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ORIGINAL ARTICLE

Assessing desertification sensitivity using a geospatial MEDALUS model in the Ziz Valley, southeastern Morocco

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Abstract
Desertification poses a critical threat to ecosystems and livelihoods in arid regions, where fragile landscapes are increasingly exposed to climatic variability and human pressure. This study aims to evaluate land degradation sensitivity in the Ziz Valley, southeastern Morocco, by applying the MEDALUS model within a GIS-based analytical framework. Multi-source datasets, including satellite imagery (Sentinel-2, ASTER DEM), climatic records (WorldClim), and socio-economic indicators, were integrated to derive four quality indices - soil, vegetation, climate, and management - subsequently combined into an Environmental Sensitivity Area Index (ESAI). The resulting high-resolution map shows that approximately 71.5% of the valley is highly sensitive to desertification, particularly in the southern oases of Erfoud and Rissani, where aridity, soil erosion, and overgrazing dominate. In contrast, only 12.3% of the area demonstrates low sensitivity. Validation using field surveys yielded an overall accuracy of 90%, confirming the model's reliability. The findings emphasize the effectiveness of geospatial data integration for quantifying land degradation processes in data-scarce arid regions. This research underscores the importance of spatial information science in supporting evidence-based land management, enhancing resilience, and informing sustainable policy for vulnerable oasis ecosystems.

Keywords Desertification · MEDALUS model · Remote sensing · Environmental sensitivity area index (ESAI) · GIS · Ziz Valley · Morocco

1 Introduction

Desertification and land degradation are pressing environmental challenges that severely affect ecosystems, biodiversity, and human livelihoods. Globally, drylands cover approximately 41% of the Earth's land surface and include nearly 45% of the world's agricultural land [1]. Morocco, characterized by extensive arid and semi-arid zones, is particularly vulnerable to these processes, with desertification continuing to advance across many regions. According to the United Nations Convention to Combat Desertification (UNCCD), desertification refers to land degradation in arid, semi-arid, and dry sub-humid areas, primarily driven by climatic variability and human activities [2]. Land degradation, in this context, refers to the decline in land productivity and ecological functionality, often resulting from unsustainable land use practices. Its manifestations include soil erosion, deforestation, reduced vegetation cover, and hydrological imbalances. Both natural drivers, such as arid climate, fragile soils, and sparse vegetation, and anthropogenic pressures, including overgrazing, deforestation, and poor irrigation practices, contribute to this phenomenon [3].

Desertification is recognized globally as a critical environmental challenge, posing severe threats to sustainable development and regional biodiversity [4]. The associated ecological and socio-economic consequences

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are widespread, drawing increasing attention from countries worldwide, including Morocco. Notably, Morocco hosts one of the largest palm groves in North Africa, where oases play a vital role in sustaining life in arid environments. Several approaches have been developed to evaluate and monitor desertification, each offering distinct advantages [5–8]. In parallel, spectral indices have proven to be effective tools in desertification research. Indices such as the Normalized Difference Vegetation Index (NDVI) and Net Primary Production (NPP) are frequently employed to detect and identify degradation trends over time [9]. These spectral indices are often integrated into the MEDALUS approach to enhance the accuracy of desertification and soil degradation assessments. Recently, machine learning algorithms have been incorporated into desertification risk modeling, improving classification precision and spatial accuracy [10]. These emerging methods reflect the growing trend toward combating land degradation using geospatial approaches based on spatial data.

The adaptation of the MEDALUS model is justified by the predominantly arid and semi-arid climate of Morocco. Assessing desertification in the study area required the application of the Mediterranean Desertification and Land Use (MEDALUS) approach. Widely recognized and commonly used at both national and international levels, the MEDALUS framework has been applied in various regions, including southern Italy [8], southern Iran [11], eastern Algeria [6], Northern Egypt [12], and the Middle Draa Valley in Morocco [5].

Despite the widespread application of the MEDALUS model, there remains a research gap in its use within the Ziz Valley, a critical yet understudied region in southeastern Morocco that faces increasing desertification pressure. Moreover, few studies integrate both biophysical and socio-economic indicators with high-resolution geospatial data in this context. This study addresses this gap by applying a comprehensive, multi-criteria MEDALUS-based assessment tailored to the region's unique environmental and hydrological conditions. The novelty lies in the integration of recent satellite datasets, updated climate records, and field validation to produce a high-resolution ESAI map, offering new insights for sustainable land management in vulnerable oasis ecosystems.

Many developing countries, including Morocco, face serious challenges such as soil degradation and the depletion of natural resources [13]. Analyzing desertification processes in southeastern Morocco requires the use of digital tools and georeferenced data. Geographic Information Systems (GIS) and remote sensing, combined with the MEDALUS model, represent modern technologies that facilitate the assessment of desertification, evaluation of environmental degradation, and enable accurate results. This methodology integrates four key indices: soil quality, vegetation quality, climate quality, and management quality. These indices are combined to produce the final Environmental Sensitivity Areas Index (ESAI) map.

The MEDALUS model, while widely applied in various Mediterranean and arid contexts such as southern Italy, Iran, and even the Middle Draa Valley in Morocco, has not been previously employed to assess desertification sensitivity in the Ziz Valley. This omission represents a significant research gap, as the valley is a critical yet vulnerable oasis system whose unique environmental and socio-economic drivers of land degradation remain spatially unquantified. Furthermore, existing desertification studies in similar regions often rely on coarser datasets and seldom integrate contemporary, high-resolution satellite imagery with recent climatic and socio-economic data within a consolidated geospatial framework. There is also a notable scarcity of research that effectively combines biophysical indices with validated field observations to produce spatially explicit desertification risk maps at a scale relevant for local land management planning. This study bridges these gaps by presenting a novel, integrated application of the MEDALUS model in the Ziz Valley. The methodological novelty lies in the synergistic use of multi-source geospatial data - including Sentinel-2 imagery, ASTER GDEM, WorldClim v2.1, and the latest census and agricultural data - to compute the four quality indices. This approach is further strengthened by field validation, enabling the generation of a high-resolution Environmental Sensitivity Area Index (ESAI) map. This work provides the first comprehensive, spatially explicit assessment of desertification sensitivity for the Ziz Valley, offering a replicable framework for informed decision-making and sustainable land management in this and other data-scarce arid regions.

The objective of this research is to assess the spatial extent and severity of desertification in the Ziz Valley using the MEDALUS approach. This assessment is based on an integrated dataset comprising climatic records, geological data, digital elevation models (DEM), satellite imagery, and field observations. The availability and quality of these data are essential for producing a robust and reliable evaluation of the region's vulnerability to desertification.

2 Data and methodology

2.1 Study area

The Ziz Valley is located in southeastern Morocco within the Draa Tafilalet region. It is bounded by the High Atlas Mountains to the North, the Hamada of Guir to the East, the Tinghir Province to the West, and Algeria to the South [14].

Administratively, the valley covers an area of an approximately 2099 km², extending from oases in Midelt Province in the North to the Tinejdad Oasis in the South (Fig. 1). This region serves as a critical ecological and socioeconomic hub, sustaining traditional palm groves of the Tafilalet Basin- one of Morocco's largest date palm cultivation areas, hosting over 220 high-quality cultivars such as Mejhoul, Boufeggous, and Bouskri.

The Ziz Valley comprises a mosaic of interconnected oases, including Errachidia, Aoufouss, Erfoud, Rissani, Jorf, and Goulmima-Tinejdad. These oases are interconnected through fluvial systems and traditional irrigation networks, forming a lifeline for local communities and agriculture in an arid environment.

The region is defined by three distinct morphostructural units. The Tafilalet Plain is dominated by Cretaceous formations consisting primarily of limestones and marls, while the High Atlas Units are characterized by Jurassic deposits, including sandstones and schists. The Errachidia Sedimentary Basin, in turn, is composed of Cretaceous sedimentary rocks such as limestones and sandstones [15].

These structural units influence the hydrological dynamics of the Ziz and Rheris Rivers, which shape the valley's oasis systems and groundwater recharge mechanisms [16].

From a climatic perspective, the Ziz Valley experiences an arid to semi-arid climate, marked by low and irregular precipitation (mean annual rainfall: <200 mm), with a pronounced gradient decreasing from upstream to downstream areas. Temperatures exhibit extreme seasonality, with hot summers (≥ 40 °C) and cold winters (≤ 0 °C), exacerbating evapotranspiration rates and soil moisture stress. In addition, the Ziz Valley experiences an arid to semi-arid regime marked by low and irregular precipitation, with an average annual rainfall of less than 200 mm. Precipitation decreases progressively from upstream to downstream areas [15]. Temperature extremes are notable, with summer temperatures often exceeding 40 °C and winter temperatures dropping below 0 °C. These conditions contribute to high evapotranspiration rates and soil moisture stress [14].

Water resources in the valley are sustained by the Ziz and Rheris Rivers, though their irrigation systems differ significantly:

- - The Ziz River: Managed by the Hassan Addakhil Dam (constructed in the 1970 s, elevation: 1,125 m), which regulates water supply for downstream oases [17];
- - The Rheris River: Relies on traditional gravity-fed systems (*Khttaras*,*Seguia*) and small-scale networks, reflecting indigenous adaptation to water scarcity [15].

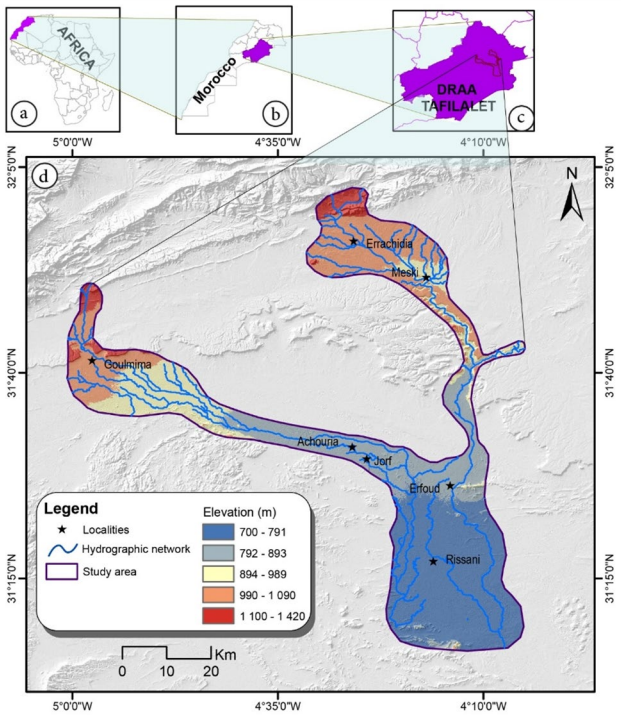

Fig. 1 Geographical location of the study area. **a** location of Morocco in Africa, **b** location of Draa Tafilalet region in Morocco, and **c** Draa Tafilalet region boundaries, **d** location of Ziz Valley in Draa Tafilalet region

Figure 2 illustrates the diversity of landscape types observed within the study area. The region is characterized by a marked environmental gradient ranging from well-irrigated agricultural lands to severe degraded palm groves. The first photograph (Fig. 2a) shows diversity in vegetation cover correlated with climatic and anthropogenic conditions. Subsequently, Fig. 2b describes the state of oases land from low sensitivity to moderate sensitivity of degradation. The remaining photographs provide information on stages of high desertification and land degradation, starting with vegetation removal, followed by drying palm groves, and culminating in sand-encroached zones (Fig. 2c and d).

2.2 Data sources and preparation

The MEDALUS model was applied using multi-source geospatial datasets that were harmonized in a GIS environment under the UTM WGS 84 Zone 30 N projection (30 m). Data integration focused on four core indices (soil, vegetation, climate, and management), each derived from specific sub-indices (Table 1).

This study integrates multi-source geospatial datasets to assess land degradation susceptibility using the Environmentally Sensitive Area (ESA) framework of the Mediterranean Desertification and Land Use (MEDALUS) approach (Table 1). All datasets were preprocessed and harmonized



Fig. 2 Representative landscape types illustrating the environmental degradation gradient within the study area. **a** Well-irrigated agricultural land with dense palm groves and stable soil conditions, representing low degradation sensitivity; **b** Moderately degraded palm grove showing signs of vegetation thinning and initial soil deterioration; **c** Highly degraded oasis ecosystem with severe vegetation loss and advanced soil salinization; **d** Sand-encroached zone with active dune migration and complete vegetation cover loss, indicating critical desertification

to a common spatial resolution (30 m), and the same projection system (UTM-30 N).

2.2.1 Soil-related indicators

Soil sensitivity to degradation was assessed through four sub-indicators: slope gradient, drainage density, soil brightness, and parent material. Digital Elevation Model (DEM) data from ASTER GDEM Version 3 (30 m spatial resolution) was used to derive slope and aspect maps, which are critical in determining erosion risk and solar exposure that influence moisture retention. Soil brightness, serving as a proxy for surface albedo, was calculated using Sentinel-2 MultiSpectral Instrument (MSI) bands B2, B4, B8, B11, and B12 acquired on September 14, 2024. Parent material information was derived from historical geological maps at scales ranging from 1:200,000, including: the Haut Atlas Midelt (1939), Tafilalet-Taouz (1986), Todrha-Mader (1988), and Nord-Ksar-Essouk (1956). These maps provided lithological classifications essential for understanding the characteristics of soil-forming materials.

2.2.2 Vegetation-related indicators

Vegetation cover and its protective role against land degradation were assessed using Sentinel-2 MSI imagery (10–20 m resolution) acquired on September 14, 2024. A Land Use/Land Cover (LULC) map was generated to evaluate fire risk, erosion protection capacity, and drought resistance. Additionally, the Normalized Difference Vegetation Index (NDVI) was computed to quantify green vegetation density, offering insights into plant cover distribution and ecosystem health.

2.2.3 Climate-related indicators

The climatic influence on land degradation was analyzed using WorldClim v2.1 data (1 km spatial resolution) covering the period 1970–2000. Precipitation and temperature data were used to compute potential evapotranspiration following the Hargreaves-Samani method [18]. An aridity index was subsequently derived based on the ratio of annual precipitation to evapotranspiration, serving as a key indicator of drought severity across the study area.

Table 1 Summary of datasets, sources, and temporal references used for ESAI mapping in the Ziz Valley

Index	Sub-index	Dataset	Spatial resolution	Temporal reference	Purpose
Soil	Slope	Digital Elevation Model (ASTER GDEM V3)	30 m	2024	Terrain steepness affecting erosion and runoff
	Drainage	Digital Elevation Model (ASTER GDEM V3)	30 m	2024	Soil water retention capacity
	Soil Brightness	Sentinel-2 MSI Bands B2, B4, B8, B12, B11, B12	10–20 m	2024	Surface albedo estimation for soil degradation assessment
	Parent Material	Geological Maps (1:200000 scale): Haut Atlas Midelt (1939); Tafilalet-Taouz (1986); Todrha-Mader (1988); Nour-Ksar-Essouk (1956)	Variable	1939–1988	Lithological classification influencing soil properties
Vegetation	Fire Risk	Land Use/Land Cover (LULC) Map derived from Sentinel-2 MSI	10–20 m	2024	Biomass fuel load assessment
	Erosion Protection	LULC Map (Sentinel-2 MSI)	10–20 m	2024	Vegetation cover role in soil stabilization
	Drought Resistance	LULC Map (Sentinel-2 MSI)	10–20 m	2024	Vegetation resilience to aridity
	Plant Cover	Normalized Difference Vegetation Index (NDVI) from Sentinel-2 MSI	10–20 m	2024	Quantification of green vegetation density
Climate	Precipitation	WorldClim v2.1 (Global Climate Data)	1 km	1970–2000	Aridity index calculation
	Evapotranspiration	WorldClim v2.1 (Temperature and Solar Radiation)	1 km	1970–2000	Water loss estimation via Hargreaves-Samani equation
	Aridity	Derived from Precipitation/Evapotranspiration ratio	1 km	1970–2000	Drought severity assessment
	Aspect	Digital Elevation Model (ASTER GDEM V3)	30 m	2024	Solar radiation exposure influence on moisture retention
Management	Population Pressure	High Commission for Planning (HCP) - Morocco National Census (2024)	Commune-level	2024	Human density impact on land degradation
	Grazing Pressure	Tafilalet Regional Agricultural Development Office (2024)	Oasis-level	2024	Livestock overgrazing risk assessment
	Land Use Intensity	LULC Map (Sentinel-2 MSI)	10–20 m	2024	Agricultural and urbanization pressure

2.2.4 Human-induced pressure indicators

Anthropogenic pressures were represented by population density, grazing intensity, and land use intensity. Population pressure data at the commune level was sourced from the 2024 Moroccan National Census provided by the High Commission for Planning (HCP). Grazing pressure was assessed at the oasis level using data from the Regional Agricultural Development Office of Tafilalet (2024). Land use intensity was mapped using the LULC classification derived from Sentinel-2 imagery, highlighting areas subjected to agricultural expansion or urbanization.

All datasets were standardized and integrated within a GIS-based framework to generate the final Environmental Sensitivity Index. This systematic integration of environmental and anthropogenic factors ensures a comprehensive assessment of desertification risk under the MEDALUS methodology.

2.2.5 Field data

A field campaign was carried out from February 3 to 9, 2025, to collect ground-truth GPS points for validating the classification results, particularly around the oases distributed throughout the study area from north to south. A total of 150 georeferenced points were collected, covering various land cover classes and different levels of land degradation. In addition, field photographs were systematically taken to complement the spatial observations and support the validation process.

2.3 Methodology

The detection of environmentally sensitive areas to desertification and land degradation was carried out using the MEDALUS approach to enhance prediction accuracy as well as promote sustainable development. The model was adapted according to the project report of the European Commission [19]. The manual emphasizes the mapping of

soil, vegetation, climate, and management quality indices, the latter was calculated by the combination of sub-indexes. Each sub-index was georeferenced using UTM WGS 1984 Zone 30 N projection system, with a spatial resolution of 30 m, then classified, and weighted on a scale ranging from 1(low sensitivity to desertification) to 2 (high sensitivity). Figure 3 illustrates the methodological framework adopted in this study, based on the MEDALUS approach. It outlines the sequential procedures used to identify and assess Environmentally Sensitive Areas (ESAs) to desertification within the study area.

The adoption of the MEDALUS methodology for this study is justified by its inherent flexibility and its proven effectiveness in arid and semi-arid environments that share key characteristics with the Ziz Valley. The model's core strength lies in its multi-criteria framework, which seamlessly integrates the four primary drivers of desertification active in the region: soil vulnerability, climatic stress, vegetation degradation, and anthropogenic pressure. This holistic approach is essential for capturing the complex interactions in oasis ecosystems, where environmental fragility and human activities are intensely interconnected.

Furthermore, the MEDALUS model is particularly well-suited for data-scarce regions. Its structure allows for the adaptation of sub-indices based on data availability without compromising the robustness of the assessment. For this study, we leveraged specific, locally relevant datasets - such as Sentinel-2 imagery to compute soil brightness and NDVI, ASTER DEM for terrain analysis, and recent census data for population pressure - tailoring the model to the specific socio-environmental context of the Ziz Valley. This capacity for customization ensures that the assessment is not a generic application but a precise reflection of the local desertification dynamics.

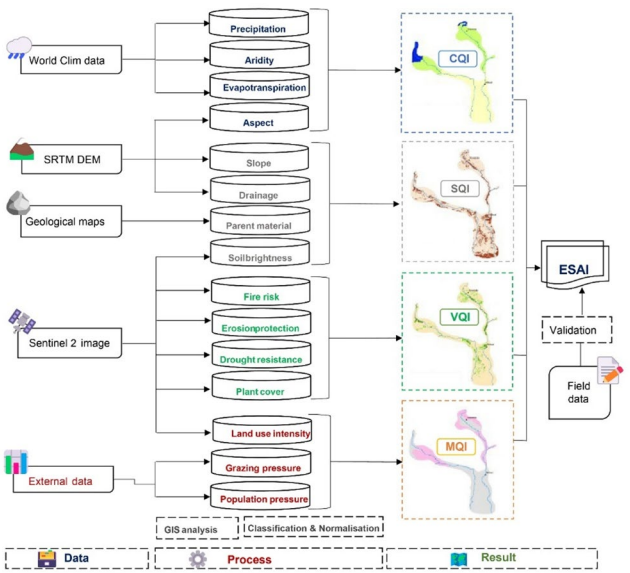

Fig. 3 Methodological flowchart based on the MEDALUS approach for assessing ESAs

The ESAI was calculated using the geometric mean of the four indices. Data processing was performed using QGIS 3.28, ENVI 5.3 and ArcGIS 10.8.

2.3.1 Soil quality index (SQI)

The SQI is one of the four MEDALUS model indices, SQI is determined using four parameters, Slope (S), Drainage (D), Soil brightness (Sb), and Parent material (Pr). The Digital elevation model (DEM) is essential for generating slope and drainage maps. The DEM was downloaded from ASTER GDEM with a 30 m spatial resolution.

Soil brightness was calculated using Sentinel 2 imagery, which is particularly suitable for this index due to its high spatial resolution and range of spectral bands. Soil brightness was used as a proxy for surface albedo, serving as an indicator of soil properties and degradation [20, 21] (Eq. 1).

$$Albedo\ (\alpha) = [((0.356 * b2)\ +\ (0.130 * b4) +\ (0.373 * b8)\ +\ (0.085 * b11)) + (0.072 * b12)\ -\ 0.018/1.016] \quad (1)$$

The parent material map was created by the digitalization of geological maps, and subsequently the lithological map. The classification of the lithological map was used to determine soil types based on parent material. The SQI plays a crucial role in the Environmentally Sensitive Areas Index, calculated using Eq. 2.

$$\mathrm{SQI} = (\mathrm{S} * \mathrm{D} * \mathrm{Sb} * \mathrm{Pr})^{\frac{1}{4}} \quad (2)$$

where, SQI is the soil quality index; S is the slope; D is the drainage; Sb is the soil brightness; Pr is the parent material.

The sub-indices were classed and weighted based on a score ranging from 1 (low sensitivity to desertification) to 2 (high sensitivity to desertification), and are presented in Table 1 in the Appendix. In the same table, each sub-index was also quantified by the area in square kilometers alongside the percentage.

2.3.2 Vegetation quality index (VQI)

The Environmentally Sensitive Area Index (ESAI) is significantly influenced by the accuracy and relevance of the vegetation-related sub-indices, which include Fire Risk (Fr), Erosion Protection (Ep), Drought Resistance (Dr), and Plant Cover (Pc). In this study, the first three sub-indices (Fr, Ep, and Dr) were derived from a Land Use/Land Cover (LULC) map, which was developed through supervised classification of Sentinel-2 satellite imagery.

The Sentinel-2 imagery served as the primary data source for generating all vegetation sub-indices. The Fire

Risk, Erosion Protection, and Drought Resistance indicators were extracted based on land cover types, while Plant Cover was estimated using the Normalized Difference Vegetation Index (NDVI). NDVI values were computed using Eq. 3, where the near-infrared (NIR) reflectance corresponds to Band 8 and the red reflectance (R) to Band 4 of the Sentinel-2 image:

$$\mathrm{NDVI} = \frac{\mathrm{NIR} - \mathrm{R}}{\mathrm{NIR} + \mathrm{R}} \tag{3}$$

where, NDVI is the normalized difference vegetation index, NIR is the near-infrared; R is the red.

This index ranges from −1 to 1, where higher values (>0.47) indicate dense vegetation, while lower values (<0.1) correspond to barren or built-up areas. The NDVI values were reclassified into three plant cover categories: High (>47%), Moderate (10–47%), and Low (<10%) (Table 3).

The vegetation quality index was calculated using the Eq. 4.

$$\mathrm{VQI} = (\mathrm{Fr} * \mathrm{Ep} * \mathrm{Dr} * \mathrm{Pc})^{\frac{1}{4}} \tag{4}$$

where, VQI is the vegetation quality index, Fr is the fire risk, Ep is the erosion protection, Dr is the drought resistance, Pc is the plant cover.

2.3.3 Climate quality index (CQI)

Climate analysis in arid regions like the Ziz Valley is inherently challenging due to sparse meteorological infrastructure, discontinuous data collection, and historical gaps in temperature and precipitation records. To address these limitations, this study utilized WorldClim v2.1 (baseline period: 1970–2000) for precipitation (P) and temperature data (available at www.worldclim.org). These datasets, though retrospective, remain a widely accepted baseline for arid regions with limited observational networks [22].

2.3.4 Evapotranspiration estimation

Precipitation (P) and temperature indices were derived from the WorldClim dataset. Evapotranspiration (ETP) was estimated based on a combination of average, maximum, and minimum temperatures, as well as solar radiation. These variables were integrated using the Hargreaves–Samani equation (Eq. 5), which allows for the empirical estimation of ETP using only temperature data [18, 23]. The solar radiation values obtained from WorldClim were converted from kilojoules per square meter per day ($\mathrm{kJ \cdot m^{-2} \cdot day^{-1}}$) to megajoules per square meter per day ($\mathrm{MJ \cdot m^{-2} \cdot day^{-1}}$) to ensure consistency with the equation's input requirements.

$$\mathrm{EPT} = 0.0023 * (\mathrm{T_{avg}} + 17.8) * (\mathrm{T_{max}} - \mathrm{T_{min}})^{0.50} * \mathrm{Rs} \tag{5}$$

where, EPT is the evapotranspiration, Tavg is the average temperature (°c), Tmax is the maximum temperature (°C), Tmin is the minimum temperature (°C), Rs is the solar radiation ($\mathrm{MJ\ m^{-2} day^{-1}}$).

The precipitation in conjunction with the evapotranspiration index has a fundamental role in creating the aridity index (AI) [24], using the Eq. 6. This index classifies the region into humid (AI ≥ 1), transitional (0.1 < AI < 1), and arid (AI ≤ 0.1) categories, following the UNEP (1992) framework for dryland classification (UNEP, 1992).

$$\mathrm{AI} = \frac{\mathrm{P}}{\mathrm{PET}} \tag{6}$$

where, AI is the aridity, P is the precipitation, PET is the evapotranspiration.

The aspect (A) is the final sub-index to calculate the climate quality index, the aspect index explains the orientation of the light reflected by the sun. The digital elevation model (30 m) is the source data to result the aspect map.

The climate quality index was calculated using the Eq. 7.

$$\mathrm{CQI} = (\mathrm{P} * \mathrm{EPT} * \mathrm{AI} * \mathrm{A})^{\frac{1}{4}} \tag{7}$$

where, CQI is the climate quality index, P is the precipitation (mm), EPT is the evapotranspiration (mm), AI is the aridity, A is the aspect.

2.3.5 Management quality index (MQI)

MQI incorporates three sub-indices: Population Pressure (Pp), Grazing Pressure (Gp), and Land Use Intensity (Lu). Population data were obtained from the 2024 census published by Morocco's High Commission for Planning. Population density was computed by dividing the population of each commune by its surface area.

Grazing pressure data were obtained from the Regional Agricultural Development Office of Tafilalet, based in Errachidia. The (Gp) index includes both sheep and goats. Land Use Intensity (Lu) was derived from a land use/land cover (LULC) map.

The MQI was calculated using Eq. 8:

$$\mathrm{MQI} = (\mathrm{Pp} * \mathrm{Gp} * \mathrm{Lu})^{\frac{1}{3}} \tag{8}$$

where, Pp is the population pressure (inhabitants/km²), Gp is the grazing pressure, Lu is the land use intensity.

2.3.6 Environmental sensitivity areas index (ESAI)

The Environmental Sensitivity Areas Index (ESAI) was derived by integrating the four thematic quality indices: Soil Quality Index (SQI), Vegetation Quality Index (VQI), Climate Quality Index (CQI), and Management Quality Index (MQI). This integration was performed using spatial analysis tools within a Geographic Information System (GIS) environment and is expressed by Eq. 9.

$$\mathrm{ESAI} = (\mathrm{SQI} * \mathrm{VQI} * \mathrm{CQI} * \mathrm{MQI})^{\frac{1}{4}} \quad (9)$$

Where ESAI denotes the Environmental Sensitivity Areas Index, SQI the Soil Quality Index, VQI the Vegetation Quality Index, CQI the Climate Quality Index, and MQI the Management Quality Index. The result of this index allows for the generation of a map identifying the Environmentally Sensitive Areas (ESAs) within the study area.

2.3.7 Validation of ESAs mapping

To ensure the reliability and accuracy of the Environmentally Sensitive Areas (ESAs) map, a quantitative validation approach was conducted using 150 georeferenced points collected during the field survey carried out between February 3 and 9, 2025. These reference points were selected to represent the diversity of land cover types and degradation levels across the study area. A confusion matrix was generated by comparing the classified ESA map with ground-truth data, allowing for the calculation of standard accuracy metrics, including overall accuracy, user's accuracy, producer's accuracy, and the Kappa (κ) coefficient [25, 26]. This validation methodology aligns with widely accepted practices in remote sensing accuracy assessment and has been applied in similar studies evaluating land degradation and desertification risk in arid and semi-arid regions [27, 28].

3 Results

The MEDALUS model proves to be an effective tool for detecting desertification processes in arid and semi-arid regions. In this study, the quality indices were integrated and normalized according to their respective influence on the sensitivity to desertification and land degradation within the study area.

Table 2 Classes and description range of the soil quality index

Index	Class	Description	Area (km²)	Area (%)	Characteristics
SQI	1	High	423.21	20.16	1–1.13
	2	Moderate	1676.08	79.84	1.13–2

3.1 Soil quality index (SQI)

The spatial distribution of the soil quality index appears to closely correspond to the soil brightness map, reflecting the influence of surface reflectance in arid and semi-arid environments. Lower soil brightness values typically indicate higher organic matter content, which is associated with healthier soil conditions. Conversely, areas with high soil brightness-indicative of higher reflectance-are generally characterized by degraded soils and greater sensitivity to desertification. Soil drainage conditions, influenced by the hydrological contribution from the Ziz and Rheris rivers, play a crucial role in enhancing soil quality. These areas benefit from effective water flow, which supports soil health and productivity. Furthermore, the lithological characteristics of the parent material also contribute significantly to soil quality. Regions underlain by limestone and sandstone are generally associated with lower desertification sensitivity and higher soil quality. In contrast, areas dominated by sand dunes and loose sands exhibit greater susceptibility to erosion and land degradation.

Topographic features, particularly slope, also influence soil quality. The majority of the land area (80.92%) is characterized by gentle slopes, which tend to mitigate the erosive processes. Nonetheless, a positive correlation between slope and erosion is observed, suggesting that steeper slopes are more prone to degradation. The analysis of the soil quality index, based on the sub-indices presented in Table 2, reveals two main classes of soil quality across the study area: moderate and high. High-quality soils occupy approximately 20.16% of the total area and are predominantly concentrated within the oasis zones. In contrast, soils of moderate quality account for 79.84% of the study area (Table 2). The integration of sub-indices highlights a distinct variation in the distribution between these two quality levels.

Figure 4 presents the spatial distribution of the Soil Quality Index (SQI) across the Ziz Valley, derived from four sub-indices: slope gradient, drainage, soil brightness, and parent material. The SQI values in the study area range from 1 to 2, corresponding to a classification into two primary classes: high and moderate soil quality. The analysis indicates that moderate soil quality dominates the landscape, accounting for approximately 79.84% of the total area (Table 2). These zones are mostly located in the central and lower parts of the valley, often characterized by gentle slopes, limited drainage efficiency, and light-colored soils with high reflectance-indicative of low organic matter content and surface degradation. In contrast, high soil quality areas represent 20.16% of the study area, primarily concentrated along the Ziz and Rheris river corridors and within oasis systems. These zones are generally associated with darker soils, well-drained terrain, and favorable parent material such as

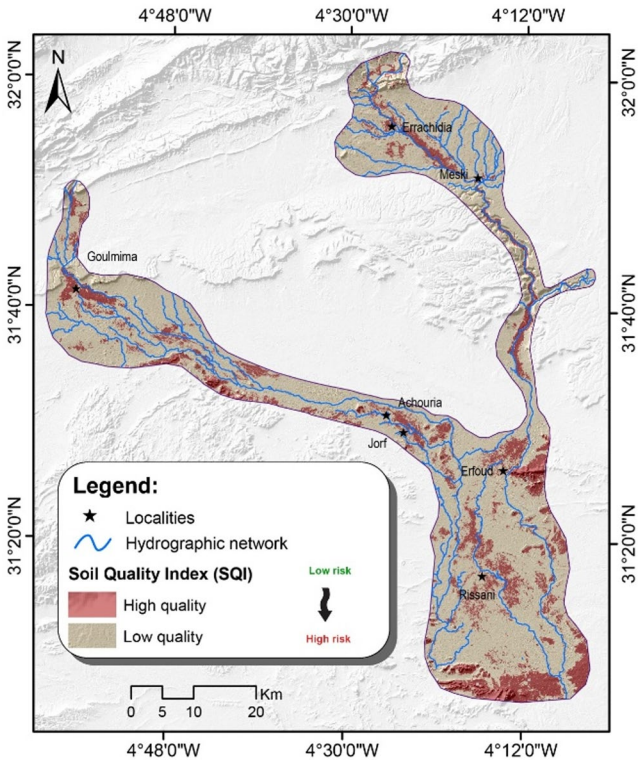

Fig. 4 Soil quality index map

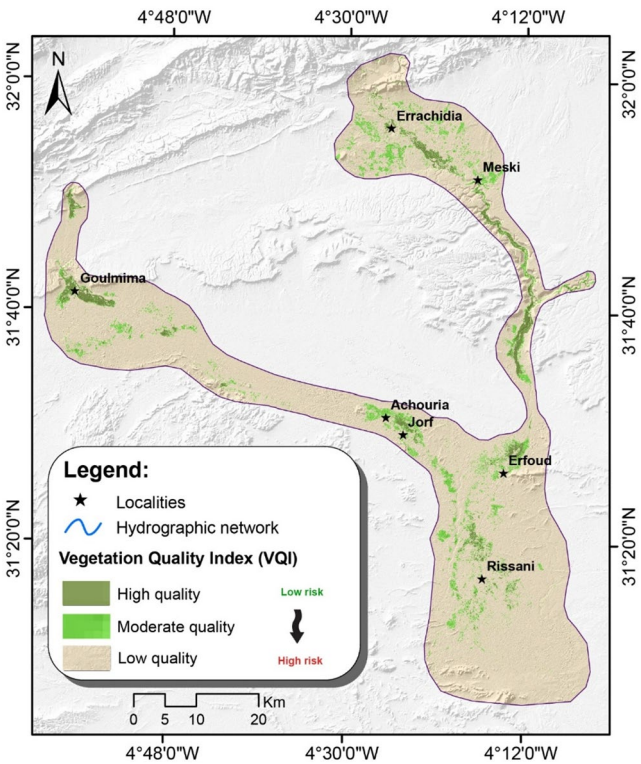

Fig. 5 Vegetation quality index map

limestone and sandstone, which contribute to improved soil structure and nutrient retention. The slope distribution further reinforces this pattern, with over 80% of the area exhibiting gentle slopes (<4%), which support soil accumulation and reduce erosion. Conversely, steeper slopes-mainly in the northern and peripheral highlands-are correlated with lower soil quality due to increased erosion potential.

3.2 Vegetation quality index (VQI)

The use of Sentinel satellite imagery, which offers high spatial resolution and spectral accuracy, was instrumental in developing the VQI. This index is primarily linked to the land use/land cover (LULC) classification, and secondarily to the Normalized Difference Vegetation Index (NDVI), which was utilized to assess vegetation cover. Vegetation-related sub-indices are key indicators for monitoring desertification processes in southeastern Morocco. Among these, fire risk is a significant factor, particularly in areas where palm groves and built-up zones coexist. These zones collectively span 266.96 km² of the study area. The combination of dense vegetation and concentrated human activity increases the likelihood of fire occurrences. Palm groves, in particular, contain substantial biomass, which serves as fuel for fires, while urban density and infrastructure further elevate the risk. The erosion protection sub-index shows that 3.90% of the area benefits from natural protection, primarily provided by palm groves and water bodies. These features help stabilize the soil and mitigate erosion, especially in oasis regions where land degradation pressure is high. Similarly, drought resistance plays a crucial role in assessing vulnerability to desertification. Areas characterized by low drought resistance-covering approximately 9.04% of the study region-exhibit reduced resilience to water scarcity due to insufficient vegetation cover and low soil moisture retention. Overall, the majority of the study area exhibits moderate to high vegetation cover, offering significant protection against desertification over an area exceeding 2,000 km². However, regions with sparse vegetation remain vulnerable to land degradation due to limited plant cover density and low ecosystem resilience.

Figure 5 illustrates the spatial distribution of the Vegetation Quality Index (VQI) across the Ziz Valley, reflecting the region's varying capacity to resist desertification through vegetation dynamics. The VQI was derived from four key sub-indices: Fire Risk, Erosion Protection, Drought Resistance, and Plant Cover, each computed from Sentinel-2 imagery and land use classification data.

The spatial analysis reveals that the majority of the study area (90.54%) exhibits low vegetation quality, with VQI values ranging from 1.37 to 2 (Table 3). These zones are primarily located in the central and southern parts of the valley, where sparse vegetation, intensive land use, and limited water availability contribute to high environmental

Table 3 Classes and description range of the vegetation quality index

Index	Class	Description	Area (km²)	Area (%)	Characteristics
VQI	1	High	62.67	2.98	1 −1.16
	2	Moderate	135.99	6.48	1.16–1.37
	3	Low	1900.62	90.54	1.37–2

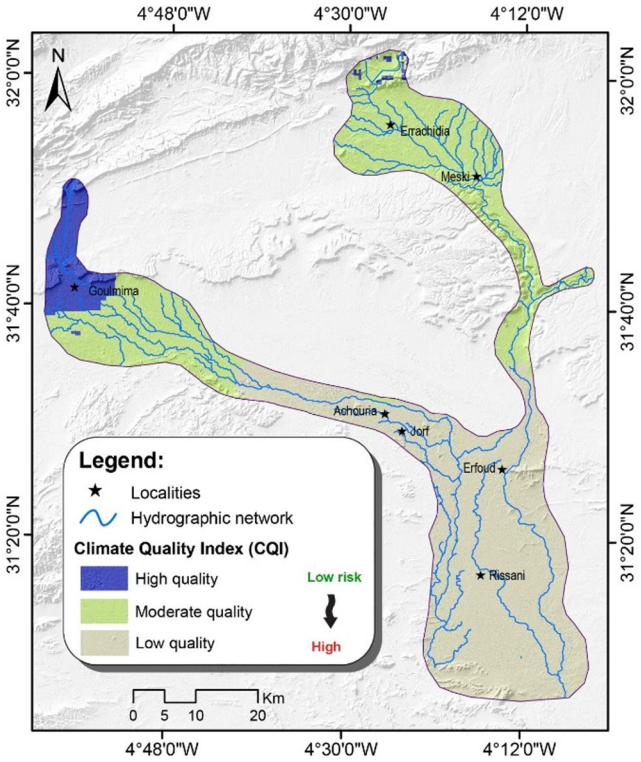

Fig. 6 The climate quality index map

vulnerability. Only 2.98% of the region demonstrates high vegetation quality, mostly concentrated in preserved or reforested palm groves and water-adjacent zones. These areas provide natural protection against soil erosion, maintain microclimatic stability, and enhance drought resilience. Moderate vegetation quality (6.48%) is observed in transitional zones between degraded and relatively stable areas. These regions often exhibit seasonal vegetation dynamics and intermediate levels of anthropogenic pressure.

3.3 Climate quality index (CQI)

The spatial distribution of four key climate-related sub-indices used in the calculation of the Climate Quality Index (CQI) across the study area, specifically: precipitation, aridity index (P/EPT), evapotranspiration, and slope aspect. These variables significantly influence desertification dynamics in arid and semi-arid environments such as the Tafilalet region.

The four climate sub-indices collectively reveal a pronounced aridity gradient extending from the northern to the southern sectors of the Ziz Valley. Precipitation is unevenly distributed, with comparatively higher values concentrated in the northern upstream areas and a marked decline toward the southern oases of Erfoud and Rissani, where annual totals often fall below 50 mm. This spatial pattern is reinforced by the aridity index (AI = P/PET), which registers severe aridity conditions throughout the southern and southeastern zones, indicating that potential water loss far exceeds available rainfall inputs. Correspondingly, potential evapotranspiration reaches its highest values in these southern sectors, driven by intense solar radiation and elevated temperatures, while lower rates characterize the relatively cooler northwestern areas. Slope aspect further modulates local moisture availability: north- to northeast-facing slopes, classified as "wet aspects," receive reduced direct solar radiation and therefore retain higher soil moisture, whereas southwest- to west-facing slopes experience greater insolation, accelerating surface desiccation and increasing susceptibility to land degradation.

Table 4 Classes and characteristics of the climate quality index (CQI)

Index	Class	Description	Area (km²)	Area (%)	Characteristics
CQI	1	High	138.8	6.61	1–1.15
	2	Moderate	829.2	39.5	1.15–1.40
	3	Low	1131.29	53.89	1.40–2

The climatic conditions of the study area are classified as arid to semi-arid, according to the United Nations Convention to Combat Desertification [29]. The Climate Quality Index (CQI), which integrates multiple climate-related variables, is categorized into three classes (Fig. 6), each representing a distinct level of climate quality across the region. High climate quality, indicating more favorable environmental conditions, accounts for only 6.61% of the study area. This limited extent is associated with extremely low annual rainfall-often below 39 mm-coupled with high potential evapotranspiration rates exceeding 2000 mm and elevated aridity index values (AI ≥ 1). These factors collectively constrain ecosystem functionality and contribute to increased vegetation stress and soil erosion, particularly within southern oases such as Erfoud, Rissani, and Jorf.

Figure 6 displays the spatial variation of the Climate Quality Index (CQI) within the Ziz Valley. The CQI values reveal a heterogeneous distribution that reflects the climatic stress gradient across the region. Approximately 53.89% of the study area falls into the low climate quality category, indicating areas with critical aridity levels, high evapotranspiration, and unfavorable slope aspects, particularly in the southern and southeastern zones (Table 4). These conditions correspond to extreme environmental stress, reducing soil moisture availability and hindering vegetation development. Conversely, only 6.61% of the area benefits from high climate quality, mainly located in upstream sectors and

localized zones with relatively better rainfall and less solar exposure. Moderate climate quality, covering 39.5%, represents transitional areas where precipitation and aridity are slightly more favorable but still insufficient to fully sustain ecological resilience. This spatial configuration confirms the climatic gradient from north to south, with increasing vulnerability toward desertification in the downstream oases of Erfoud, Rissani, and Jorf.

3.4 Management quality index (MQI)

Population pressure plays a significant role in resource depletion, as the demand for water and soil productivity rises with human needs. Similarly, grazing pressure is most intense in the southern part of the Ziz Valley (including Erfoud, Rissani, and Jorf), where approximately 1188.2 km², or 56.6%, of the land is subject to heavy livestock grazing, accelerating land degradation.

Land use intensity reflects the dominance of bare lands and built-up areas, indicators of substantial human alteration of the landscape. Notably, high management quality is limited to only 3.86% of the total study area. These findings underscore the negative impact of inadequate land management practices, which in turn influence other quality indices and amplify the risk of desertification across the region.

Figure 7 illustrates the spatial distribution of the (MQI), derived from three anthropogenic sub-indices: population pressure, grazing intensity, and land use intensity. The analysis indicates a clear predominance of low management quality, covering 70.14% of the study area, particularly in the central and upper parts of the Ziz Valley. High management quality, accounting for 29.14%, is localized primarily around oasis zones where land management practices are better structured-often characterized by traditional agricultural systems and lower population density (Table 5). Spatial disparities in MQI reflect contrasting land use dynamics and grazing patterns, with degraded zones in the south (Erfoud, Rissani, Jorf) showing intense anthropogenic pressure. These areas suffer from excessive livestock density and unregulated land conversion, accelerating soil degradation and reducing ecosystem resilience.

Figure 8 presents the final ESAI map, resulting from the geometric integration of the four quality indices-soil, vegetation, climate, and management-within a GIS environment. The map delineates the spatial variability of land sensitivity to desertification across the Ziz Valley, highlighting distinct vulnerability gradients.

The ESAI classification reveals a strongly skewed distribution of land sensitivity across the Ziz Valley. The vast majority of the study area - approximately 71.51% - falls within the high sensitivity category, primarily concentrated in the southern zones around Erfoud, Rissani, and Jorf.

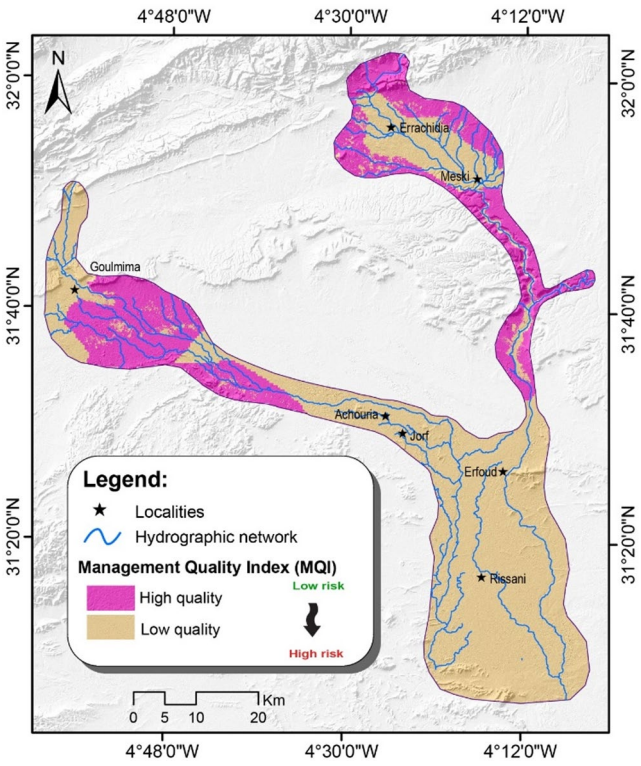

Fig. 7 The management quality index map

Table 5 Classes and description range of the management quality index

Index	Class	Description	Area (km²)	Area (%)	Characteristics
MQI	1	High	611.8	29.14	1–1.26
	2	Low	1487.49	70.14	1.26–1.50

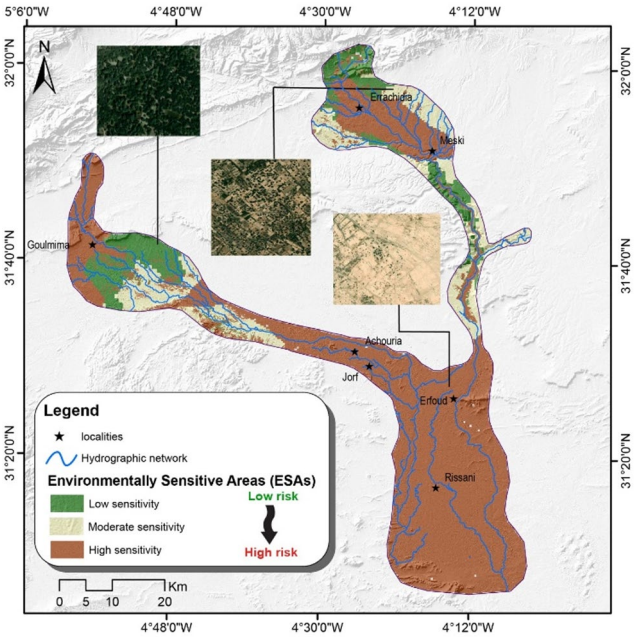

Fig. 8 The ESAs map

These areas are characterized by a critical convergence of poor vegetation cover, harsh climatic conditions, degraded soils, and intense anthropogenic pressure, making them the most urgent targets for intervention. A transitional belt of moderately sensitive land accounts for 16.18% of the territory, forming an intermediate zone between oasis centers and severely degraded peripheries; these areas are subject to seasonal environmental fluctuations and represent priority sites for preventive restoration and sustainable land-use planning. The remaining 12.31% of the valley exhibits low sensitivity, largely confined to stable oasis systems with relatively favorable hydrological conditions, denser vegetation cover, and more efficient land management practices.

To assess the reliability of the desertification sensitivity map generated using the MEDALUS model, a validation was performed using 150 field-based reference points, distributed among three desertification sensitivity classes: low (45 points), moderate (50 points), and high sensitivity (55 points). The confusion matrix revealed a strong agreement between the predicted and observed classes, with classification accuracies of 88.9% (40/45) for the low sensitivity class, 92.0% (46/50) for the moderate class, and 89.1% (49/55) for the high sensitivity class. The overall accuracy (OA) of the model reached 90.0% and the resulting Kappa value was 0.85. These validation results confirm the MEDALUS model's applicability and reliability in mapping desertification sensitivity in arid and semi-arid environments such as the Ziz Valley.

Field validation conducted between February 3 and 9, 2025, confirmed the three distinct ESA classes identified through the MEDALUS model. The spatial classification reveals a pronounced environmental degradation gradient across the Ziz Valley. Low sensitivity areas are characterized by oases that are ecologically stable and resilient, largely attributed to efficient irrigation infrastructure, well-developed hydrological networks, favorable climatic conditions, and dense vegetation cover. Soils in these zones exhibit low levels of salinization, structural stability, and are suitable for sustaining palm grove agriculture (Fig. 9a). Moderate sensitivity zones encompass areas exhibiting early to intermediate signs of degradation, with moderate levels of soil salinity and seasonal vegetation cover, along with signs of reduced drainage efficiency. These areas are generally situated in semi-arid zones with fragile ecosystems subjected to anthropogenic pressure, water scarcity, and elevated temperatures (Fig. 9b). High sensitivity areas are highly susceptible to desertification, with key features including elevated soil salinity, the presence of sand dunes, low soil moisture, and minimal vegetative cover. These regions receive sparse precipitation, are exposed to extreme thermal conditions, and suffer from overgrazing. Oasis ecosystems in these zones are severely deteriorated, frequently affected by phytopathologies such as Bayoud disease (*Fusarium oxysporum*), exacerbating their vulnerability to land degradation (Fig. 9c).

4 Discussions

The results in this research were generated based on different types of data and valued based on the field, which make the results acceptable in the scientific community. The findings of this study reveal an alarming degree of land degradation in the Ziz Valley, with over 71% of the total area classified as highly sensitive to desertification. These results are consistent with recent multi-decadal trends observed in other oasis systems of southeastern Morocco, where degraded land has nearly tripled since the 1990s due to increasing aridity, human-induced pressures, and groundwater overexploitation [1]. The progressive decline of vegetation cover and soil quality reflects a broader regional pattern reported by Karmaoui et al. [14], where dryland expansion and oasis shrinkage threaten the sustainability of agricultural and ecological systems [14].

4.1 MEDALUS as a model of desertification assessment

The MEDALUS model is a type of modeling that regroups a well-defined formula, in addition to multiple functions, metadata, and data sources. The original approach is clarified in the manual on key indicators of desertification and mapping environmentally sensitive areas to desertification, that was used by [19]. Among the positive aspects of this model is the possibility of adding or removing one or multiple sub-indices, in addition to changing them with another sub-factor that own data. Monitoring desertification based on this model in the first option adopted by multiple countries, in this case, in Mediterranean countries besides Morocco. An essential step following the application of the model and the calculation of the indices, is the measure of the impact of desertification and land degradation in the region, as well as the relation between these phenomena and the nature of the zone.

The MEDALUS model results have four indices, each index representing the situation of desertification in the study area. The soil index was the first factor in the MEDALUS equation, this factor is a combination of four sub-indices. The soil is one of the basic factors that influence directly palm growth from different sides, beginning with organic matter, in this research, organic matter is replaced soil brightness, which acts as an alternative sub-indicator. The latter has a significant impact on the soil quality index map, which is explained by the salinity as a reflectance of



Fig. 9 Classification of environmentally sensitive areas (ESAs) based on field observations. **a** Low sensitivity: stable oasis with dense vegetation; **b** Moderate Sensitivity: transitional areas with seasonal vegetation; **c** High Sensitivity: severely degraded zones with sand encroachment

subsurface elements and the distribution of regions with low quality and high sensitivity, passing by the lithological nature of the oases. The upper valley composed of schist and limestones, with limited agricultural capacity due to steep slopes and good drainage. The middle valley is characterized by sedimentary formations along with resistant slope and drainage capacity prioritizing oases zones for development. Conversely, the lower valley is made up of sandy dumps and Quaternary dunes linked to gentle slopes and moderate to poor drainage, these sub-indices make components in evaluating the vulnerability of desertification in Ziz valley. The vegetation quality index is the key indicator in assessing the productivity of the oases land, detecting desertification and arrive at an optimal solution. The VQI relies on soil stability, in this context the main sub-indices are used, fire risk, erosion protection, drought resistance, and plant cover. Regions with low fire risk, high plant cover, resilience to drought and erosion are less sensitive

to desertification, conversely, areas with high fire risk, limited plant cover, and low drought resistance, are extremely vulnerable to desertification, these results indicate the situation of the land. The position of the climate quality index in this approach is crucial, assessing desertification phenomena based on precipitation, evapotranspiration, aridity, and aspect. To facilitate the discussion of the results, CQI play a sensitive role in this model due to the causal relation between climate quality, vegetation, soil, and management. Climate quality serves as the main driver establishing the fundamental parameters for vegetation development, soil stability, and water availability. In southeastern Morocco, extreme climate conditions, including limited precipitation, higher evapotranspiration, and aridity impact negatively soil moisture followed by vegetation quality, and low plant cover affects the stability of the soil and increases the land's vulnerability to desertification. The ecological sensitivity can be aggravated due to inefficient management practices, consisting of high population pressure, excessive grazing, and misapplication of the land use. On the other hand, improved management practices decrease the effects of desertification in the areas. The combination of these four factors evaluates desertification sensitivity and provides a better understanding of the mechanisms underlying these phenomena.

4.2 Comparison between Ziz and Middle Draa valleys

Morocco southeastern environment, humans, and agriculture, are particularly affected by desertification. The Ziz and Draa valleys are the two largest oases and river valleys in Morocco, the Ziz valley is identified by a variety of lithological formations, and conventional irrigation systems, in addition to the palm groves production despite dry conditions. The Draa valley located approximately into the Sahara region [5], in characterized by extreme climate conditions, and represents the largest region of arid ecosystem. Desertification forces affect Ziz and Draa valleys, the desert and the aridity decrease vegetation cover and community's livelihood, while increasing soil erosion, socio-economic problems, and climate change revolution. Hence, both valleys highlight the necessary of the preservation of the oasis environment and protecting the sustainability of agriculture and water availability in these regions.

4.3 Climatic stress and hydrological depletion

Climatic drivers-particularly low and erratic precipitation combined with extreme evapotranspiration-play a fundamental role in shaping desertification vulnerability in the study area. Our results confirm that areas with low precipitation and high aridity index values are strongly correlated with zones of high environmental sensitivity. These patterns are amplified by the depletion of groundwater resources, with aquifer levels in parts of the valley dropping by 3–12 m over the past two decades due to the combined effect of drought and intensified water extraction [15]. The diminishing recharge rates from the Ziz and Rheris rivers, aggravated by reduced snowfall in the High Atlas, further exacerbate water scarcity and accelerate land degradation processes.

4.4 Anthropogenic pressures and land use change

Human-induced pressures such as population growth, intensive livestock grazing, and unsustainable land use practices are key contributors to desertification in the valley. Our Management Quality Index (MQI) highlights critical pressure points in the southern oases of Erfoud, Rissani, and Jorf, where land use intensity and grazing pressure are particularly high. Similar findings have been reported in the Middle Draa Valley and Oued Labiod (Eastern Algeria), where unregulated development and overgrazing lead to vegetation loss and soil destabilization [6, 7]. Furthermore, the decline in traditional oasis agriculture-driven by rural exodus, aging populations, and limited water availability-has resulted in the abandonment of arable lands. This not only reduces land productivity but also weakens the resilience of agroecological systems [30]. The degradation of khettaras (traditional underground canals), a vital component of indigenous water governance, further reflects the socio-economic vulnerability of oasis systems to environmental shocks.

4.5 Resilience through traditional knowledge and technological integration

Human-induced pressures such as population growth, intensive livestock grazing, and unsustainable land use practices are key contributors to desertification in the valley [14]. Our Management Quality Index (MQI) highlights critical pressure points in the southern oases of Erfoud, Rissani, and Jorf, where land use intensity and grazing pressure are particularly high. Similar findings have been reported in the Middle Draa Valley and Oued Labiod (Eastern Algeria), where unregulated development and overgrazing lead to vegetation loss and soil destabilization [6]. Furthermore, the decline in traditional oasis agriculture-driven by rural exodus, aging populations, and limited water availability-has resulted in the abandonment of arable lands. This not only reduces land productivity but also weakens the resilience of agroecological systems [31]. The degradation of khettaras (traditional underground canals), a vital component

of indigenous water governance, further reflects the socio-economic vulnerability of oasis systems to environmental shocks [32].

4.6 Contributions of the enhanced MEDALUS model

This study offers a robust, reproducible, and data-integrated approach for assessing desertification sensitivity using updated remote sensing datasets (Sentinel-2, ASTER GDEM), climatic records (WorldClim v2.1), and socio-economic indicators (2024 census, grazing data). The integration of biophysical and anthropogenic factors-validated through field surveys-allows for the production of high-resolution ESAI maps that reflect the spatial heterogeneity of land degradation in arid environments. Our findings demonstrate the model's adaptability to complex oasis ecosystems and its potential application to other dryland regions. Future research should explore scenario-based simulations, integrate machine learning classification for sub-index refinement, and evaluate the socio-economic cost of inaction to inform policy frameworks.

5 Conclusion

This study provides a comprehensive, high-resolution assessment of desertification sensitivity in the Ziz Valley, leveraging an integrated MEDALUS-GIS framework. Our findings reveal a critical situation, with over 71% of the area classified as highly sensitive, underscoring the severe synergy between climatic aridity, soil vulnerability, and unsustainable anthropogenic pressures in this fragile oasis ecosystem. The primary contribution of this work lies in its demonstration of how modern geospatial data—from high-resolution satellite imagery to recent socio-economic datasets—can be systematically operationalized to quantify and map complex degradation processes with high spatial explicitness in data-scarce regions. The validated methodology offers a transferable blueprint for land vulnerability assessment in arid environments worldwide. Looking forward, this research opens several avenues for further investigation. Future work should focus on integrating InSAR data to assess land subsidence from groundwater extraction, coupling the ESAI with CMIP6 climate projections to model future risk scenarios, and embedding machine learning techniques to dynamically weight the MEDALUS indices based on localized feedback. Furthermore, a deeper socio-hydrogeological study is needed to quantify the tipping points of oasis resilience. Such advancements will be crucial for transitioning from static sensitivity mapping to dynamic forecasting, ultimately informing proactive and adaptive policy interventions to safeguard these vital socio-ecological systems against escalating desertification threats.

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Declarations

Conflict of interest The authors declare that they have no competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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