith (1965, 1978) were the first to develop methods to estimate the relationship between erosion and agricultural practices. Therefore, population growth and socioeconomic development are likely to cause rapid expansion of agricultural land and thus impact water erosion trends (Cheng et al., 2006; Xue et al., 2019).

The city of Metlili has experienced strong population growth from 1966 to 2017, according to population census statistics (Fig. 6). This phenomenon occurred in most Algerian cities after independence (ONS). An increase in the birth rate and a decrease in mortality due to improved living conditions and population stability in the oasis drive this demographic growth after abandoning their previous nomadic lifestyle.

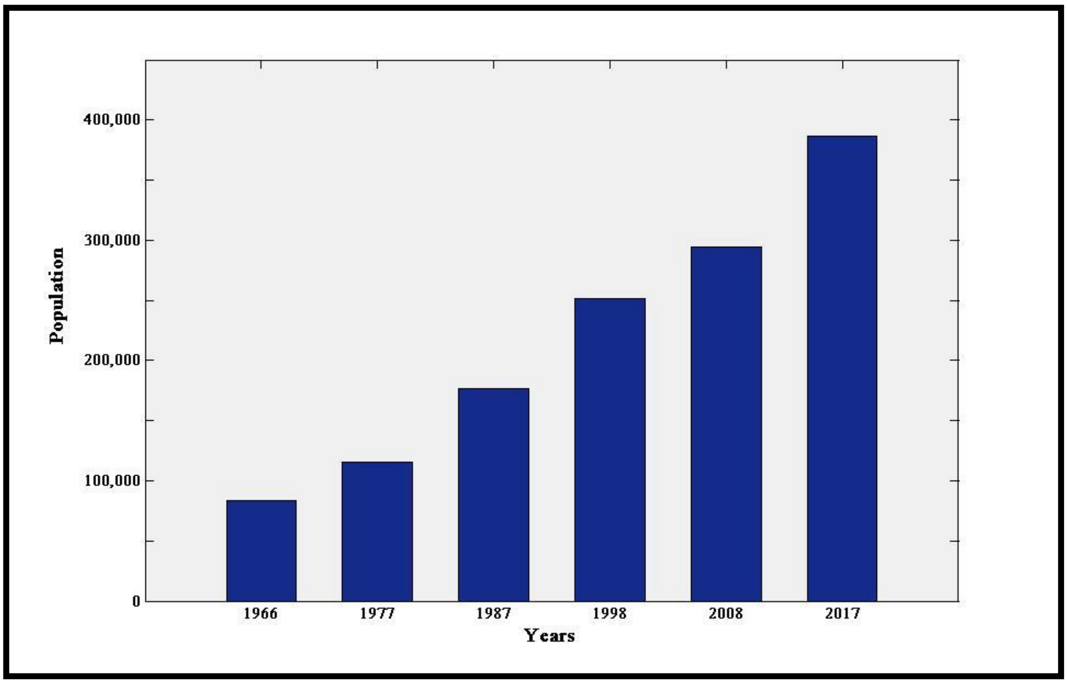

Fig. 6. Population growth from 1966 to 2017.

Given that soil is the primary raw material on which humans depend, population density is the most important factor affecting changes in the oasis area (Xie et al., 2014) as illustrated in our study. Population growth led to increased demand for housing and facilities, and consequently, an expansion of the built-up area by 134% between 1984 and 2001 and 52% between 2001 and 2019. Such a connection has been highlighted in the study by Zhang et al (2021).

The expansion of palm groves in the Metlili oasis is attributed to the residents' social culture that supports agriculture, as evidenced by the questionnaire results. The survey indicated that 55% of respondents are engaged in agriculture as a primary or secondary activity along with another sector (Fig. 7A). In addition, family farming predominates at 88% (Fig. 7B), and 53% of the respondents own agricultural lands (Fig. 7C). This is an extremely important proportion that results from the incentives provided by the government to strengthen the agricultural sector in desert areas through programs approved over the last thirty years that have directed the expansion of the oasis towards the periphery (Ghardaïa State Directorate of Agriculture, 2017, and Atlas agriculture 2014). The most important program is the agricultural concessions program, the granting of agricultural land ownership "APFA" under Law 83-18 enacted on July 13, 1983, to develop the desert areas. This led to a significant transformation of the agricultural land area (SAU). Moreover, the 1997 agricultural recovery program has also affected the agricultural land use. Several of these programs are responsible for the increase in the area of palm groves in the Oasis of Metlili.

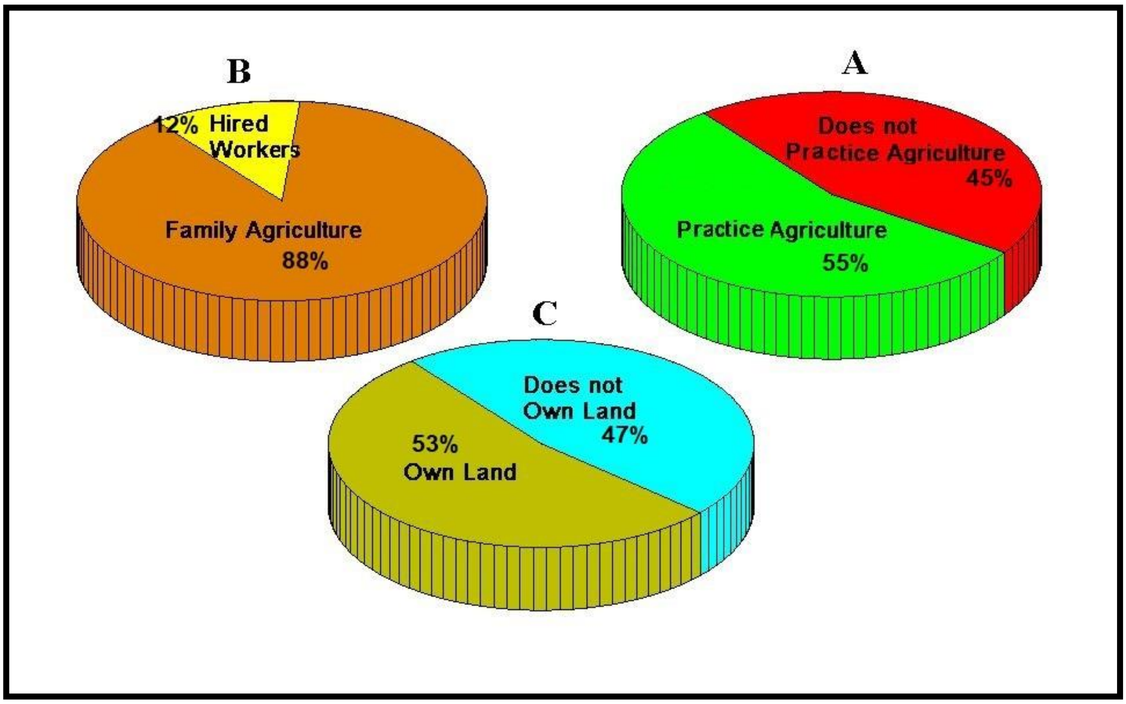

Fig. 7. Field questionnaire results.

Human activities, including population growth, economic development, and technological advancements, are the main factors controlling agricultural land changes in Algeria and other countries, such as the southern regions of China (Muyibul et al., 2018; Xystrakis et al., 2017; Zuo et al., 2014) and the northwestern regions of China (Zhou et al., 2017; Zuo et al., 2014). One project that led to economic development in northwest China was the "Go West" project, promoted by the Chinese Government in 2000 (Muyibul et al., 2018; Zuo et al., 2014).

The increase of oasis size in general and palm grove area in particular directly impacted the evolution of areas prone to water erosion, which explains the results obtained from the EPM model. Areas subjected to severe erosion have decreased as a result of the palm grove area expansion. Indeed, this increased vegetation cover has significantly contributed to the protection of these areas from the water erosion phenomenon (Mati et al., 2000). However, areas prone to moderate erosion have increased from 1984 to 2019.

The results of our study indicate a decrease in erosion severity in Metlili Oasis over the last three decades. However, areas exposed to erosion remain high. Therefore, it is necessary to increase palm groves to minimize the erosion risk. Especially since the results of our study have confirmed the direct relationship between the population and the oasis area, and the inverse relationship with the erosion extent that decreases with increasing oasis area. In addition, vegetation cover is beneficial for human and environmental sustainability. Numerous studies have focused on the impact of vegetation cover or different land use patterns on soil physical properties, soil structure, moisture retention capacity, and fertility (Gui et al., 2011; Wang et al., 2010).

Conclusion

Oases are fragile ecosystems facing many challenges to their sustainability. This includes the Oasis of Metlili, located within a large watershed area, which puts it at risk of water erosion. This is an increasingly important natural phenomenon in environmental patterns and is classified as a natural hazard due to its potential negative consequences. This study focused on evaluating water erosion using the widely recognized Erosion Potential Model (EPM). The results indicate that the extent of water erosion has decreased over the last 35 years. Areas prone to severe erosion have decreased by 56.8% from 1984 to 2001, and by 22.26% between 2001 and 2019. In contrast, areas exposed to moderate and low erosion have increased over the last 35 years.

These results reflect the positive impact of the inhabitants' activities within the oasis. These activities have increased the palm groves on the oasis outskirts by 40.39% in the first period, and by 53.86% in the second period. Additionally, the total oasis area has increased by 56.02% in the first period and by 53.62% in the second period. This growth is due to the predominant agricultural activity, high ownership of agricultural lands, and the spread of family farming as indicated by the questionnaire results.

The findings of this study can be a useful tool to assist authorities in taking necessary procedures to manage and protect the natural resources of the Metlili Oasis. This can be accomplished by implementing appropriate development programs that protect the oasis system from disappearing and ensure its sustainability. This can be done by encouraging the population to engage in reforestation operations, increasing and diversifying the vegetation cover with various crops such as staple crops, different types of dates, vegetables, fruits, and fodder appropriate for the region's environment and climate. This will enhance soil protection against water erosion, as areas prone to erosion are still significant.

This study also highlights the importance of remote sensing techniques (RS) and geographic information systems (GIS) in the study of natural phenomena, especially in areas where field work is difficult and data are scarce.

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Conflict of Interest

The authors declare that they have no conflicts of interest.

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