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Research article

Dune system evolution in the Rissani region (Morocco) using GIS and spatial data

Evolução do sistema de dunas na região de Rissani (Marrocos) utilizando SIG e dados espaciais

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Abstract: Dunes are accumulations of sand deposited by the wind. They are dynamic formations, characterized by shape variability and mobility. Their evolution depends on interactions among the sand dune system and several control variables, including sand supply, wind regime, topography, vegetation, and human activity. In the desert plain of Tafilalet, sand dunes form a key geomorphological feature that reflects significant environmental changes. This study aims to monitor and quantify the development of the sand dune system in the Tafilalet–Rissani plain (southeastern Morocco) and to identify the main factors influencing this process. The analysis is based on aerial photographs (1966), multispectral Landsat satellite images (1987 and 2001), and high-resolution Google Earth imagery (2023), from which land cover classifications were produced. Cartographic data were complemented by meteorological information on wind and precipitation. The results of the spatiotemporal analysis indicate that the Tafilalet–Rissani plain is affected by sand influx in the form of barchan chains on its western side and linear sand dunes (sifs) to the east of Rissani. During the period 1966–1987, the results obtained showed an increase of 616.6 ha, equivalent to 29.4 ha/year, in the Tinghras-Ouattara site and 333.7 ha (15.9 ha/year) at the Tizouint-Essifa site. During the period 2001-2023, an increasing trend of 4.8 ha/year was observed at the Tinghras-Ouattara site. For the Tizouint-Essifa site, a regression of 8.4 ha/year was observed. The decrease in the progression of the sand encroachment is due to human intervention. This study provides a solid foundation for planners and decision-makers to develop appropriate management strategies to address sand encroachment in Moroccan desert regions.

Keywords: evolution; sand dunes; Tafilalet; Rissani; sand encroachment; Morocco.

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Resumo: As dunas são acumulações de areia depositadas pelo vento. São formações dinâmicas, caracterizadas pela variabilidade em forma e mobilidade. Sua evolução depende da interação entre o sistema de dunas de areia e várias variáveis de controle, incluindo o fornecimento de areia, o regime de vento, a topografia, a vegetação e a atividade humana. Na planície desértica de Tafilalet, as dunas de areia formam uma característica geomorfológica-chave que reflete mudanças ambientais significativas. Este estudo tem como objetivo acompanhar e quantificar o desenvolvimento do sistema de dunas na planície de Tafilalet-Rissani (sudeste de Marrocos) e identificar os principais fatores que influenciam esse processo. A análise baseia-se em fotografias aéreas (1966), imagens multiespectrais do satélite Landsat (1987 e 2001) e imagens de alta resolução do Google Earth (2023), a partir das quais foram produzidas classificações da cobertura do solo. Os dados cartográficos foram complementados com informações meteorológicas sobre vento e precipitação. Os resultados da análise espaciotemporal indicam que a planície de Tafilalet-Rissani é afetada pelo influxo de areia, na forma de cadeias de barcas ao longo de seu lado ocidental e de dunas de areia lineares (sifs) ao leste de Rissani. Durante o período 1966-1987, os resultados obtidos mostraram um aumento de 616,6 ha, equivalente a 29,4 ha/ano, no sítio Tinghras-Ouattara, e de 333,7 ha (15,9 ha/ano) no sítio Tizouint-Essifa. Durante o período de 2001-2023, observou-se uma tendência de aumento de 4,8 ha/ano no sítio de Tinghras-Ouattara. No sítio Tizouint-Essifa, observou-se uma regressão de 8,4 ha/ano. A diminuição na progressão da invasão de areia é devida à intervenção humana. Este estudo fornece uma base sólida para que os planejadores e tomadores de decisão desenvolvam estratégias adequadas de gestão para lidar com a invasão de areia nas regiões desérticas do Marrocos.

Palavras-chave: evolução; dunas de areia; Tafilalet; Rissani; invasão de areia; Marrocos.

1. Introduction

Sand encroachment refers to the advance of sand grains over surfaces or objects, resulting in the accumulation of sand and the formation of sand dunes, whether continental or coastal (FAO, 1988). Sand dunes are defined as accumulations of wind-deposited sand composed of grains measuring between 0.062 and 2 mm (Boulghobra & Dridi, 2016; Ma *et al.*, 2024). Sand dunes are among the most sensitive and dynamic forms of land cover (Prodanov *et al.*, 2023; Ben Kacem *et al.*, 2025a; Cai *et al.*, 2025). They are characterized by significant diversity in their formation and evolution processes. Sand dunes are large sedimentary accumulations whose shape, size, and orientation vary according to multiple controlling factors, both physical and anthropogenic.

The formation and evolution of wind-driven deposits in the Tafilalet plain results from a complex interaction between the wind regime and regional environmental conditions. Sand dune systems develop through the combined influence of sand availability, wind, vegetation, topography, precipitation, and human activity (Bagnold, 1941; Callot & Oulehri, 1996; Benmohammadi *et al.*, 2000; Beveridge *et al.*, 2006; Livingstone *et al.*, 2007; Tsoar *et al.*, 2009; Parteli *et al.*, 2009; Adnani *et al.*, 2016; Herzog *et al.*, 2021; Manzolli *et al.*, 2023; Lancaster, 2023; Dłużewski & Woronko, 2024; Courrech du Pont *et al.*, 2024). The sand dunes of southeastern Morocco, therefore, constitute an important archive for understanding the processes and dynamics of sand encroachment.

The processes of sand dune formation, evolution, migration, and morphological change represent major areas of research in geomorphology (Pickart & Hesp, 2019; Ma *et al.*, 2023). These aspects are essential for understanding sand dune dynamics and for

addressing the problem of sand encroachment in arid and semi-arid environments. Monitoring of sand dune systems has been conducted in various regions using different techniques, depending on the spatial and temporal scales of the study. Common approaches include the use of aerial photographs and satellite imagery (Chemin, 1984; Bogle *et al.*, 2014; Bouarfa & Bellal, 2018; Laaouane *et al.*, 2019; Ben Kacem *et al.*, 2025b; Nmiss *et al.*, 2025; Benbih *et al.*, 2025; Sebbab *et al.*, 2025; Taha *et al.*, 2026) and GPS tracking (Elbelrhiti, 2012; Sbai & Mouadili, 2023), as well as drone and LiDAR technologies (Robine *et al.*, 2023; Bristow & Duller, 2024; Ma *et al.*, 2024).

The identification, quantitative assessment, and temporal monitoring of sand dunes remain challenging tasks in geomorphology. To contribute to this field, the present study focuses on the Tafilalet–Rissani plain. The main objective is to analyze the spatiotemporal evolution of the Rissani sand dune system and to identify the processes governing the spatial expansion of sand dunes. A cartographic approach was adopted, using analyses of multi-date materials such as aerial photographs and high-resolution satellite images. Climatic data, including wind speed, wind direction, and precipitation, were also used to assess the influence of climate on dune migration. Although previous studies have addressed sand creep in Tafilalet, they have either focused on short time periods or relied on qualitative descriptions.

2. Study area

The study area is located in southeastern Morocco, between latitudes 31°05′ and 31°24′ N and longitudes 4°08′ and 4°23′ W, specifically in the southern part of the Tafilalet plain (Fig. 1). Administratively, it belongs to the province of Errachidia. Covering an area of approximately 620 km², the Tafilalet–Rissani plain comprises two districts that include six territorial communes: Essfalat, Bni M'hamed Sijilmassa, Moulay Ali Cherif, Rissani, Essifa, and Aarab Essbah Ziz. Together, these municipalities have a total population of 74,015 inhabitants.

The Tafilalet plain lies within Morocco's pre-Saharan zone-east of the eastern Anti-Atlas, west of the Tertiary Hamada of Guir, south of the Cretaceous Hamada of Meski and the Arfoud palm grove, and north of the Taous massif. It also serves as a natural spreading area for the waters of the Ziz and Ghéris rivers. The study area is an alluvial plain with two main types of relief: the plain itself, which is predominant, and scattered elevations that appear as isolated hills, such as Jbel Bezma (813 m), Jbel Haroune (795 m), and Jbel Ejjbiel (780 m) north of Rissani.

The lithological formations in the Rissani area are mainly schist-sandstone, which are particularly susceptible to erosion. Quaternary deposits have left behind significant alluvial accumulations, largely composed of sandy-silty materials that form a considerable stock easily mobilised by wind, especially during sandstorms. The sediments carried by the Ziz and Ghéris rivers and their tributaries are primarily clay-sandy, making them vulnerable to wind transport (Margat, 1958; Allali & Benmohammadi, 2013; Sebbab *et al.*, 2024).

Situated in the pre-Saharan climatic zone, the Tafilalet plain experiences an arid to semi-arid climate (Joly, 1962; Akdim *et al.*, 2017) with a strong continental influence. The mean aridity index is 0.03 (Lamqadem *et al.*, 2018). In the Radier Arfoud resort, maximum temperatures can reach 45°C in summer, while winter temperatures range between -3°C and 7°C. The annual average precipitation is 67.7 mm (1967-2023), with high temporal variability. Annual potential evapotranspiration is around 1,200 mm (Navas *et al.*, 2013).

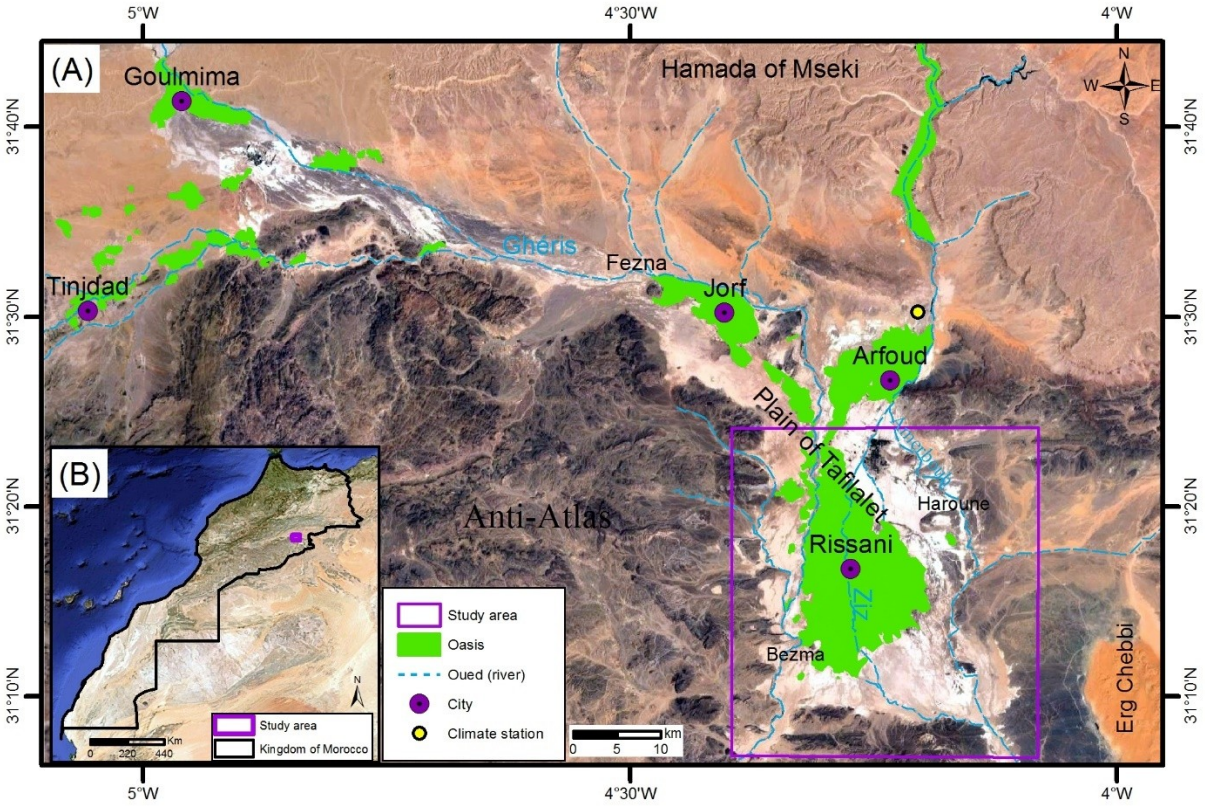

Figure 1. Location of the study area. (A) Rissani in the Tafilalet plain; (B): an overview of the Morocco map.

Figura 1. Localização da área de estudo. (A) Rissani na planície de Tafilalet; (B): uma visão geral do mapa de Marrocos.

Wind patterns show pronounced seasonal and daily variations in both intensity and direction. The monthly average wind speed peaks at 9.1 m/s in May and June and drops to 5.8 m/s between December and February. In 2024, the maximum recorded daily speed reached 17 m/s. Wind rose analysis indicates a dominant south–north (S-N) direction, along with secondary flows from the SSW-NNE and southwest–northeast (SW-NE) directions (Fig. 2).

The soils of the Tafilalet plain belong to the class of poorly developed gray sub-desert soils with alluvial inputs. In agricultural zones irrigated by floodwater spread, the turbidity of these waters has led to the formation of silty-clay soils several meters thick (Guemimi, 1991; El Khoumsi *et al.*, 2017). As noted by Guemimi (1991), soil salinization is a major characteristic of Tafilalets, resulting from the capillary rise of irrigation water.

Vegetation cover in the Tafilalet plain is sparse. It consists mainly of open steppe vegetation dominated by low xerophytic species such as *Salsola sp.*, *Zilla spinosa*, and *Aristida plumosa*, which exhibit various adaptations to arid conditions (Dresch, 1982). These xerophytes temporarily contribute to aeolian deposits (nebkas). Non-herbaceous species are limited to *Tamarix*, which grows mainly along traditional water channels (oueds and seguia), and *Acacia raddiana*, found in peripheral spreading areas such as Bou M'aayz, Adrar, and Tiklmet.

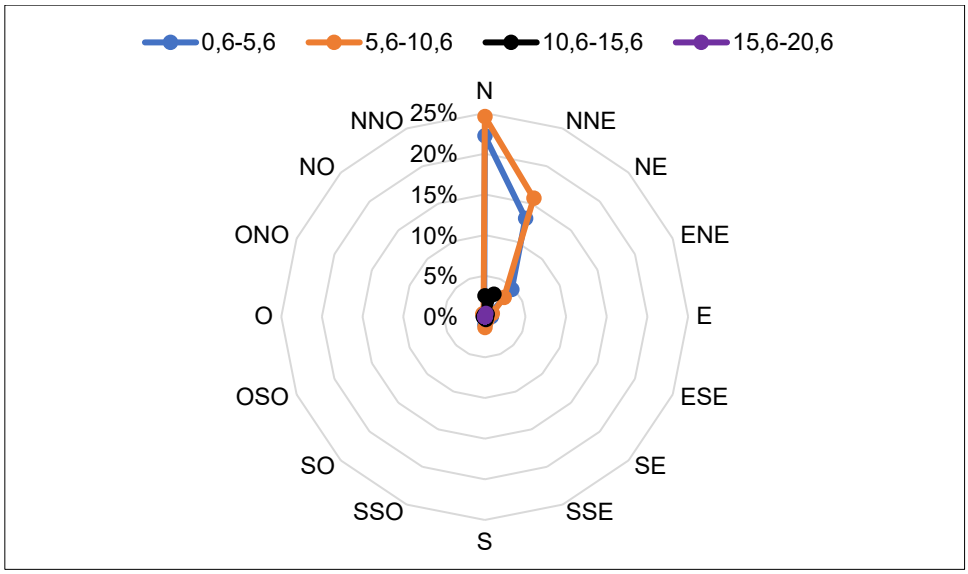

Figure 2. Wind rose (m/s) recorded in Arfoud during 2023 and 2024.

Figura 2. Rosa eólica (m/s) registrada em Arfoud durante 2023 e 2024.

The Rissani palm grove organizes its agricultural practices into three layers: palm trees, fruit trees, and low-growing crops. The region also benefits from diverse water resources, including groundwater extracted by pumps or khattaras, floodwaters, the low-flow channels of the Ziz and Ghéris rivers and their tributaries, and water supplied by the Hassan Addakhil Dam.

The Tafilalet plain has been inhabited since ancient times due to several factors, including flat terrain, the presence of Atlas-derived water, fertile soil, and a strategic location along the trans-Saharan caravan route (Laaouane & Ben Kacem, 2018). The local population has long demonstrated the ability to exploit environmental advantages and adapt to constraints, creating a balanced agro-system. Historically, Tafilalet has played a central role in Morocco's development. It was a major crossroads of trade and cultural exchange whose influence extended far beyond the region (Mezzine, 1987). The ancient city of Sijilmassa, now in ruins, bears witness to this legacy. Moreover, Tafilalet is the birthplace of the Alaouite dynasty, the ruling family of the Kingdom of Morocco.

3. Data and methods

3.1 Spatial data and processing

The characterization and spatiotemporal monitoring of the sand dunes in the Tafilalet Plain were conducted using an integrated approach combining aerial photographs, satellite imagery, and meteorological data (Table 1). These cartographic resources provided valuable information on the sand dune systems that could not be obtained through in situ observations alone.

To monitor the spatiotemporal evolution of sand encroachment and to quantify the dynamics of the sand dune system, aerial photographs from the 1966 mission at a scale of 1:30,000, multispectral Landsat images (TM and ETM+), and Pleiades imagery from 2023 were acquired. The aerial photographs were produced by the National Agency for Land Conservation, Cadastre, and Mapping through its Technical Documentation Service.

Landsat satellite images covering the period from 1987 to 2001 were obtained free of charge from the United States online platform, namely "Geological Survey" (https://earthexplorer.usgs.gov). The radiometric resolution of TM and ETM+ sensors is 8 bits. The satellite images from Google Earth Pro have a fine spatial resolution of 2 m.

Table 1. Spatial data used in the monitoring of the sand dune system in the Tafilalet-Rissani plain.

Tabela 1. Dados espaciais utilizados no monitoramento do sistema de dunas na planície de Tafilalet-Rissani.

Satellite image				
Satellite	**Sensor**	**Spatial resolution in m**	**Date of acquisition**	**Source**
Landsat 5	TM	30	1987	https://earthexplorer.usgs.gov
Landsat 5	ETM+	30	2001	
Google Earth Pro.	-	2	2023	Google Earth Pro.
Aerial photograph				
Spatial data	**Scale**	**Date of taking**	**Source**	
Aerial photograph	1/30,000	1966	The National Agency for Land Conservation of the Cadastre and Mapping (Technical Documentation Service)	

The method adopted to identify and quantify the evolution of sand encroachment in Rissani using aerial photographs consisted of five main steps (Fig. 3): (1) acquisition of aerial photographs, (2) georeferencing using ArcGIS® software, (3) digitalization of the main landscape units of the Tafilalet plain, (4) calculation of the surface area of wind-deposited zones, and (5) final data export.

The processing of satellite images followed four principal stages:

1. Color composition, image enhancement, and extraction of the study area;
2. Image classification, color composition, and validation of results;
3. Vectorization and surface measurement of sand accumulation zones;
4. For high-resolution images, sand deposits were digitised by creating KML files in Google Earth Pro, then imported into ArcGIS® for vector conversion and final processing.

To quantify the annual progression or regression of the Rissani sand dune system, the surface measurement technique was applied. This involved calculating the area of sand accumulations for each observation year (1966, 1987, 2001, and 2023) in hectares. The average annual rate of sand encroachment was then computed for three distinct periods: 1966–1987, 1987–2001, and 2001–2023. Although these measurements reflect specific temporal snapshots, they offer information about the various phases of dune evolution within the study area.

This research also involved several field visits to validate the results obtained and assess the role of human activities in the evolution of the phenomenon. In this context, interviews were conducted with locals and resource persons, particularly elderly residents.

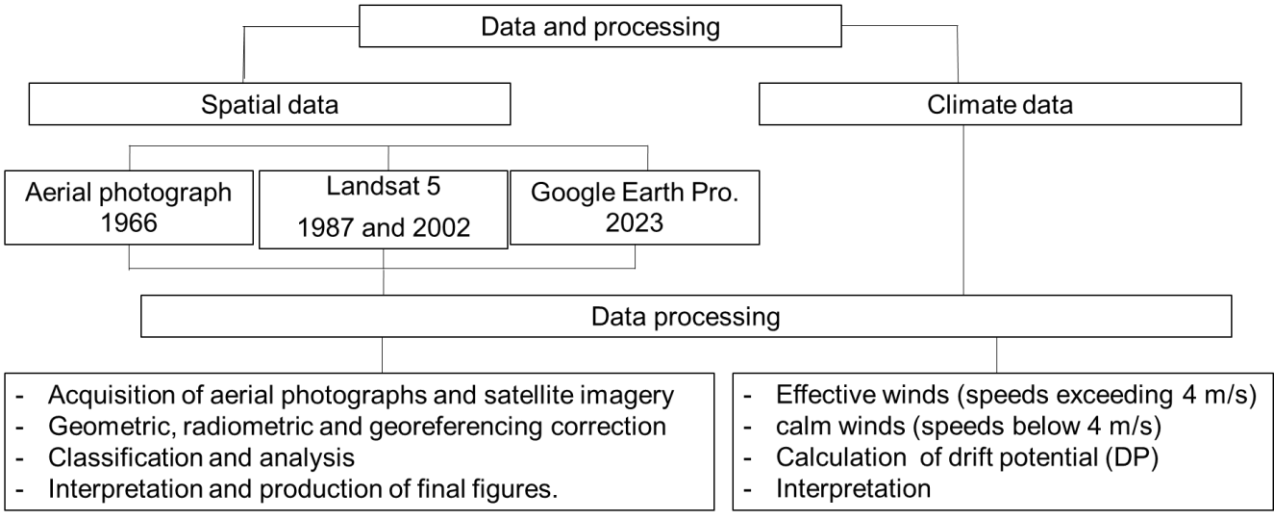

Figure 3. The Methodological approach adopted for the processing and analysis of spatial and climate data.

Figura 3. A abordagem metodológica adotada para o processamento e análise de dados espaciais e climáticos.

3.2 Climate data and processing

The climate is the primary factor controlling the progression of sand dunes, with wind and precipitation representing the main parameters for studying the sand dune system in pre-Saharan Morocco. Unfortunately, wind records at Rissani are very limited, due to the absence of climate stations in this region and the irregular operation of anemometers at the Radier Arfoud weather station. In addition, the original anemometric data of the latter are not available. Only data presented in some studies are available. These data showed clearly visible contradictions compared to the 2023 and 2024 data. Therefore, the use of these anemometric data remains of little interest for our work. To address this problem, this study is based on the available data at the climate station of the General Directorate of Meteorology in Arfoud from 2023 to 2025. Although these data reveal insufficient periods to characterize the wind regimes at Rissani, they can highlight some of the characteristics of the winds.

To assess the role of winds in sand dune advancement, an analysis of anemometric recordings was conducted. In this analysis, effective winds (speeds exceeding 4 m/s) and calm winds (speeds below 4 m/s) were distinguished. Furthermore, the calculation of drift potential (DP) is essential for evaluating sand movement in Rissani. The DP was determined using Fryberger's equation (1979):

$$\mathrm{DP} = \mathrm{V2}\ (\mathrm{V} - \mathrm{Vt})$$

With:
DP = Drift Potential;

V = wind speed at 10 m from the ground

Vt = critical speed, allowing the mobilisation of dune sand.

The critical speed adopted in this work was chosen taking into account the study by Bagnold (1941). This study suggested a critical velocity of 4.6 m/s when the diameter of the sand is between 0.18 and 0.20 mm. The average diameter of the sandy material of Tafilalet meets this criterion, with 0.19 mm (Ben Kacem *et al.*, 2025a).

The evolution of sand dunes in the Rissani sector also finds part of its explanation in rainfall variability (Ben Kacem *et al.*, 2025b). In this sense, we also examined the relationship between annual precipitation and sand dune progression in Rissani during two chronological periods between 2005 and 2023 (2005-2012 and 2012-2023).

4. Results and discussions

4.1. Identification of wind accumulation areas in the Tafilalet-Rissani plain

The analysis of aerial photographs (1966), Landsat images (1987 and 2001), and Google Earth Pro. images (2023) covering the Rissani area reveal several distinct sandy zones (Fig. 5,7,10). Along the western front of the Rissani palm grove, multiple sandy areas appear, distributed irregularly across the region. From north to south, the Tizouint–Essifa sector shows a high level of sand accumulation, with surface areas ranging from 400 to 974 ha. This is followed by the Zaouïa Errmel–Ouled Ejmiea area, which extends from west of Qsar Zaouïa Errmel to west of Ouled Ejmiea.

The phenomenon is particularly pronounced from west of Tinghras to Ouattara, which represents the most active deposition zone in the Rissani sector, accounting for about 45% of the total area of the sand dune complex forming Rissani's western front. The sand dune system in this zone, elongated in a southwest–northeast (SW-NE) direction, is primarily composed of barchan dunes, barchanoid ridges, and transverse dunes (Fig. 4b).

To the east of the Rissani palm grove, near the west of Oued (river) Amrbouh and northwest of Qsar Haroune, another significant sandy zone is observed, extending from southeast to northwest and covering an area between 200 and 233 ha. Sand accumulation in this sector occurs in the form of well-developed longitudinal dunes (sifs), indicating a bidirectional wind regime with major sand input from the SE-NW and NW-SE directions (Fig. 4a).

Another major sandy zone is located southeast of Rissani, north of the confluence of the Ziz and Amrbouh rivers, and east of Jbel Adrar. This area is clearly visible on the available cartographic documents. The sand accumulations in this sector consist mainly of transverse dune chains. The dunes in this site have a SW-NE orientation and are related to the braking effect of the wind load exerted by the coal-bearing outcrops of de Hassi Elbid.

The final sandy zone identified in the Rissani area lies at the eastern edge of the Tafilalet plain, near Qsar Derkaoua. Covering an area between 1,092.4 and 1,230 ha, it is locally known as Rasse Errmel. This aeolian accumulation zone occupies a transitional area between the Tertiary Hamada of Guir and the Tafilalet plain, where prevailing winds promote sand deposition through the deceleration of wind flow and sediment precipitation.

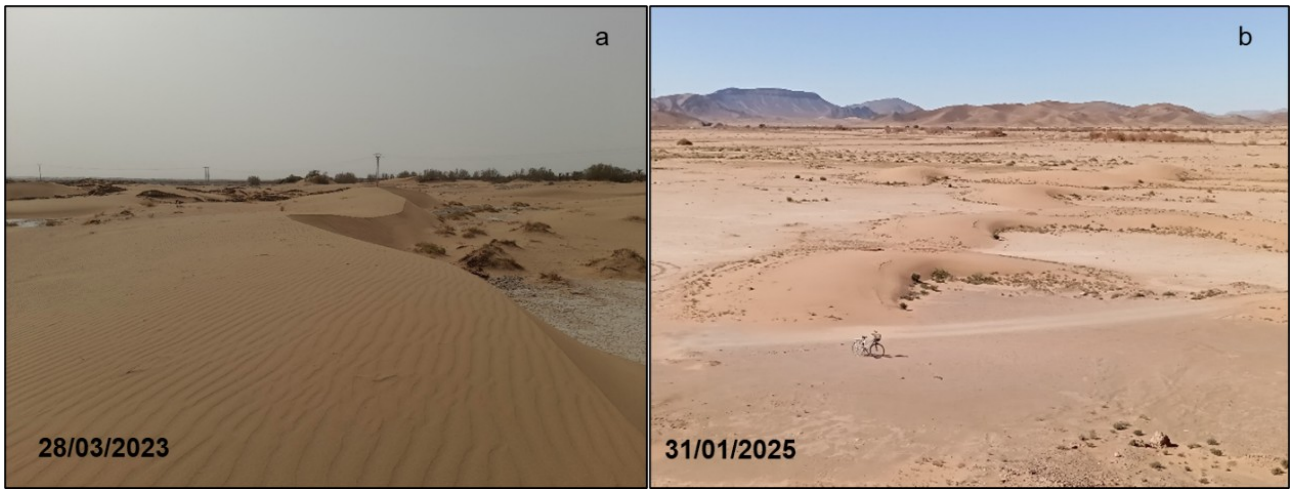

Figure 4. Sand dunes in the plain of Tafilalet-Rissani. a: Longitudinal dune (Sif) in the Haroune field (31°18'41.69"N, 4°10'18.05"O); b: barchan field west of Tinghras (31°11'40.61"N, 31°11'40.61"N).

Figura 4. Dunas de areia na planície de Tafilalet-Rissani. a: Duna longitudinal (Sif) no campo de Haroune (31°18'41.69"N, 4°10'18.05"O); b: campo barchan oeste de Tinghras (31°11'40.61"N, 31°11'40.61"N).

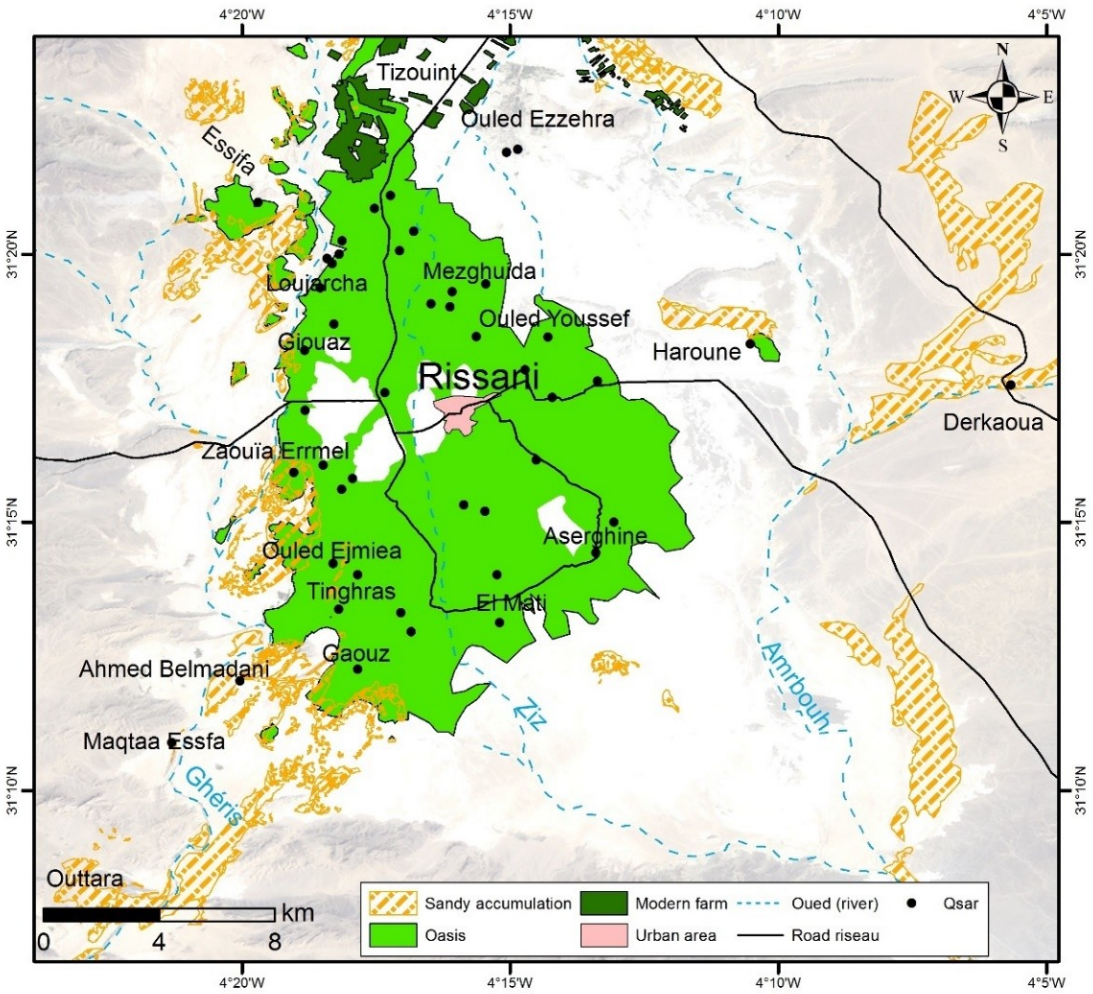

Figure 5. Spatial extension of the sand accumulations in Rissani (2023).

Figura 5. Extensão espacial das acumulações de areia em Rissani (2023).

4.2. Evolution of the sand dune system in the Rissani sector

The 1987 satellite image was captured after a severe drought that affected Morocco in general and the Moroccan Southeast in particular. As shown in Table 2 and Figures 6 and 7A-B, significant changes are visible in the spatial extent of sandy areas. Sand encroachment became more pronounced compared to the situation in 1966. The 1987 Landsat image does not make it possible to track dune shape changes, but allows for a comparison of sandy surface areas with those measured in 1966 (Table 2). Over a period of 21 years (1966–1987), the sandy area of Tinghras–Ouattara expanded by 616.6 ha, corresponding to an average annual increase of 29.4 ha/year. The results also indicate an increase of 333.7 ha (15.9 ha/year) at Tizouint–Essifa and 197.7 ha (8.6 ha/year) at Zaouïa Errmel–Ouled Ejmiea. In the bimodal sandy areas east of Rissani, the rate of expansion was relatively slow. The Derkaoua area showed a progression of 41.4 ha, equivalent to an average annual increase of 2 ha/year, while in the Haroune area, the surface occupied by longitudinal dunes decreased slightly, at an average rate of –0.14 ha/year.

According to data obtained from the exploration of the 2001 Landsat image, the evolutionary trend in sand encroachment in the Rissani area has continued to increase, with a rate lower than that of the 1966-1987 period (Fig. 6-7C). In this sense, from 1987 to 2001, we recorded an increase of 238.4 ha, representing a progression of 17 ha/year in the area of Tizouint-Essifa, 87 ha (6.2 ha/year) in the area of Tinghras-Outtara, and 36.9 ha, with an annual increase of 2.6 ha/year in the area of Zaouïa Errmel-Ouled Ejmiea. Moreover, to the east of Rissani, the fields of Haroune and Derkaoua experienced an increase of 12.4 ha and 46.5 ha, respectively. The directions of the aeolian displacement, as shown in Figure 6, are SO-NE for the western front of Rissani and SW-NE and NE-SW in the fields of Haroune and Derkaoua.

Table 2. Monitoring of sand encroachment in ha inside the Rissani sector from 1966 to 2023.

Tabela 2. Monitoramento da invasão de areia em ha no setor de Rissani de 1966 a 2023.

Site/year	1966	1987	2001	2023
Tizouint-Essifa	401.9	735.6	974	788.4
Zaouïa Errmel-Ouled Ejmiea	381.6	561.3	598.2	602.7
Tinghras-Ouattara	642.9	1259.5	1346.6	1452.3
Haroune	202.1	199	211.4	233.8
Derkaoua	1092.4	1133.8	1180.3	1230.4
El Mati	0	0	0	53.5

Currently, few changes are visible in the dune system of the Rissani sector, with a slow or even negative annual progression of sand encroachment. Field surveys and the analysis of available cartographic documents indicate an overall increase in the extent of most sandy areas within Rissani compared to their situation in 2001, along with the emergence of a new sandy area of 53.5 ha south of Qsours El Mati and Ouled Bou Brahim (Fig. 5,7D). At this stage, the sandy areas of Tinghras–Outtara, Zaouïa Errmel–Ouled Ejmiea, and Haroune cover 1453.3, 602.7, and 233.8 ha, respectively. In contrast, the Tizouint–Essifa area shows a regression of 185.6 ha between 2001 and 2023. On an annual scale, dunes in the Tinghras–Outtara, Zaouïa Errmel–Ouled Ejmiea, and Haroune sectors have expanded at average rates of 4.8 ha/year, 0.2 ha/year, and 1 ha/year, respectively. Conversely, in Tizouint–Essifa and Derkaoua, dune surfaces have decreased at an average

rate of 8.4 ha/year, mainly due to the cultivation of sand-covered areas. In the site of El Mati, the abandonment of some farmable land during dry years is one of the main factors causing the formation of aeolian accumulations.

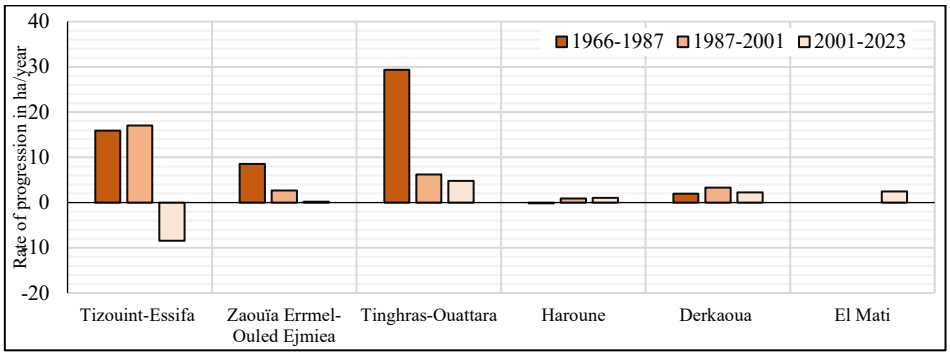

Figure 6. Variability of the annual growth rate in the Rissani sector.

Figura. 6. Variabilidade da taxa de crescimento anual no setor Rissani.

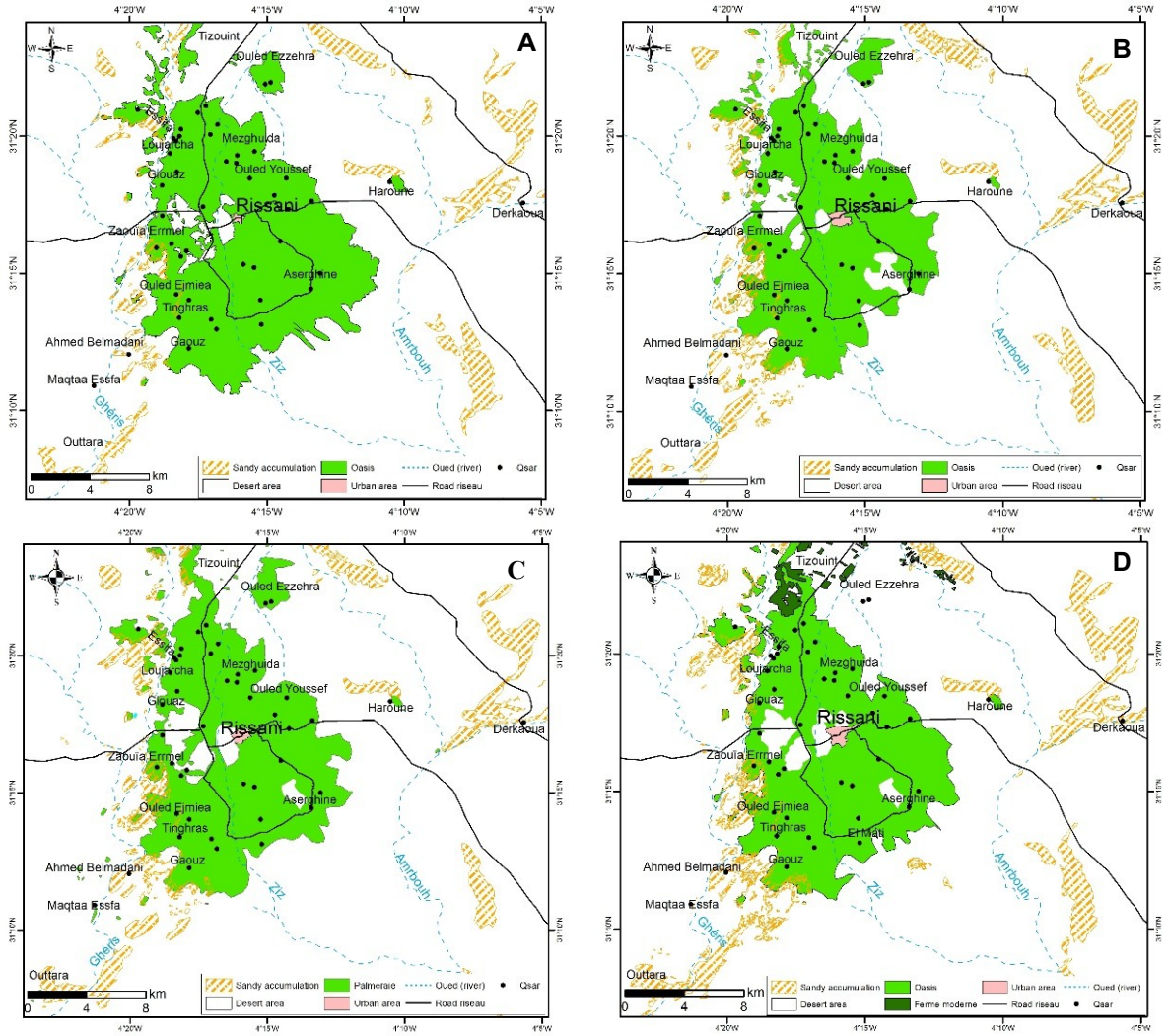

Figure 7. Progress of sand encroachment in the Tafilalet-Rissani plain. A- situation of 1966; B- situation of 1987; C- situation of 2001; D- situation of 2023.

Figura 7. Progresso da invasão de areia na planície de Tafilalet-Rissani. A- situação de 1966; b- situação de 1987; c- situação de 2001; d- situação de 2023.

The following aspects partly explain the growing dynamics of sand encroachment in the Rissani sector over this period: The implementation of grids in deflation areas and the abandonment of sand-covered land in southern Rissani have contributed to the increase in the extent of sand encroachment. The evacuation of sand and the development of both modern farms in the Tizouint perimeter (Fig. 8) and traditional agriculture in the Essifa perimeter (Fig. 9) have contributed to a reduction in the surface area of sandy deposits in the Tafilalet region.

Among the actions of sand evacuation and fight against sand encroachment carried out by the local population and revealed by the Sheikh (the chief) of a terroir and his Mzarigues (assistants), the treatment and development of 24 ha within the Erremlia khettara after sand evacuation for a total cost of 320,000 dh. The contribution of the Regional Office for Agricultural Development of Tafilalet consists in setting up grids at the margins of protected areas. In addition, new oases (modern farms) have been developed on lands bordering the northern palm grove of Rissani. In this sense, the data obtained showed the treatment and valorisation of 718 ha at the Tizouint site.

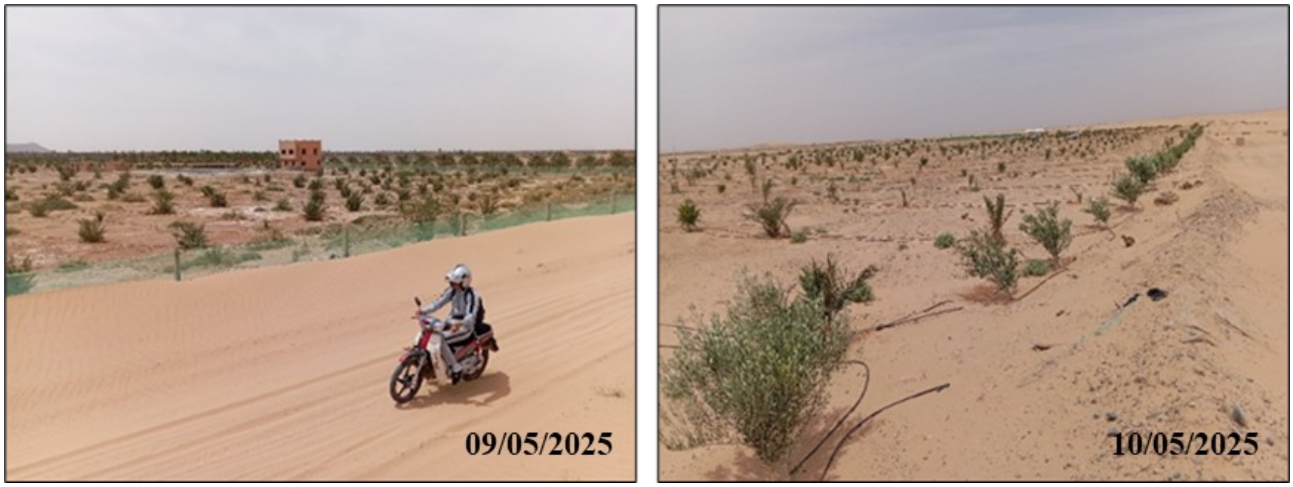

Figure 8. New modern-type agricultural holdings north of the palm grove of Rissani.

Figura 8. Novas explorações agrícolas de tipo moderno ao norte do palmeiral de Rissani.

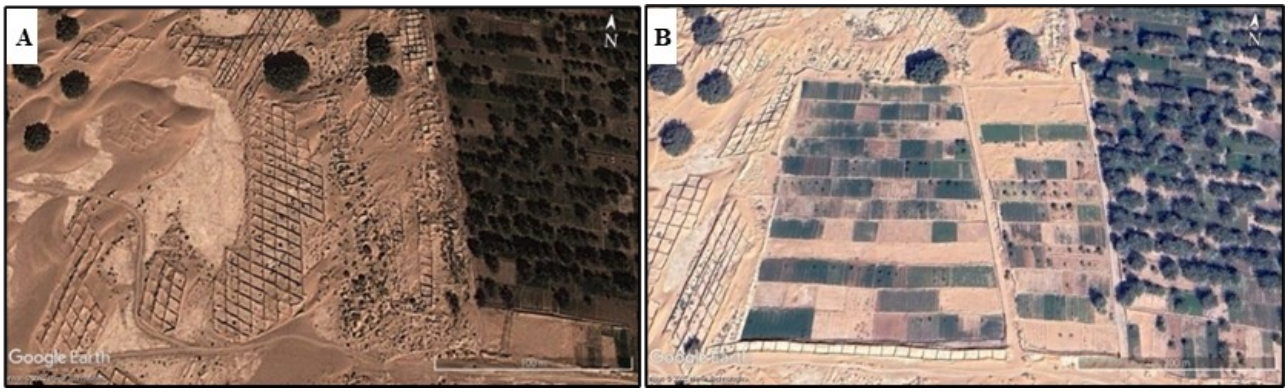

Figure 9. Evacuation of the sand and cultivation at the Essifa site. A- the blocked sector situation of 2012; B- the same sector put into cultivation after the treatment situation of 2023 (Google Earth Pro).

Figura 9. Evacuação da areia e cultivo no local de Essifa. A- situação do setor bloqueado de 2012; B- o mesmo setor, colocado em cultivo após a situação de tratamento em 2023 (Google Earth Pro).

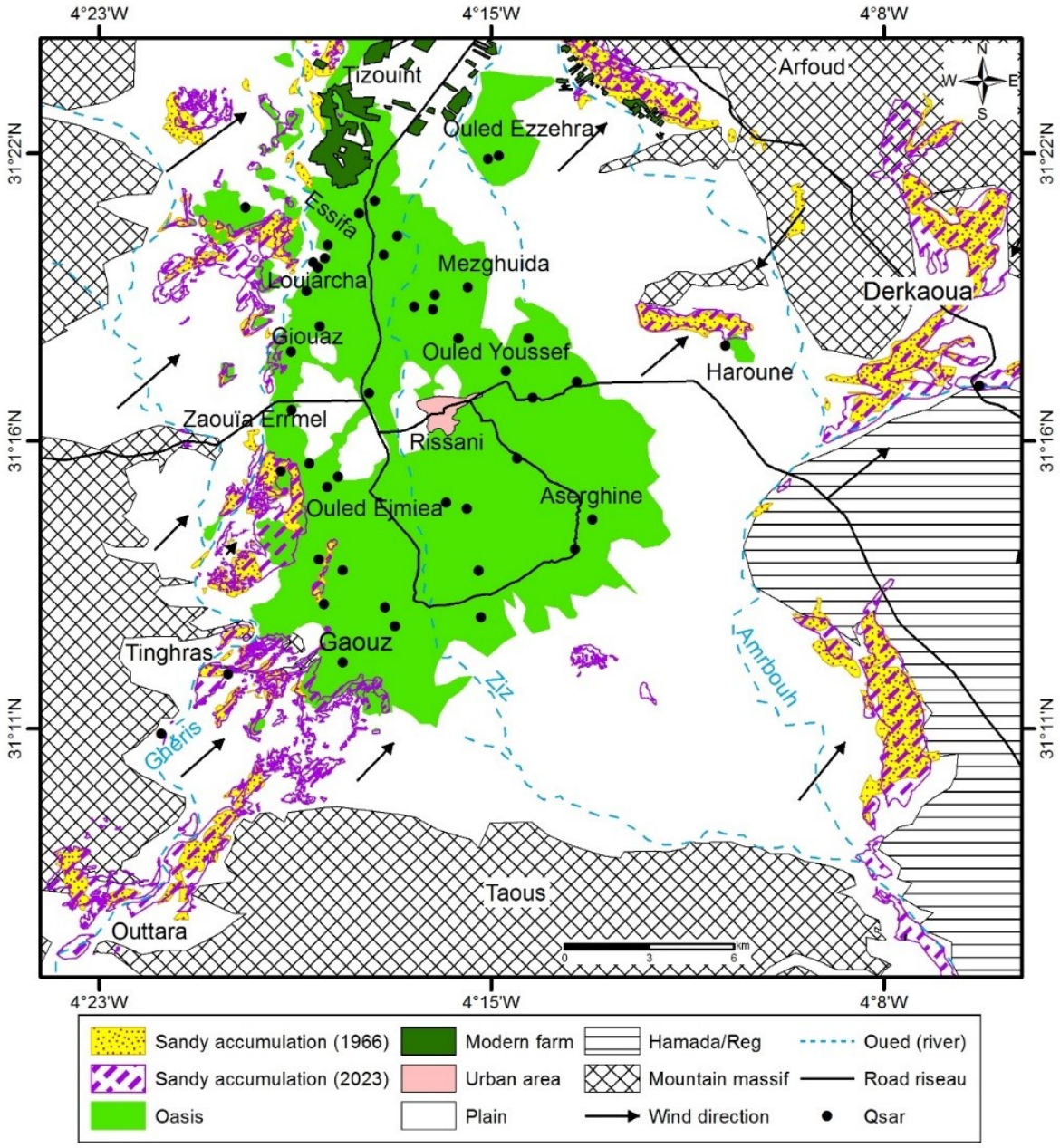

Figure 10. Summary of the evolutionary monitoring of sand encroachment in the Tafilalet-Rissani plain.

Figura 10. Resumo do monitoramento evolutivo da invasão de areia na planície de Tafilalet-Rissani.

4.4. Climatic factors controlling the dynamics of sand dunes in Tafilalet

Wind is the primary factor in the study of aeolian systems in general and sand dune dynamics in particular (Livingstone *et al.*, 2007; Roig-Munar *et al.*, 2020; Lancaster, 2023; Bristow & Duller, 2024; Abd Elaal *et al.*, 2024). Identifying the main characteristics of wind regimes in the Tafilalet plain is therefore essential. Wind activity in this region varies in both intensity (speed) and direction across annual, seasonal, and daily scales (Benalla *et al.*, 2003; Kabiri *et al.*, 2003; Tidjani *et al.*, 2009; Pedrosa & Claudino-Sales, 2023). These two parameters, which govern dune migration, also vary spatially across southeastern Morocco (Khardi, 1992). The wind is considered calm or inactive when its speed is below 4 m/s (Bensaid, 2006; Reddadi *et al.*, 2015), whereas active or effective winds are those exceeding 4 m/s.

Monitoring the characteristics of winds requires data series covering long periods in order to identify reliable trends. However, the data used in this study do not represent the period 1966-2023, but only the years 2023 and 2024. This observation period may show significant variations and not be representative of the trends observed over the long term.

The frequency analysis of anemometric data recorded at the Arfoud station during 2023 and 2024 shows that active winds represent 76% of total observations, whereas calm winds account for only 24% (Table 3). On a monthly scale, effective winds are most frequent between March and October, while calm winds prevail mainly in January and December. The wind measurements further indicate that active winds predominantly originate from the N, NNE, and NE sectors, with additional contributions from the S and ENE directions.

Table 3. Variations of efficient winds and calm winds in the Arfoud station between 2023 and 2024.

Tabela 3. Variações de ventos eficientes e de ventos calmos na estação de Arfoud entre 2023 e 2024.

Winds	Jan.	Feb.	Mar.	Apr.	May	Jun	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
Calm winds (%)	74.2	31	0	0	0	0	0	0	8.3	19.4	45	70.9
Active winds (%)	25.8	69	100	100	100	100	100	100	91.7	80.6	55	29.1
Total %	100	100	100	100	100	100	100	100	100	100	100	100

Based on the aerological data recorded in 2023, wind frequency analysis by intensity distinguishes four categories: 0.6–4.6 m/s, 4.6–8.6 m/s, 8.6–12.6 m/s, and 12.6–16.6 m/s. The last three classes are the most effective in transporting sandy material. Moderate winds (6–10 m/s) are the most frequent and are mainly orientated S–N and SSW–NNE, with secondary orientations SW–NE and N–S. Weak winds (0.6–4.6 m/s), which account for 32% of total observations, are orientated S–N and SW–NE. Strong winds (>11 m/s), responsible for significant sand displacement, represent only 5.4%.

The 2024 data (Table 4) confirm the dominance of moderate winds (4–10.8 m/s), which represent 72% of total records and originate mainly from the N and NNE sectors. Strong winds, though less frequent, are orientated predominantly SSW–NNE and, to a lesser extent, S–N.

Table 4. Frequency distribution of wind speed (m/s) during the year 2024 in the Arfoud station.

Tabela 4. Distribuição de frequência da velocidade do vento (m/s) em 2024 na estação de Arfoud.

Speed in m/s		Overall total (%)
Wind fables	2.3 – 4	20.50
Moderate winds	4 – 5.7	21.80
	5.7 – 7.4	25.70
	7.4 – 9.1	17.40
	9.1 – 10.8	7.20
Strong winds	10.8 – 12.5	4.40
	12.5 – 14.2	1.70
	14.2 – 15.9	0.80
	15.9 – 17.1	0.60
Total		100.00

Using the equation of Fryberger (1979), the drift potential (DP) was calculated during the period 2023-2024. The results obtained showed that Tafilalet has a potential annual displacement of 270 UV, reflecting moderate wind energy. The average volume of displaced sandy material exceeds 18 m³/m/year. Regarding the migration coefficient, the results obtained revealed values with opposite tendencies, and this according to the years. We measured a coefficient of 0.3 during the year 2023 and of 0.06 during the year 2024. As mentioned by Callot & Oulehri (1996), when the migration coefficient tends to 1, a unidirectional wind shift develops. While, when the migration coefficient is close to 0, a multidirectional shift takes place. For the resulting direction, a value of 13° (NNE) was found.

Precipitation is a determining factor in the progression of sand encroachment due to the water film ensuring the moisture of the sands, and, consequently, wind transport becomes difficult, according to studies by Coudé-Gaussen (1994), Bogle *et al.* (2015), Sinsin (2020), Robine *et al.* (2023), Manzolli *et al.* (2023), Pedrosa & Claudino-Sales (2023) and Ben Kacem *et al.* (2025b), who indicated that dune mobility can be more difficult during precipitation events.

Time-scale rainfall analysis helps establish the relationship between sand encroachment rates and precipitation. Data from the Rissani area indicate that total rainfall between 1966 and 1987 averaged 74 mm/year. The years 1973, 1975, 1976, 1977, 1980, 1982, 1983, 1986 and 1987 were all below the “normal” range and marked by a high frequency of dry to very dry conditions. Climate data from 1987–2001 show a continuation of this aridity, with annual precipitation averaging only 49.8 mm. The relationship between sand dune mobility and rainfall variability was analyzed in the Haroune sand dune field east of Rissani (Fig. 8). Two key periods were considered: 2005–2012 and 2012–2023. During 2005–2012, longitudinal dunes in this area shifted approximately 24.47 m northeastward, with an average annual migration rate of 3.3 m/year. Total precipitation for this period reached 547.1 mm. In contrast, during 2012–2023, dune displacement decreased to an average of 2 m/year, while total precipitation rose to 922.5 mm. It is essential to note that the dune field of Haroune has not been subjected to the same type of human interventions as the site of Tizouint-Essifa.

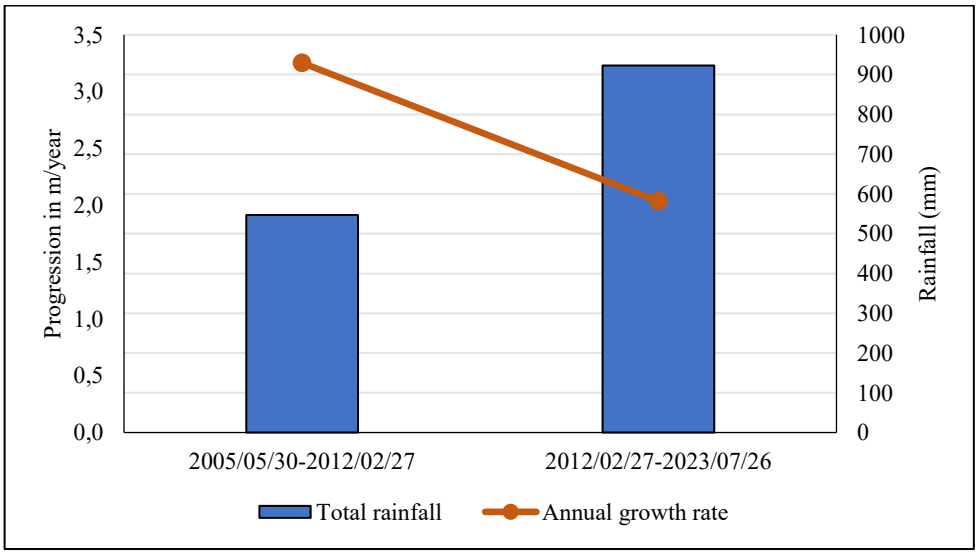

Figure 11. Migration rate of longitudinal dunes and precipitation in the Haroune field for the two studied periods.

Figura 11. Taxa de migração das dunas longitudinais e precipitação no campo de Haroune para os dois períodos estudados.

5. Conclusions

The sand encroachment affecting the Tafilalet plain constitutes a dominant geomorphological characteristic of the area. This process poses a serious threat, as it intensifies the degradation of the oasis-based agrosystems of Tafilalet. In this article, the examination of the Rissani sand dune system enabled the identification of the principal factors governing sand dune formation and the directions of their mobility. The initiation and progression of sand encroachment, like other manifestations of desertification, involve complex interactions. These processes cannot be attributed solely to natural variables, since human activities also exert a significant influence.

The Rissani perimeter is continuously supplied with aeolian sediments, expressed through barchan dunes along the western margin of the study area and sifs in its eastern sector. The findings of this article demonstrate that the control measures implemented have effectively limited dune expansion and facilitated the productive use of sandy surfaces for agricultural purposes. Human settlements and infrastructure in arid environments therefore require preliminary assessments of wind dynamics to reduce the risk of sand encroachment. A thorough understanding of sand dune system behavior is essential for the design of appropriate mitigation measures and land-use strategies. By analyzing sand encroachment processes, this study enhances knowledge of sand dune dynamics and provides a basis for informed planning and development in Saharan and pre-Saharan regions.

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